Journal of Environmental Science and Sustainable Development

Volume 3
Issue 2 *December*

Article 2

12-31-2020

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Recommended Citation
Hollingsworth, Ian D. (2020). PILLARS OF SUSTAINABLE DEVELOPMENT–LAND CAPABILITY AND CONCEPTUAL PROJECT DESIGN. *Journal of Environmental Science and Sustainable Development*, 3(2), 210-234.
Available at: https://doi.org/10.7454/jessd.v3i2.1069

Journal of Environmental Science and Sustainable Development
Volume 3, Issue 2, Page 210-234
ISSN: 2655-6847
Homepage: http://scholarhub.ui.ac.id/jessd

PILLARS OF SUSTAINABLE DEVELOPMENT–LAND CAPABILITY AND CONCEPTUAL PROJECT DESIGN

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(Received: 21 September 2020; Accepted: 5 December 2020; Published: 31 December 2020)

Abstract

Conserving land capability is a pillar of sustainable development strategy. Land units comprising unique combinations of native vegetation, soils, geology, and landforms are used to interpret local environmental processes and land capabilities. An emerging practice is extrapolation modeling of edaphic parameter surfaces in Digital Soil Mapping (DSM) using statistical correlation. Commercial studies of land capability for sustainable development, including a mine closure in a national park, another closure for grazing land restoral, urban stormwater flood mitigation, and wind farm development in plantation forestry, are presented to illustrate applications and review the utility of DSM data. The first case, a mine closure plan in Kakadu National Park in the Arnhem Land region of Australia's Northern Territory, involved the application of ecological methods to identify land unit patterns and design soil covers to support land capability for biodiversity. Species distribution models with good predictive performance (Receiver Operating Characteristic, ROC > 0.8) were used to assess biodiversity outcomes in the conceptual mine landform design. The second case, a coal project near Rockhampton in Central Queensland, assessed land capability from routine soil surveys and land unit mapping to plan mine rehabilitation for grazing land use. The third case, an end-of-pipe stormwater detention basin in Darwin, discussed the justification for capital works and low impact urban development practices. The fourth case involved the decommissioning of a wind farm project on a forestry plantation near Maryborough, Central Queensland. The study used surveyed soil and landscape properties and modeled DSM data with plant-available soil water capacity to three meters depth to evaluate the forest site quality and quantify the potential production loss. Applications of land capability for sustainability planning are demonstrated, and the utility of edaphic modeling is discussed. Uncertainty in DSM data and the implications for interpreting land capability need to be more clearly communicated.

Keywords: Ecosystem restoration; Ecological engineering; Land capability; Sustainable development.

1. Introduction

Overall, life cycle cost-benefit analyses that incorporate post-rehabilitation costs will support optimal sustainable designs. For mine rehabilitation, design support for post-mining land use is a critical cost issue (ICMM, 2019) and failure leads to broad social liability (DES, 2019).

DOI: https://doi.org/10.7454/jessd.v3i2.1069

Urban environments can cause overwhelming environmental degradation in previously undeveloped landscapes. Environmental infrastructure maintenance in urban settings is a multiple construction cost over the design life (Eckart, McPhee, & Bolisetti, 2017). Low impact development design paradigms that replace hard surfaces with vegetation, green rooves, permeable paving, and soil storage can be cost-effective and maintain the water, solute, and energy balance (Carter & Keeler, 2008; Wang, Harvey, & Jones, 2010; Wong, 2011). Any disjunct between ecosystem support and sustainable design tends to increase construction and maintenance costs and decrease environmental performance. Integrating geomorphology with the soil and vegetation to support functional, self-sustaining ecosystems is a critical issue for successful rehabilitation programs where landscapes are highly disturbed.

Ecologically engineered solutions either reduce the natural environment's developmental footprint or provide initial conditions that support restoration trajectories, which return natural levels of ecosystem function to disturbed landscapes (Tongway & Ludwig, 2011). Design for sustainability relies on incorporating the links between the geomorphic, soil and vegetation aspects of land capability into the conceptual project design. Environmental technologies that perpetuate land capability and local ecosystem processes such as water and solute balance within and around project areas are needed where the impact is unavoidable.

Conserving the productivity of prime farmland has the highest priority in mine rehabilitation regulation in the US, Australia, and elsewhere. For example, the US Surface Mining Control and Reclamation Act of 1977 specifies reinstating soil profiles to restore original productivity to reclaimed farmland. To this end, rehabilitated land is cropped to demonstrate that yields are sustained, while topographic properties of the reclaimed mine landscape that influence runoff patterns and infiltration for plant growth are also considered (Sinclair, Dobos, & Hipple, 2008). Although, validation by crop production isn’t specified in Queensland, the Strategic Cropping Land Act restricts mining and urban development in and around strategically important agricultural land across the state (DILGP, 2017). Technical guidelines for mine rehabilitation guide reinstatement of pre-existing land capability based on soil properties reflecting root depth limits and available soil water storage for plant growth and drainage (DME, 1995; DSITIA & DNRM, 2013).

Legislation in the US pertaining to sustainable rehabilitation of prime and high capability farmland (Surface Mining Control and Reclamation Act of 1977, SMCRA) specifies handling and placement of topsoil and subsoil materials to conserve root zone properties and

DOI: https://doi.org/10.7454/jessd.v3i2.1069

topographic slope requirements (30 CFR823, 2005). As a result, productivity of land reclaimed after surface mining for coal improved in most states (Sinclair, Dobos, & Hipple, 2008). Material handling and root zone soil properties (DME, 1995) get similar attention in Australian rehabilitation guidelines (DSITIA & DNRM, 2013) but without the validation step in the US conservation standards. Compaction impairs edaphic factors, affecting the abundance and flow of water into and below the root zone (Skousen et al., 2011). Soil covers constructed in rehabilitated open cast mine landscapes may be more chemically fertile but physical properties, principally rockiness and compactness, reduce vigor and diversity of revegetation compared with natural analog sites.

Woodland composition and the health and vigor of plant communities is closely associated with patterns of soil water storage, root zone depth and drainage in hillslope landscapes (Hollingsworth, 2010). Forestry site productivity is also closely associated with soil physical fertility, particularly plant-available soil water storage and root zone depth (Hollingsworth, Boardman, & Fitzpatrick, 1996; Liegel, 1991). Designing soils and landscapes are important aspects of sustainable rehabilitation design. Restoring soil quality amounts to restoring the capacity to function within ecosystem boundaries, sustain biological productivity, maintain environmental quality, and promote plant and animal health. To this end, soil reinstatement is a key requirement in guidelines for sustainable environmental rehabilitation of disturbed landscapes.

Restoring natural levels of biodiversity is a priority in areas with high conservation value. The edaphic and topographic settings are not defined as for cropland, rehabilitation defaults to species lists with little appreciation for limiting edaphic factors in the mined landscape. Consequently, natural ecosystem objectives for conservation land use are not met if clear habitat targets have not been defined. Hollingsworth (2010) developed an ecological design methodology based on natural analogs to restore land capability in highly disturbed areas. Selecting the reference ecosystems in this method to represent relatively pristine habitats and desirable restoration outcomes imply that the spatial scale and extent of environmental processes to be restored are understood (Ludwig & Tongway, 1995) and that natural analogs represent an appropriate environmental range for a project to develop reasonable sustainable design and validation methods.

Land capability restorations are best to be considered at the conceptual project design stage. At this stage, sustainable design is broadly concerned with perpetuating natural ecosystem processes such as water and solute balance and restoring desirable habitats and vegetation's edaphic properties. Site soil and land resource surveys are historically used to support restoration objectives. However, edaphic factor modeling produced from Digital Soil Mapping (DSM) and legacy soil surveys in Australia (Rossel et al., 2015) and globally (Thompson et al., 2020) can potentially augment, or replace, site surveys for land capability assessment.

Global and national digital soil mapping programs provide raster (25 m grid) edaphic data alternatives to site-based surveys (Arrouays, et.al., 2020; Thompson et.al., 2020; Rossel et al., 2015) with reliability estimates that don’t match traditional scale-based soil mapping guidelines (McKenzie & Austin, 1993). Estimated values from DSM are provided with 5 and 95 percentile values to describe reliability (Rossel et al., 2015). However, the ease of integrating this relatively high resolution edaphic data with GIS applications at site scales may need to be balanced against uncertainties associated with extrapolated soil data, which can be difficult to interpret (Arrouays et al., 2020).

Design validation that demonstrates environmental sustainability in land rehabilitation checks whether expectations are reasonable and rehabilitation methods effective. Sustainable rehabilitation of forest land capability can refer to historical site quality data. Sustainable rehabilitation of agricultural land can refer to soil and land capability guidance (DSITI & DNRM, 2015; Sinclair et al., 2008) and simulation modeling in rehabilitated landscapes (DSITI & DNRM, 2015; DSITIA & DNRM, 2013). Design validation can be particularly difficult where multiple biodiversity objectives cannot be resolved.

Validation of biodiversity objectives by simulation modeling refers to the ecological scale of natural analog selection, detailed survey support for natural environmental processes in analog areas, and convincing species distribution modeling of revegetation outcomes (Hollingsworth & Odeh, 2009). Presence-absence attributes are more readily predicted than continuous or scalar variables, while common features require less survey support than rare or scarce features. One hundred positive observations of presence-absence were needed to generate a ROC (Receiver Operating Characteristic) measure of predictive reliability >0.8 for common species, which was the cutoff for selecting reliable prediction models, while scarce features may need in excess of 400 positive observations in an analog area survey for reliable prediction (Hollingsworth, 2010). Confidence interval measures of uncertainty and reliability in DSM products can mask low statistical correlation coefficients <0.2 (Rossel et al., 2015) where survey support is lacking.

Land capability, the capacity to support pre-existing long-term productivity and ecosystem processes in a landscape, is a guiding concept in sustainable project design. Land units representing unique combinations of vegetation, soil, geology, and landform patterns and elements can be used to describe land capability. Land capability can be qualified according to the ecological scale and sustainable land use objectives. Ecological scale entails area and landscape context. For instance, hillslope or catchment, and includes the direct project footprint and surrounding receiving environments. Sustainable design reduces operational impacts to receiving environments to acceptable levels, limits the direct project footprint, and aims to restore pre-existing land capability at the project closure.

The investigations presented here are concerned with selecting analogs for land capability restoration and validating conceptual designs' environmental performance. Commercial land capability assessment studies have been reported here that include the application of historical land survey methods and, in one case, current DSM products to illustrate critical issues of information accuracy and environmental conceptualization.

2. Methods

The ecological design process (Hollingsworth, 2010) is outlined in Figure 1.

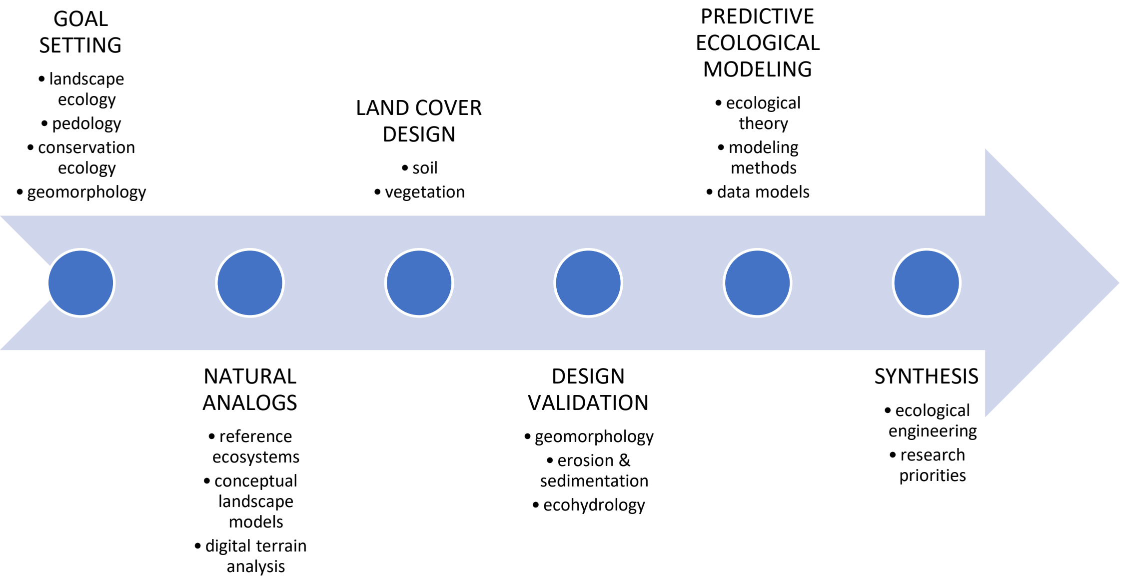


Figure 1. Conceptual framework of design using natural analogs

Source: Hollingsworth (2010)

Application of the ecological design method (Figure 1) using a simulation approach for natural ecosystem restoration as outlined in Hollingsworth & Odeh (2009). The case studies presented in this paper listed in Table 1 include natural ecosystem rehabilitation and restoring agricultural, silvicultural, and urban land capability. Each case's goals reflected either federally legislated requirements, local government urban development constraints, or state rehabilitation standards for sustainable development. Ranger uranium mine and Central Queensland Coal studies included detailed field environmental surveys supporting costed construction plans. Rapid Creek catchment and Land Wind Farm in the Toolara Forest were desktop studies supporting risk assessments.

Table 1. Case study projects and goals

Case study	Application	Goals
1. Ranger uranium mine closure plan (2010)	Mine landform design	Self-sustaining natural ecosystems
2. Central Queensland Coal project (2020)	Progressive mine rehabilitation plan	Restore grazing land capability
3. Rapid Creek catchment (2019)	Flood mitigation	<1% residential area flood risk
4. Forest Wind project (2020)	Windfarm closure plan	Restore forestry site quality

In the first case, mine rehabilitation design methods were developed that match topographic and edaphic soil and landscape design objectives in disturbed areas with natural analog area properties similar in ecological scale to the mined landscape (Hollingsworth, 2010). According to Australian soil and land survey guidelines, a stratified, gradient section sampling design with four replicates was used to survey soil, vegetation, and landscape properties (McDonald et.al., 2009). Analog areas were identified from a non-hierarchical classification of digital terrain attributes that reflected water movement, sedimentation, and erosion processes and relief. Edaphic design parameters in the rehabilitation were set to restore land capability for analog native vegetation and local water balance in hillslope topography.

In the second case, a free survey of soil and landscape properties was made according to Australian guidelines (McDonald et.al., 2009) to support progressive mine rehabilitation plans designed to restore pre-existing, Class C, grazing land capability (DES, 2019) according to guidelines for agricultural land evaluation in Queensland (DSITI & DNRM, 2015; DSITIA & DNRM, 2013). Class C of the agricultural land class system was divided into three subclasses–C1, C2, and C3 (Table 2). Native vegetation cover type is a key criterion in the classification.

Table 2. Regional land systems suitability ranking and agricultural land class correlation.

CODE	Pastoral Management	Typical Vegetative Cover
C1	Good quality grazing and/or highly suitable for pasture improvement	Brigalow vegetation—appropriate for fattening beef cattle; good grazing on sown pastures and can withstand ground disturbance Brigalow vegetation and/or transitional vegetation to Poplar Box vegetation communities
C2	Moderate quality grazing and/or moderately suitable for pasture improvement	Eucalypt woodland, Poplar Box, narrow-leaved Eucalyptus, gum-top woodlands—low-moderate PAWC and low-moderate fertility; good grazing on native pastures without ground disturbance; appropriate for beef cattle breeders
C3	Low quality grazing, grazing of native pastures with limited suitability for pasture improvement	Tea-tree vegetation—usually characterized by steep country or mangrove flats
D	Not suitable	Unsuitable due to extreme limitations

In the third case, an end-of-pipe urban stormwater retention basin construction project in Darwin Northern Territory was contrasted with low impact development guidelines that apply ecological engineering to urban design. The final cost-benefit ratio was 1.7 (excluding maintenance costs) for a 25 ML stormwater basin completed in 2019 to mitigate suburban flood risk to 39 properties. The basin was designed to accommodate runoff from expanding urban development and loss of native woodland cover in the catchment headwaters (DLPE, 2015) and was paid for from government asset sales.

Alternative ecological stormwater mitigation approaches that involve distributed rather than end-of-pipe solutions to stormwater management perpetuate natural runoff and infiltration rates (Houle et al., 2013). Life cycle costs for end-of-pipe environmental civil works are typically multiple construction costs (Gunes et al., 2011; Henderson, 1986; Jackson, Bitew, & Du, 2014). Ecological engineering design solutions include vegetated roofs (Carter & Keeler, 2008), wetland filters (Houle et al., 2013), vegetation retention, and permeable paving (Wang et al., 2010) that increase infiltration and use soil water storage capacity to mitigate stormwater risks, in contrast to constructed hard surfaces and catchment outlet civil works in environmental engineering designs. Swales, cisterns, and water tanks augment distributed water storage capacity to restore natural catchment water balance.

In the fourth case, decommissioning plans for a proposed wind farm in the Toolara State Forest (60,000 hectares) near Maryborough, Central Queensland, were reviewed to restore forestry productivity at decommissioning after windfarm turbine sites were rehabilitated. The edaphic constraint associated with retained concrete pad turbine foundations on *Pinus carribea* forest productivity was assessed from historical soil surveys and site productivity data, as well as modeled plant-available soil water store to 3 m depth from the national DSM coverage (Rossel et al., 2015).

2.1. Natural Analogs

To design the restoration of the natural habitat at ERA Ranger Uranium Mine, natural analog areas were selected using patch analysis in ArcGIS software (Rempel, Kaukinen, & Carr, 2012) of terrain attributes associated with habitat variations at similar scales as the disturbance (Hollingsworth, 2010), along with standardized soil and land survey methods (McDonald et al., 2009). Digital terrain attributes reflecting water and sediment movement, relief, and slope were classified using a non-hierarchical method (ALOC) in the PATN multivariate analysis package (Belbin, 1995). Landforms similar in habitat range and scale to the mine were then classified using ALOC on a hexagonal grid overlay of terrain attribute classes. Approximately 300 stratified sampling (200 m transect separation) sites were surveyed across the broader landscape using a gradient section survey design (Austin & Heyligers, 1989) to select natural analog areas. Analog areas with similar habitat contributions to the mine site were chosen for detailed grid surveys to support species distribution modeling. Approximately 100 grid survey (50 m grid) sites were studied in a selected analog area that comprised the range of habitats in targeted hillslope landforms.

Rehabilitation studies for Central Queensland Coal used standard soil and land survey methods (McDonald et al., 2009) at approximately 250 sites in a free survey designed to check map units in a regional land system (DPI, 1995). In addition, they described component land units and provided soil morphology and fertility profiles for growth media management in rehabilitation plans designed to sustain land capability after mine closures (DME, 1995b, 1995a, 1995d, 1995c).

To review stormwater management in the urban Rapid Creek catchment, Darwin Northern Territory, a published water balance study of a savanna woodland analog (Cook et al., 1998), was used as context.

Wind farm turbine pad rehabilitation options in the Forest Wind study were assessed from the mean effect on *Pinus carribea* plantation production from residual concrete foundations at 226 wind turbine sites in the Toolara Forest near Maryborough, Queensland. Forest productivity impairment was assessed from Toolara Forest site productivity mensuration reporting and: (i) DSM modeled plant showed available soil water storage in profiles to three meters depth (Rossel et al., 2015), which is a recognized site productivity factor for *Pinus caribaea* (Liegel, 1991); (ii) historical soil survey data, including soil great group, drainage class, depth to impedance layer, and landscape position attributes (Toolara State Forest, personal communication). Forest productivity plot measurements, DSM modeled grid points data, and historical soil survey site closest to wind farm turbine pads were selected and linked using proximal analysis in ArcMap. An analysis of the main effects of soil and landscape parameters on forestry productivity was made using Minitab 17 statistical software.

2.2. Land Cover Design

For land cover design at ERA Ranger Uranium Mine, water balance components and edaphic properties of mine materials used in a cover construction trial were measured, and the implications for cover design were evaluated by simulation using a water balance model. For a rehabilitated waste rock cover design at the Central Queensland Coal project, topsoil and subsoil stripping was specified to reinstate natural soil profile support. For the Rapid Creek urban stormwater catchment, the water balance of the native woodland was referred to (Cook et al., 1998) as an analog for distributed stormwater mitigation design. For the Forest Wind decommissioning plan in the Toolara Forest, the critical design issue involved reinstating the soil depth over the residual concrete wind turbine foundations needed to restore forest productivity.

3. Results and Discussion

3.1. ERA Ranger Uranium Mine

The terrain modeling results for a broad landscape surrounding ERA Ranger Uranium Mine and the combined habitat class-map that was derived from those results are depicted in Figure 2. Slopes were less than 3%, and the erosion/deposition index values were typical of low relief, water-shedding surfaces. However, the upland plateau landform dominated the landscape to the north and west of the study area. The upland plateau contrasted with the lowland peneplain on which the mine site was located. The three-dimensional drape of the habitat class-map shown in Figure 2a distinguished the upland plateau landscape in the north of the study area from the peneplane lowlands typical of the area comprising the mining landscape. Tan colored polygons in the landscape classification map Figure 2b match the habitat composition of the mine area (Ranger). Analog areas 7J and Georgetown were candidates for field survey support to describe ecological land capability.

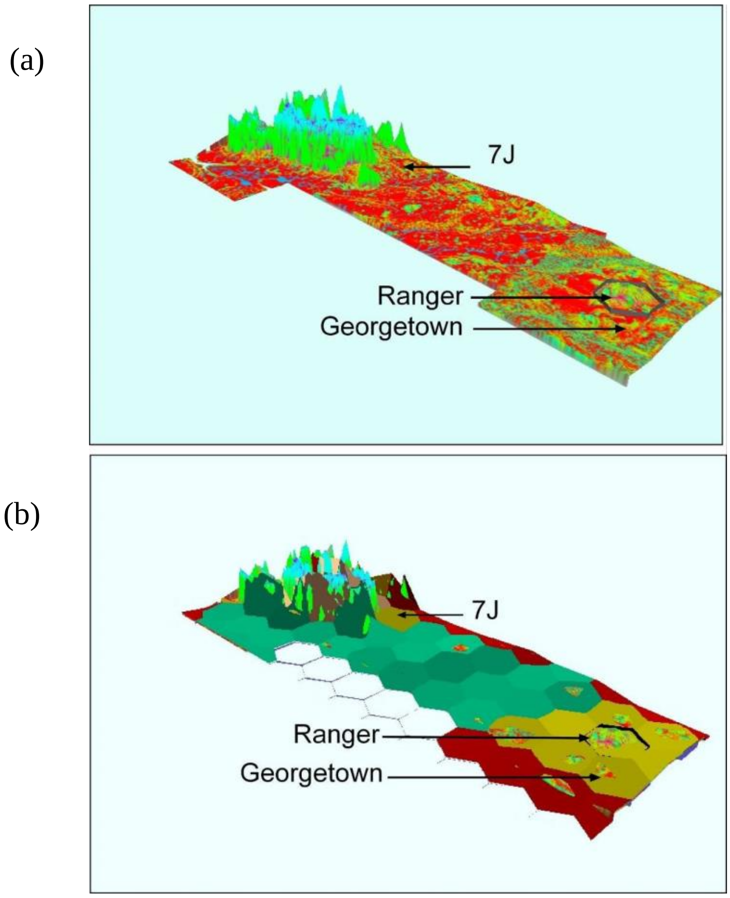


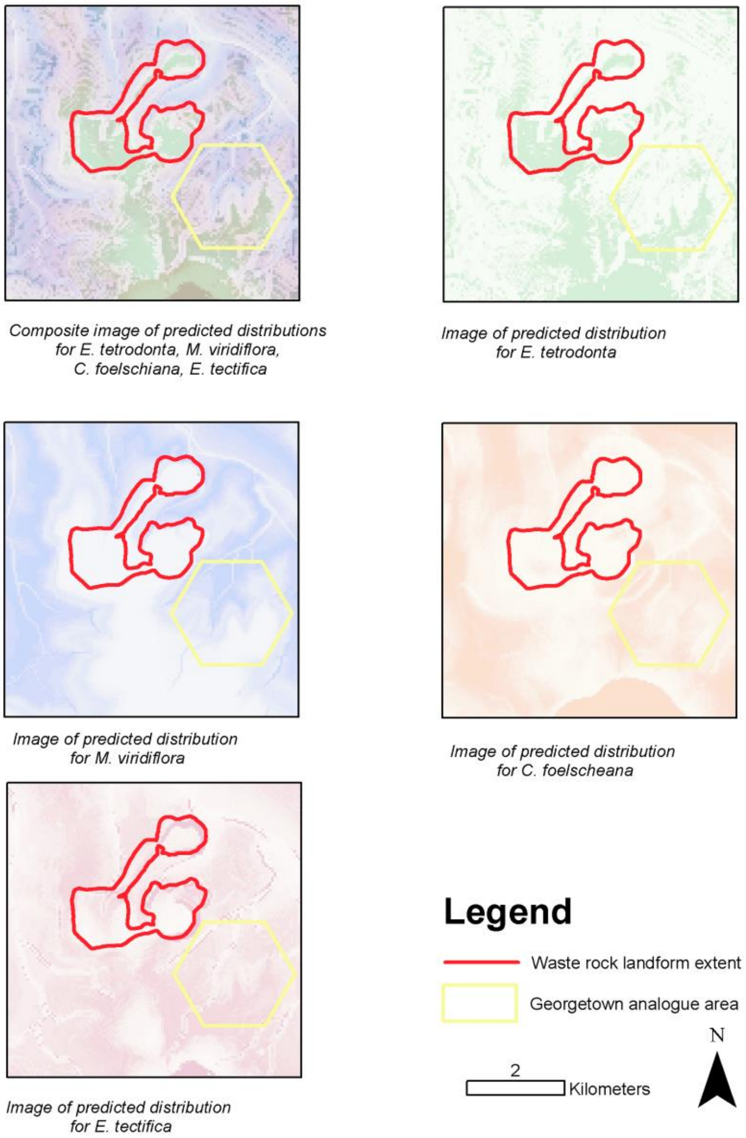
Figure 2. (a) Habitat classes in three-dimensional view, showing the extent of the Ranger final landform (10 x vertical exaggeration); (b) color-coded landscape classification in three-dimensional perspective view. Analogous landform polygons are tan colored.

Source: Hollingsworth (2010)

The natural analog areas represent lowland environmental variation in context with the mine landform without sacrificing environmental variation found over an extensive area. Appreciating the connectedness of landscape is important, as upland landforms can exert strong localized influences on soils, vegetation, and probably local climate in surrounding lowlands. The approach used preserved the context of hill slope environmental variation at the mine scale and carefully excluded extraneous escarpment environments that fringe upland plateau landscapes. The Georgetown area was selected for detailed survey based on its closer representation of substrate and geomorphic process in the Ranger mine landform to support the species distribution modeling used to validate landscape design.

The ROC and cross-validated receiver operating characteristic (CVROC) of generalized additive models (GAM) were used to select reliable species prediction models (SDMs). According to the validation statistics for SDMs of common and abundant woodland species, *E. tetrodonta*, *C. bleeseri*, *C. foelscheana*, *A. mimula*, *M. viridiflora*, and *P. spiralis* showed good discrimination and stability according to the interpretation of combined ROC and CVROC values (0.5–0.7: poor discrimination ability; 0.7–0.9: reasonable discrimination; 0.9–1: very good discrimination) (Swets, 1988). The predicted distribution of these four woodland species in and around Ranger mine are mapped individually and overlaid on Figure 3. The predicted pattern of *E. tetrodonta* and *E. tectifica* dominating the slopes and crests of the rocky low-rise waste rock landform and *M. viridiflora* and *C. foelscheana* on the lower slopes and drainage depressions matched observed natural species distributions.

DOI: https://doi.org/10.7454/jessd.v3i2.1069



Composite image of predicted distributions for E. tetrodonta, M. viridiflora, C. foelschiana, E. tectifica

Image of predicted distribution for E. tetrodonta

Image of predicted distribution for M. viridiflora

Image of predicted distribution for C. foelscheana

Image of predicted distribution for E. tectifica

Figure 3. Predicted species distributions for *Eucalyptus tetrodonta, Melaleuca viridiflora, Corymbia foelscheana, and Eucalyptus tectifica*

Source: Hollingsworth (2010)

Water balance simulation of Ranger mine waste rock cover design scenarios, including surface compaction, revegetation, and the drainage-limiting layer's thickness, is summarized in Figure 4. The annual drainage flux and hence solute flux to the surrounding environment estimated from the historical rainfall record is sensitive to surface compaction and the subsoil drainage-limiting layer. The highest range of annual drainage flux was associated with the current cover configuration. Effective revegetation of the existing cover reduced the drainage flux by half. Furthermore, increasing the thickness of a subsoil clay drainage-limiting layer from 0.3 to 1 and 2 meters (Scenarios C and D) reduced the drainage flux significantly (*p <

0.05). The lowest annual drainage flux range was achieved through the surface compaction treatment. However, surface compaction turns the landscape into a desert in a high rainfall tropical environment.

The waste rock cover was vughy with preferred pathway flow. Consequently, the water balance simulation of the estimated drainage flux was insensitive to changes in the water retention characteristics, i.e., large changes in the moisture characteristics produced only small changes in the drainage flux below 2.0 meters. The critical factors to cover performance were infiltration rate though the surface and groundwater recharge through a subsoil drainage-limiting layer.

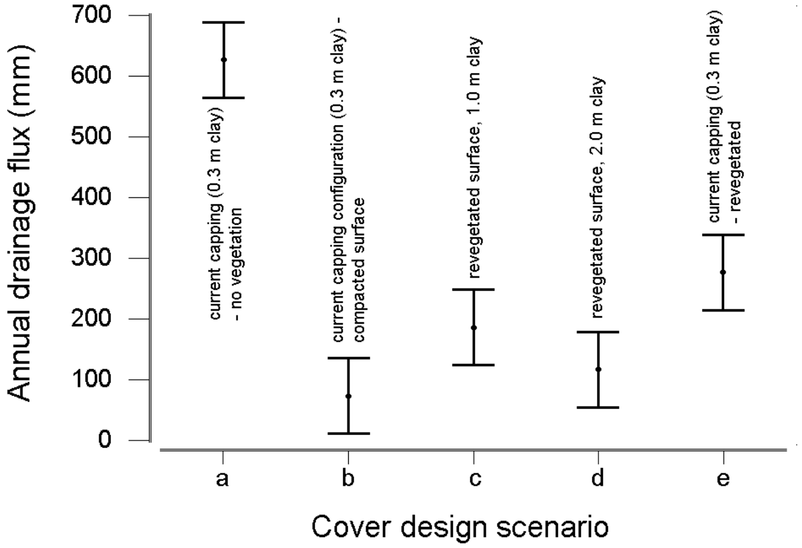


Figure 4. Average annual drainage flux showing 95% confidence intervals for different cover design configurations.

Source: Hollingsworth (2010)

3.2. Central Queensland Coal (CQC)

Representative soil types of the three soil map units in the CQC project area were cross-referenced with the relevant land systems identified in Lands of the St Laurence Region, Queensland (DPI, 1995). The soil map units are described in Table 3. Sections of good quality agricultural land within the project area were revised from 1,009 Ha (in 1:250,000 scale from regional mapping) to 406 Ha in 1:25,000 scale site mapping in this survey. Approximately 4,083 Ha of C2 class agricultural land is suitable for extensive dryland grazing of native or improved pastures.

Table 3. Land unit descriptions including land system associations

Unit ID	Map unit Description	Australian Soil Classification
	Woodstock, Ws Dissected low plateaus on gently dipping sedimentary rocks; red and brown, massive, gradational loams and clay loams supporting Eucalypt woodland (narrow-leaved ironbark, pink bloodwood, wattles)	
1	footslope	C2; Ferric-Sodic Dystrophic Brown Kandosol Thick Very gravelly Sandy Loamy Deep
	Torilla, Tl Undulating rises and low hills on deeply weathered sedimentary and metamorphic rocks; Red, gradational clay loams and uniform clays supporting Eucalypt woodland (narrow-leaved ironbark, pink bloodwood)	
1	hillslope	C2; Ferric Dystrophic Red Kandosol Medium Moderately gravelly Clay-loamy Clayey Deep
	Tooloomba, Tb Gently undulating plains and rises on sedimentary rocks; Bleached sandy and loamy surface, over brown and gray, alkaline sodic clay subsoils supporting Eucalypt woodland (narrow-leaved ironbark, Queensland peppermint)	
1	hillslope	C2; Ferric Dystrophic Red Kandosol Medium Moderately gravelly Clay-loamy Clayey Deep
	Styx, Sx Narrow floodplains along the Styx river; massive brown loams supporting Eucalypt woodland (blue gum, Moreton Bay ash)	
2	alluvial plain	A; Alluvial Soils *Non-Gravelly* Deep (Tenosols, Rudosols, Vertosols) Sandy Loam to Clay textures
3	valley flat	D; Alluvial Soils *Gravelly* Shallow (Tenosols, Rudosols, Vertosols) Sandy Loam to Clay textures
	Blackwater, Bl Level to gently undulating alluvial plains and rises on clay sediments with melon hole microrelief; gray and brown cracking clay soils supporting Brigalow woodland.	
4	alluvial plain	C1; Brown and Grey Sodic Vertosols Non-gravelly Medium Clay over Medium Heavy Clay
	Somerby, So Level to gently undulating terrace plains and rises on cracking clay sediments with melon hole microrelief; gray and brown, strongly sodic soils supporting Brigalow woodland.	

Unit ID	Map unit Description	Australian Soil Classification
4	alluvial terrace plain	C1; Brown and Grey Sodic Vertosols Non-gravelly Medium Clay over Medium Heavy Clay
	Plainview, Pv Gently undulating to level terrace plains on sediments; black and gray, strongly sodic bleached loamy and clay-loamy surface, over brown and gray, alkaline sodic subsoils.	
5	terrace plain	C2; Vertic Mesonatric Grey Sodosols Medium Non-gravelly Clay-loamy Clayey Moderately deep

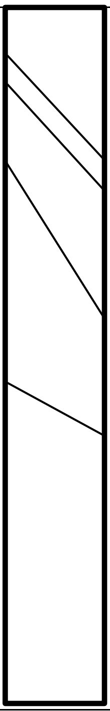
Conceptualization of soil types is shown in Table 4.

Table 4. Soil type conceptualization example

Concept:	Unit 4: Uniform textured cracking clay soils with shrink-swell properties on terrace plains and alluvial plains of Tooloomba Creek and the Styx River. Endohypersodic Crusty Brown & Grey Vertosols Non-gravelly Fine Medium fine Moderately deep; Episodic Crusty Brown Vertosol Gravelly Fine Medium Fine Moderately deep; Endohypersodic Epipedal Grey Vertosol Non-gravelly Fine Medium fine Moderately deep; Endohypersodic Crusty Brown Vertosol Non-Gravelly Fine Medium fine Moderately deep				
Detailed:	Reference sites 001, 002, 020, 041, 042, 048, 052, 066, 067, 113 in				
Surface properties:	Terraces, cleared for pasture, gravelly, melonhole gilgai microrelief, imperfectly drained, slope <1%				
Effective root depth	0.8 m		PAWC	75<100 mm	
Land capability	Sql	Capability	Suitability	Ag. Land class	Gqal
	No	V	2	C1	Yes
Limitations	Bicarb P, PAWC, Gilgai, EC, pH, Drainage, Water erosion				

DOI: https://doi.org/10.7454/jessd.v3i2.1069

Range in Characteristics

Depth cm		Morphology	pH	EC dS/m	ESP %	Chloride mg/kg	Bicarb P mg/kg	Erosion risk
0		**A1**						
10		LMC	6.5-8.1	0.03-0.04	2.6-10	20-40	<2	DI=2
20		dark grey						K=0.02
30		**A3** MC	6.9-8.8	0.03-0.7		190		
40								
50		**B2ss** MHC	7.5-8.2	0.03-0.91	16.4-22.5	310-1680		DI=2
60		greyish	brown					K=0.02
70		**B3** MHC	7.6-8.5	0.03-1.3		2580		
80								
90		brown						
100								
110		**C1** MHC	8.1-8.5	0.03-1.4	29	2890		
150								

The maximum recommended stripping depths of *primary* and *secondary soil media* in the progressive rehabilitation plan derived from the soil type descriptions shown in Table 5. Subsoil sodicity and chloride content was a constraint to suitability for subsoil stripping and reuse. The volume of primary media (topsoil) available across the CQC project area was estimated at 1.8 M cubic meters and secondary media (subsoil) at 7.8 M cubic meters. When a handling loss of 10% is allowed, volumes are reduced to 1.6 M cubic meters and 7.0 M cubic meters, primary media, and secondary media, respectively. The objective of the progressive rehabilitation plan is to use these materials to restore prior land capability values (Table 2) to the mine area.

Table 5. Growth media stripping depths

Soil map unit	Topsoil depth (m)	Subsoil depth (m)	Land class	Area (m^2)	Subsoil volume (m^3)	Topsoil volume (m^3)
Alluvial Soils–Gravelly sandy alluvial soils (Rudosols)						
Unit 2, 3	0.3	1.0	D	232,070	232,070	69,621

Soil map unit	Topsoil depth (m)	Subsoil depth (m)	Land class	Area (m^2)	Subsoil volume (m^3)	Topsoil volume (m^3)
Earthy Soils–Kandosols Gravelly red and brown earths sandy to loamy over clay loam						
Unit 1	0.3	0.6	C2	409,571	245,743	122,871
Sodic Texture-contrast Soils–Sodosols Gravelly gray and brown texture-contrast soil clay loam over highly sodic cracking clay subsoil (Sodosol)						
Unit 5	0.1	0.5	C2	13,946,673	6,973,336	1,394,667
Cracking Clay Soils–Vertosols Non-gravelly gray and brown cracking clays with highly sodic subsoils soils (Vertosols)						
Unit 4	0.3	0.5	C1	681,605	340,803	204,482
Total					4.8M m^3	1.4M m^3

Recommended soil stripping depths for primary and secondary media are identified on Figure 5.

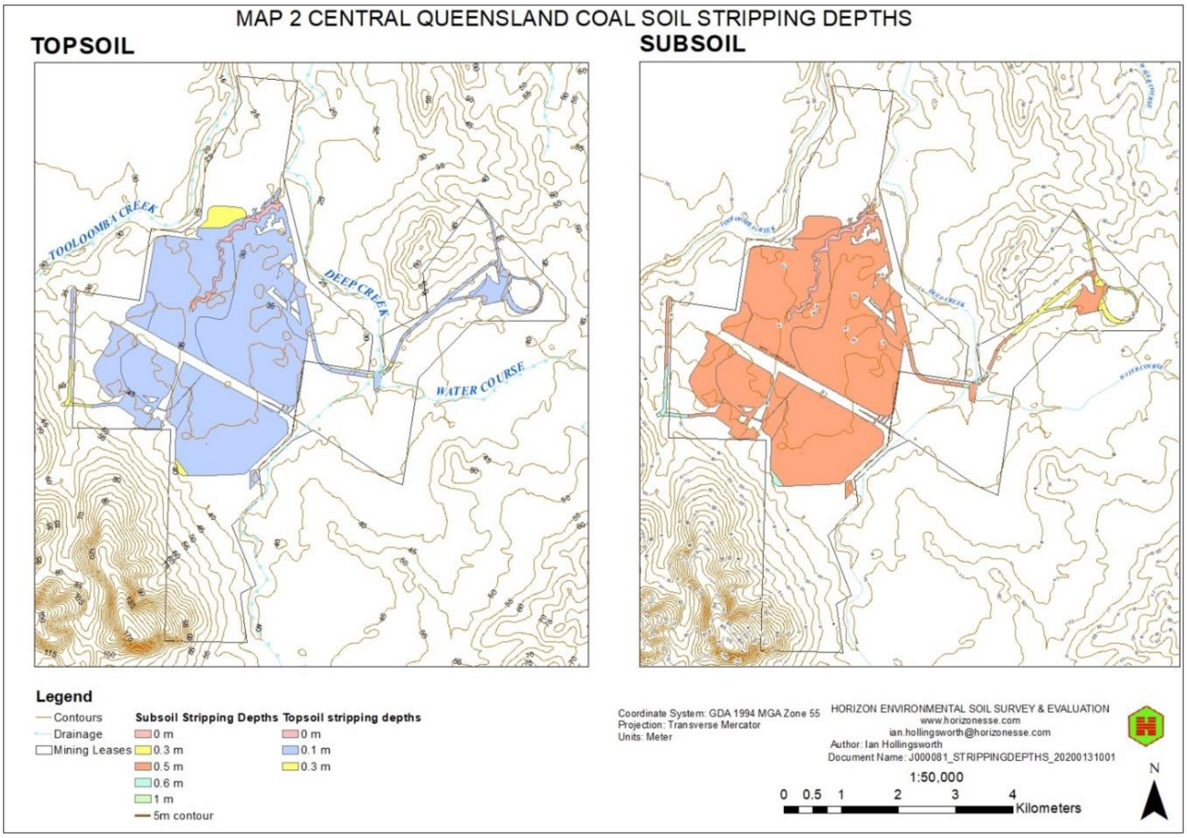


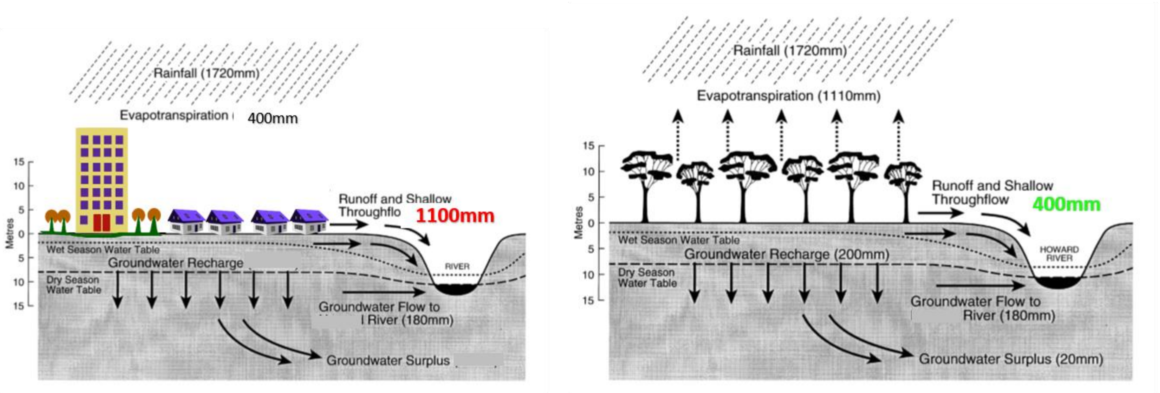
Figure 5. Topsoil and subsoil stripping depths

3.3. Rapid Creek catchment Stormwater Management

Heightened flood risk arises from the additional 700 mm of runoff reporting to Rapid Creek (Skinner, Townsend, & Fortune, 2009) compared with natural analog water balance (Cook et al., 1998) is depicted in Figure 6. Constructed 25ML stormwater retention basin (Figure 7) at the outlet from catchment headwater urban development was completed in 2019 at a cost of AUS$11.7 M. Estimated benefits are AUS$6.6M (DLPE, 2015) to flood mitigation for 36 residential properties built on the floodplain.

Storm water is the largest source of contaminants and flood risk

Storm water has value as a resource and an amenity



The broad community cost can be calculated in $100M

(Cooke et al 1998 Journal of Hydrology)

Perception that it is costly, impractical and unenforceable.

Figure 6. Conceptual model of urban and natural water balance

Source: Cook et al. (1998)

Figure 7. Rapid Creek stormwater retention basin

DOI: https://doi.org/10.7454/jessd.v3i2.1069

3.4. Toolara Forest Wind Farm Rehabilitation

The main effects plots (Figure 8) show the relative strength of the mean productivity response to each soil factor individually on the range standardized productivity. No mean effect was observed of available water capacity (AWC) on forest productivity. Rossel et al. (2018) extrapolated AWC data from regional soil survey data outside the project area by environmental correlation (particularly with elevation) with correlation coefficients <0.2. This extrapolated DSM data was unrelated to site productivity and excluded from further analysis.

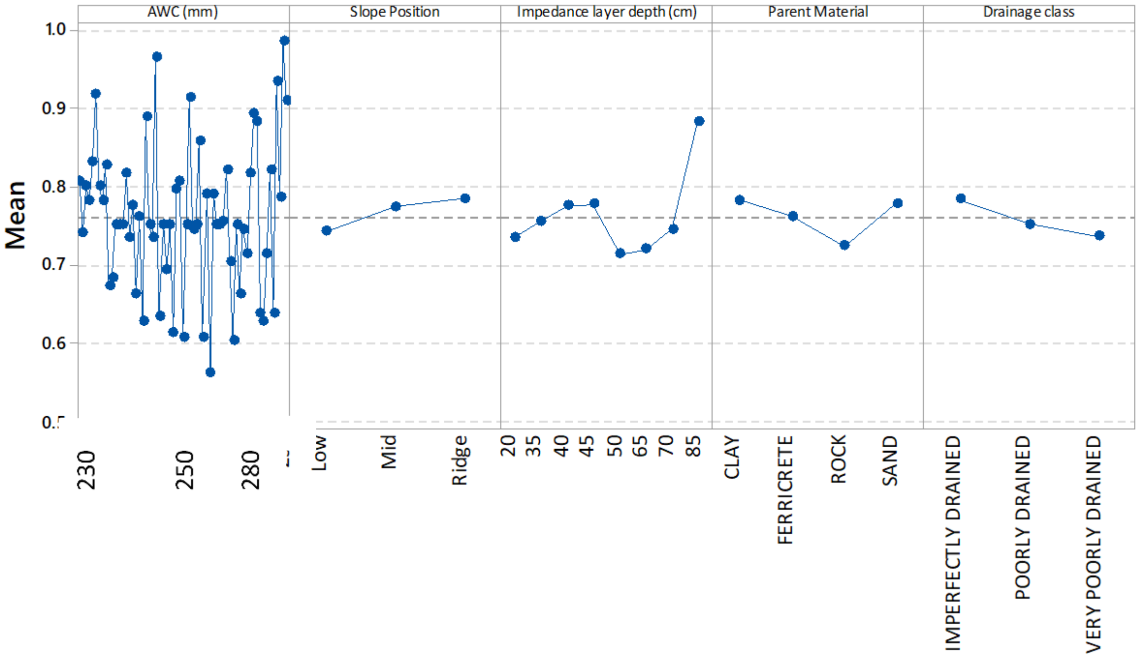


Figure 8. Main effects plot of edaphic factors and range standardized forest productivity

The site productivity model developed from soil and landscape survey data is summarized as

a. Range Standardized Yield Potential = 1 - (Root Zone Limitation effect + Poor Drainage Effect).

Where: as

b. Depth to Impedance Effect = 0.2 when depth to impedance is ≤0.85 m,

c. Poor Drainage Effect = 0.1 where drainage is poor (permeability ≤50 mm/day).

Assuming that the site quality data is normally distributed, the depth to impedance (root zone limitation) and drainage have a linear effect on productivity and are additive in combined effect. Consequently, a change from well-drained or imperfect drainage to poor or very poor drainage and root zone limitation introduced at ≤ 85 cm depth is predicted to reduce forest yield by 30%. Wind farm construction will impact 226 sites or 22 hectares, which have an estimated productivity of 15 cubic meters per hectare per year. This totals 330 cubic meters per year. The volume production with remediation varies between different concrete foundation remediation options from pre-construction levels to a minimum of 216 cubic meters per year.

Remediation involving removing a concrete wind turbine plinth, partial excavation of the retained foundation, and fracturing of any retained foundation is predicted to sustain pre-construction forest productivity, provided soil stockpiles are well managed. Matching soil reinstatement to existing soil depth and drainage conditions ensures that topsoil and subsoil are handled separately to maintain topsoil fertility. Subsoil edaphic constraints may need to be mitigated, and reinstatement managed to place the topsoil last, on top of the subsoil. Successful treatment of subsoil can make up for shortfalls in topsoil in rehabilitation planning.

4. Conclusion

Land capability is integral to landscape restoration to meet sustainability objectives for agricultural, forestry, and urban development. In principle, land capability in areas disturbed by development needs to match natural analog areas to support sustainable development. Failure to do this entrains resources that can add up to multiples of construction costs.

Unless substrate conditions are extreme in disturbed areas, ecosystems will potentially function similarly to comparable ecosystems on natural analog sites. Consequently, designs using analogous natural landscapes can identify long-term outcomes and accelerate natural remediation processes if initial conditions are critical to long-term remediation. Accurate representation of water, nutrients, erosion, and sediment distribution processes in disturbed and natural landscapes support realistic restoration goals and shifts the initial focus of environmental investigations from particular issues such as erosion or biodiversity to integrated landscape design to sustain land capability.

Land unit analysis and mapping can provide a holistic ecological context for sustainable design that current DSM approaches focused on modeled edaphic properties with uneven survey support do not clearly communicate. Note that thorough uncertainty analysis was beyond the scope of the commercial case studies reported here. However, given the availability of DSM products at resolutions applicable to sustainability investigations at site scales it is important to understand how uncertainty limits the utility of this information. More transparent and efficient methods than confidence intervals are needed to communicate the reliability of modeled DSM information and how it can be included in site survey support to avoid poor outcomes.

Author Contributions

Ian D. Hollingsworth as author are fully handling the whole article.

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