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RESEARCH ARTICLE

Monitoring of sustainable land management using remotely sensed vegetation cover and variable tolerable soil erosion targets across New South Wales, Australia

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Abstract

The monitoring of land management practices is vital for the protection of soil resource and the environment. Here, we present a new approach to monitor sustainable land management using widely available remotely sensed data, such as MODIS fractional vegetation cover data. The method is based on the concept of maintaining sufficient vegetation cover to prevent hillslope water erosion beyond tolerable soil erosion targets. The targets were based on long-term natural erosion rates plus a small constant and are spatially and temporally variable, not static as in most reported studies to date. Where vegetation cover is more than that required to prevent nontolerable erosion under normal conditions for that calendar month, the site (pixel) is deemed to be managed sustainably. Monthly indices are then combined to form a yearly sustainable land management index (SLMI), presented as raster maps with a spatial resolution of 100 m. We explored this new method through case studies over New South Wales (NSW), Australia, over the period 2010 to 2021, with a particular examination of 2020. Results were further stratified by land uses and natural resource management regions, which revealed useful data and trends. The method is offered as an example of the potential use of readily available vegetation cover data to quantitatively assess and monitor levels of sustainable land management across landscapes. We believe it overcomes the limitations of previous methods to monitor vegetation cover and land management from remote-sensed data alone. Other users are encouraged to adapt the broad approach to meet local requirements.

KEYWORDS

monitoring, remote sensing, sustainable land management, tolerable soil erosion, vegetation cover

1 | INTRODUCTION

There is an ever-increasing need for the protection of soil and land resources through the adoption of sustainable land management practices. This is imperative to meet the rising demands on agricultural production and for the provision of vital ecosystem services such as maintaining biodiversity, water quality and carbon stocks. Effective monitoring of soil condition and levels of sustainable land management is key to the protection of soil resources and is highlighted in several international environmental agreements (Cowie et al., 2011). The concept of land degradation neutrality (LDN) is now being promoted as a global Sustainable Development Goal (UNCCD, 2016) in order to maintain healthy and productive land by adopting measures that avoid, reduce and reverse land degradation, with monitoring programs being a core component (Cowie et al., 2018).

Such monitoring programs can contribute to the identification of regional areas and land management issues in need of priority treatment. Although schemes to monitor soil condition, and hazards, are widespread, there are fewer reported schemes on the direct monitoring of broader sustainable land management. Existing schemes include the FAO Framework for Evaluating Sustainable Land Management (FESLM) (FAO, 1993), Land Use Impact Model (LUIM) (McNeill and MacEwan 2007); the Land Management within Capability (LMwC) framework (OEH, 2014, Gray et al. 2015) and monitoring for *Land Degradation Neutrality* (Cowie et al., 2018). The difficulty and cost of gathering land management data in the field is an obstacle to the development and implementation of these land management monitoring schemes. Different approaches to the monitoring of sustainable land management that are based on readily available remote-sensed data are required.

Schemes for the monitoring of vegetation cover using remotely sensed data have been proposed as surrogate methods to monitor land management, particularly in relation to rangeland management, with early international examples presented in Pickup et al. (1994), Booth and Tueller (2003) and Ludwig et al. (2007) and a recent Australian example presented in Guerschman et al. (2018). An ongoing issue with such vegetation cover monitoring schemes has been how to effectively distinguish between changes arising from (i) natural influences such as climatic (weather), topographic and soil factors and (ii) land management influences such as stocking rates. To identify the land management influences, recent innovative schemes have applied a 'relative benchmarking' approach, where the vegetation cover over target pixels is compared in an automated process to the vegetation cover over nearby reference sites that represent minimally disturbed and preferably physically equivalent locations (Bastin et al., 2012, 2014; Donohue et al., 2022; Hobbs et al., 2018; Nauman et al., 2017). Whilst providing valuable data and insights into land management over their subject areas, these approaches have difficulties and limitations in effectively identifying equivalent reference sites to meaningfully compare with the target sites.

Other approaches to the monitoring of sustainable land management with remotely sensed data have focused on the assessment and monitoring of soil erosion, typically using modelling tools such as the Revised Universal Soil Loss Equation (RUSLE), the Revised Wind Erosion Equation (RWEQ) or new albedo-based wind erosion models, with useful studies in Australia (Hairsine et al., 2009; Jeanneau et al., 2021; Leys et al., 2017; McKenzie et al., 2017; Teng et al., 2016; Yang, 2020; Zhang et al., 2022) and in other countries (Karydas et al., 2020; Panagos et al., 2014). However, modelled soil erosion rates alone are not necessarily indicative of levels of sustainable land management, as again, physical factors such as climate, topography and soil condition need to be distinguished from purely land management factors.

Some schemes for monitoring land management are based around targets for minimum ground cover, below which erosion is likely to occur and imply unsustainable land management. Estimates of 50% cover to prevent wind erosion and 70% cover to prevent water erosion have been applied in Australia (Lang, 1979; Leys, 1999; Leys et al., 2017; McKenzie et al., 2017). However, these single threshold values do not recognize that different cover targets are required to prevent erosion under different topographic and climatic conditions. More steeply sloping lands with high rainfall erosivity require higher targets than gently sloping lands with low rainfall erosivity (Lang & McDonald, 2005). An alternative approach for establishing targets for vegetation cover and associated land management performance across the landscape is required.

The approach we adopt here involves the concept of tolerable soil erosion and more specifically, setting vegetation targets at variable levels to ensure that 'tolerable soil erosion' is not exceeded across the landscape. Tolerable soil loss values are considered to vary depending on the environmental objective or required outcome. Values based on retaining agricultural productivity will differ from those that are based on long-term soil formation and denudation rates or impacts on surrounding aquatic environments (Li et al. (2009) and Bui et al. (2011)). In Australia, tolerable erosion rates to retain agricultural productivity are typically assigned at 0.5–1.0 Mg ha^{-1} year^{-1} (Bui et al., 2011; Edwards & Zierholz, 2000) This appears slightly higher than the long-term erosion/denudation rates for the erosive east coast Australian catchments derived from cosmogenic radionuclide studies by Codilean et al. (2021) but is considerably higher than the reported Australian wide equilibrium soil formation and denudation median rate of 0.1 $\mathrm{Mg\,ha^{-1}\,yr^{-1}}$ (Bui et al., 2011). The tolerable erosion rates applied in Europe and North America are typically substantially higher, normally over 1 $\mathrm{Mg\,ha^{-1}\,year^{-1}}$ (Montgomery, 2007; Verheijen et al., 2009).

However, there are also drawbacks associated with the allocation of single uniform tolerable erosion levels such as 0.5 $\mathrm{Mg\,ha^{-1}\,year^{-1}}$, as levels that might be considered 'tolerable' will vary across the landscape, being considerably higher in steep terrain than in gently sloping terrain. Erosion rates can be high under steep terrain, even under natural ecosystem conditions, e.g., over 1 $\mathrm{Mg\,ha^{-1}\,year^{-1}}$ in southeastern Australia (Jeanneau et al., 2021; Yang et al., 2022). The concept of natural erosion rates recognize that erosion occurs even under natural areas with no human interference (Bartley et al., 2015; Vanacker et al., 2014). We set our variable tolerable erosion targets at slightly greater than the natural erosion rates.

In this study we explore an approach for the monitoring of vegetation cover relative to variable tolerable erosion levels that are based on natural soil erosion rates plus a small constant, building on a framework we initiated in Yang et al. (2022). It is based on the concept that sustainable land management should have vegetation cover levels sufficient to prevent erosion beyond tolerable erosion targets that vary across the landscape. Our aims were to:

- demonstrate a method that uses readily available satellite-derived fractional vegetation cover data to create continuous metrics of sustainable land management over time and space,
- apply the method in case studies over NSW and a natural resource management (NRM) region over 2020 and the period 2010–2021,
- assess the performance of the method as a useful tool for monitoring sustainable land management.

2 | METHODS

2.1 | The study area

The state of NSW in eastern Australia covers an area of 810,000 $\mathrm{km^2}$, slightly larger than France or Texas (Figure 1). The climate varies from moist, warm temperate in the north and east, to hot arid in the far west and sub-alpine in the highlands of the southeast. The landscape of the east features the Great Dividing Range, a mountain range reaching a maximum height of just 2200 m. This transitions to gently undulating slopes of central NSW, and then to the flat plains of the western inland regions. Soils vary from very high to very low fertility types, depending on climatic, parent material and topographic conditions (DPIE, 2021a; OEH, 2018). Land uses vary in response to the wide range of environmental conditions, including nature reserves, native and plantation forestry, grazing on native and introduced pastures, horticulture, dryland and irrigated cropping and urban development.

The Central Tablelands Local Land Services (LLS) region was selected for a case study, being suitably representative of the physical and climatic condition of the 11 natural resource management (NRM) regions in NSW. The region occupies an area of 31,365 $\mathrm{km^2}$ in the centre of the State (Figure 1), within the tablelands of the Great Dividing Range. The elevation is mostly above 600 m reaching 1390 m. The predominantly gently sloping terrain becomes steeper towards the east of the region. Major rivers, including the Macquarie and Lachlan Rivers, drain to the west, forming part of the Murray-Darling catchment system. Land use is dominated by grazing on native and improved pastures, with grain cropping activity in flatter areas, particularly in the west. Horticulture including orchards and vineyards is limited but increasing in extent throughout the region.

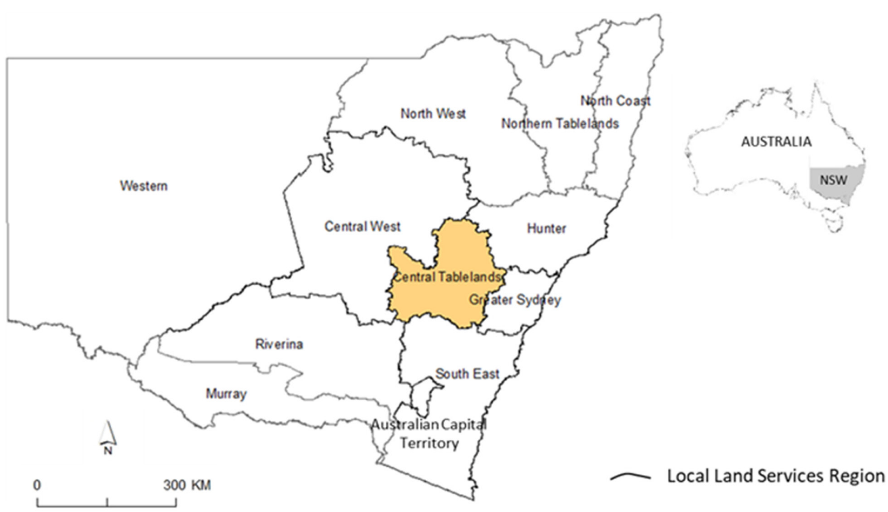

FIGURE 1 NSW local land service regions, with the Central Tablelands LLS highlighted

Native ecosystems in national parks and reserves, and plantation forestry, are common in the steeper eastern areas (DPIE, 2021b). Further physiographic and natural resource management details are available from the LLS region's website (LLS, 2022).

2.2 | Vegetation cover data

The vegetation cover data were sourced from the Moderate Resolution Imaging Spectroradiometer (MODIS) (Collection 6) with a spatial resolution of 500 m. The twice-daily satellite overpasses were used to create monthly composites which have minimal gaps due to cloud or other data omissions.

The MODIS data were applied to derive fractional vegetation cover (FVC) products comprising photosynthetic green vegetation (PV), nonphotosynthetic vegetation (NPV) and bare soil (BS) as described by Guerschman et al. (2015) and Guerschman and Hill (2018). This FVC product (version 3.1.0) incorporated an increased number of validation sites and has reduced uncertainty relative to previous versions. Using the combined PV and NPV layers was considered to give more meaningful estimates of vegetation cover than the traditionally used green vegetation indices such as the normalized difference vegetation index (NDVI, Lu et al., 2003) or the enhanced vegetation index (EVI, Teng et al., 2016).

Monthly time series products from January 2001 to December 2021 were downloaded through the CSIRO MODIS product website (CSIRO, 2021) and are also viewable, with trend plots and tabular data, in the GEOGLAM—RAPP website (GEOGLAM, 2021). Data were downscaled to 100 m using the resampling tool in ESRI's ArcGIS.

2.3 | The process

In overview, the broad approach adopted was to assess whether vegetation cover across NSW lands was sufficient to prevent hillslope water erosion beyond tolerable levels. The tolerable erosion rate has two components: (i) spatially variable long-term natural erosion rates (varies for each pixel) plus (ii) a small additional tolerable erosion rate (constant across all lands). The sum of these two components gives the required spatially variable tolerable erosion rate across the State. Where the actual vegetation cover is more than the cover required for the effective prevention of nontolerable erosion, the land is considered to be sustainably managed. Recent rainfall conditions are also qualitatively considered when interpreting the results. In the current study, only hillslope water erosion is considered, but future versions are expected to include wind erosion. A broad outline of the process is presented in Figure 2 and described in more detail in the following subsections.

2.3.1 | Derive natural erosion rates (NE)

The spatially varying natural, long-term sheet erosion levels were derived for each pixel across NSW using GIS techniques, rather than relying on reported single basin-wide estimates of long-term erosion derived from techniques such as cosmogenic radionuclide denudation rates (Bartley et al., 2015; Codilean et al., 2021, and other studies reported in Bui et al., 2011).

The natural erosion rates were determined for each of the 12 calendar months over the 2001–2021 period (e.g., average for April) for each pixel. This step involved the use of layers presenting average 'bare soil' erosion rates for each calendar month over the 2001–2021 period, this being the magnitude of erosion under zero vegetation cover (in Mg ha^{-1} $month^{-1}$). It was calculated using the RUSLE (Renard et al., 1997), as per methods outlined in Yang (2020) and Yang et al. (2022), with the cover factor C set at 1.0, indicative of bare soil.

Natural vegetation cover across the State was derived by spatially interpolating (splining) the vegetation cover of protected natural reserves (such as National Parks) over the 20-year period across the entire state (Figures 3a,b). Such reserves were taken to represent 'natural' conditions for that area of the state. It is evident that vegetation cover even under protected land status in the dry far west is much lower than in the moist east of the state.

For each level of natural vegetation cover, there is a corresponding cover factor ($C_{natural}$) that can be multiplied by the bare soil erosion rate, to give the expected natural erosion (NE) rate under that natural vegetation cover level.

$$\text{NE} = \text{bare soil erosion x } C_{natural} \quad (1)$$

A quantitative relationship determined by Yang (2014) and also reported by Yang et al. (2022) allows the derivation of the $C_{natural}$ factor. For example, if a natural conservation area has an average vegetation cover of 95% a $C_{natural}$ value would be 0.0003 based on Yang (2014). This $C_{natural}$ is then applied to the bare soil erosion rate to estimate the average NE rate based on Equation 1. The 'natural' annual water erosion rate (2001–2021) across NSW at 100 m resolution is shown in Figure 4a.

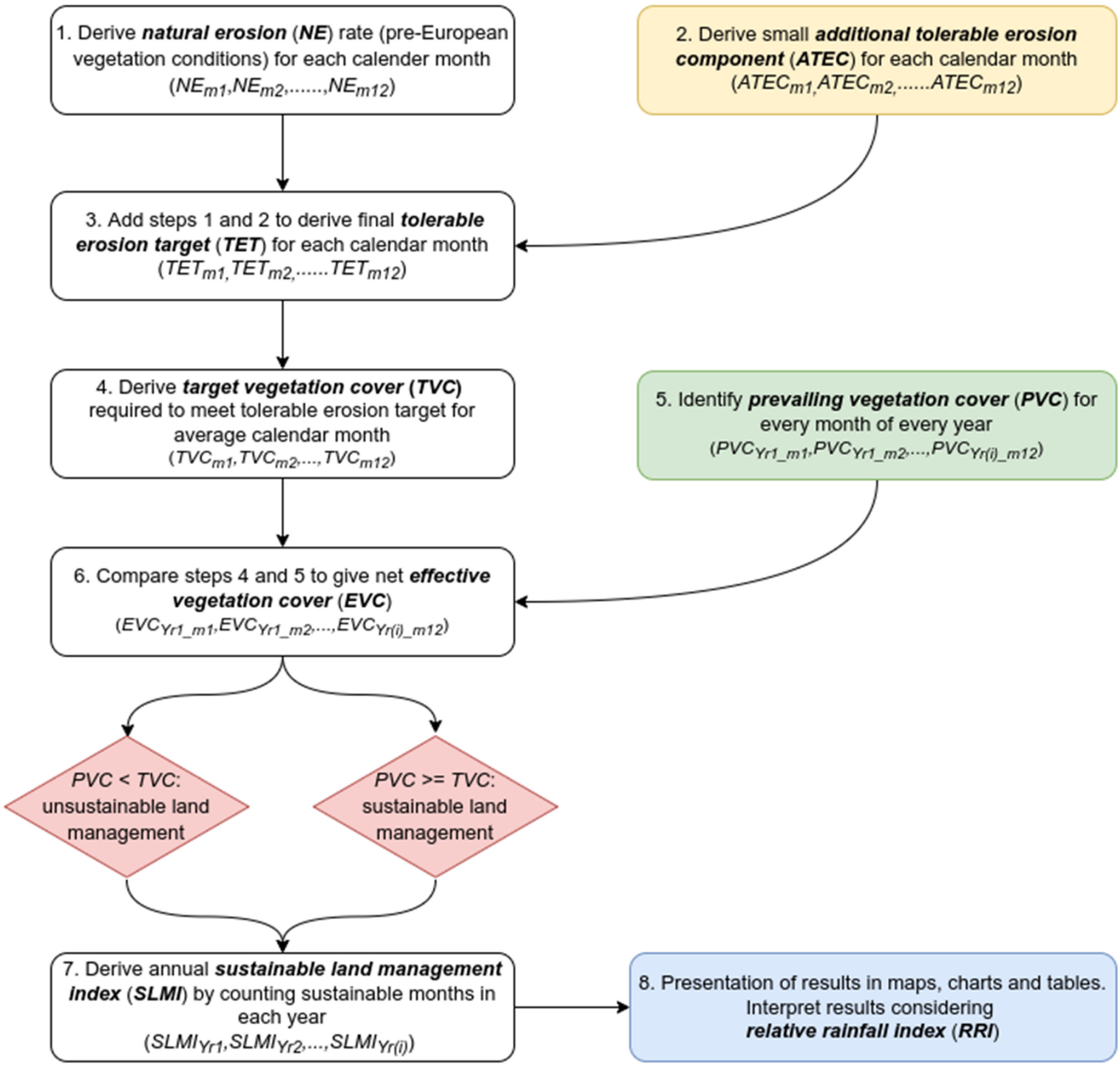

FIGURE 2 Flowchart of overall process

2.3.2 | Determine a small additional tolerable erosion component (ATEC) for adding to the natural erosion component.

Following a process of trial and error, it was recognized that setting a tolerable erosion target equivalent to natural erosion alone (from step i) was too lenient and thus too easy to be met by land managers in gently sloping agricultural lands, and did not lead to meaningful final results. It was determined that an additional small constant was required to be added to the natural erosion component to achieve meaningful and realistic final tolerable erosion targets.

The small *additional tolerable erosion component (ATEC)* was set at a constant 0.1 Mg ha^{-1} year^{-1} being the median of the long-term soil formation/denudation rate in Australia from pre-2011 Australian studies as reported by Bui et al. (2011). After exploring a number of different settings for the ATEC, ranging from nil upwards, this setting at 0.1 Mg ha^{-1} year^{-1} was found to achieve the best final results in all landscapes (including flat to steep terrain).

This ATEC for each month could be most easily derived by simply dividing the annual rate by 12 to derive an approximate monthly value of 0.009 Mg ha^{-1} month^{-1}; however, more accurate monthly estimates were attained by applying weighting factors of state-wide average ratios of monthly erosivity to annual erosivity. Equation 2 is an example of the weighting for January or month 1 (R_{m1}), and the same method has been applied for all 12 months:

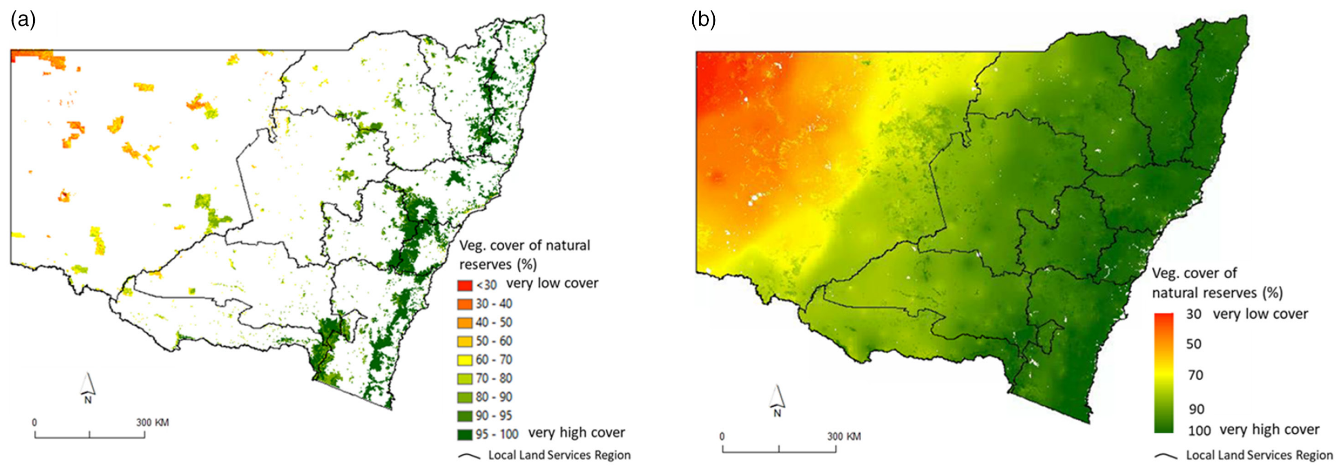

FIGURE 3 (a) Natural vegetation cover of natural reserves, (%, average annual 2001–2021). (b) Interpolated natural vegetation cover, average annual % (based on natural reserves, 2001–2021)

TABLE 1 Additional tolerable erosion components (ATECs) by calendar month for NSW, for an annual target of 0.1 Mg ha^{-1} year^{-1}

Month	ATEC (Mg ha^{-1} month^{-1})
Jan	0.0132
Feb	0.0201
Mar	0.013
Apr	0.0046
May	0.0042
June	0.0047
July	0.0025
Aug	0.0027
Sept	0.0031
Oct	0.0066
Nov	0.0128
Dec	0.0124
Year (Mg ha^{-1} year^{-1})	0.100

$$ATEC_{m1} = ATEC_{ann}{}^{*}\, R_{m1} / R_{ann} \quad (2)$$

where $ATEC_{m1}$ and $ATEC_{ann}$ are the additional tolerable erosion components in month 1 and annually; R_{m1} is the monthly rainfall erosivity in month 1 and R_{ann} is the annual rainfall erosivity (Yang, 2014; Yang & Yu, 2015). The *additional tolerable erosion components* for each calendar month are presented in Table 1.

2.3.3 | Derive final tolerable erosion target (TET)

The derived spatially variable natural erosion (NE) rate was supplemented with the small, constant additional tolerable erosion component (ATEC) to derive the final tolerable soil erosion target (TET) for each calendar month (Equation 3). The addition of the average monthly rates gave the annual rate across NSW, as presented in Figure 4b.

$$TET = NE + ATEC \quad (3)$$

After exploring a number of different combinations and settings for the NE and ATEC components, this relationship was found to achieve the most meaningful setting of the final TET. It was shown to provide targets that were realistic and meaningful for all land uses, from nature conservation on steeply sloping terrain to cropping use on gently sloping or flat land.

2.3.4 | Derive target vegetation cover (TVC)

The vegetation cover required to prevent erosion above the final tolerable erosion target was derived for each calendar month for each pixel. It involved the determination of the C factor for each pixel by rearranging the relationship of Equation 1 but using the final tolerable soil erosion target (TET) instead of natural erosion (NE).

$$C_{m1} = TET_{m1} / \text{bare soil erosion}_{m1} \quad (4)$$

The equivalent target vegetation cover relating to this C factor was again derived using the relationship of Yang (2014).

$$TVC_{m1} = \left(-0.7541 - \ln\left(C_{m1}\right)\right) / 0.074, \quad (5)$$

where C_{m1} is the cover factor in month 1 (1–12), and TVC_{m1} is the *target vegetation cover* (%) needed in month 1 to achieve the *tolerable erosion target* of month 1.

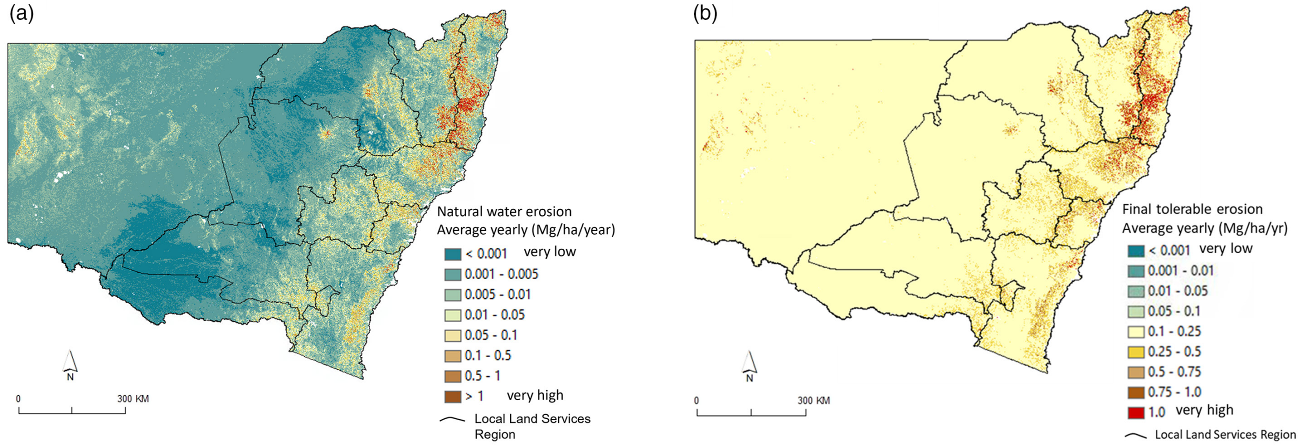

FIGURE 4 (a) *Natural erosion* (*NE*, from water 2001–2021) using vegetation cover from natural reserves (Mg ha^{-1} yr^{-1}). (b) Final *tolerable erosion target (TET)* (natural erosion plus the small *additional tolerable erosion component* (*ATEC*) (2001–2021, Mg ha^{-1} yr^{-1})

2.3.5 | Identify prevailing vegetation cover (PVC)

The total vegetation cover (photosynthetic and nonphotosynthetic vegetation) at each pixel was derived for each month of the subject years (2010–2021), as described in s2.2, to give the prevailing vegetation cover (PVC).

2.3.6 | Compare prevailing vegetation cover (PVC) with target vegetation cover (TVC) to derive net effective vegetation cover (EVC)

The difference between the *prevailing vegetation cover* and the *target vegetation cover* was derived for each pixel to give the net effective vegetation cover (EVC) for each month of each year. Where prevailing vegetation cover exceeds the required target level, the EVC is positive and land management was deemed to be sustainable.

$$\mathrm{EVC_{m1}} = \mathrm{PVC_{m1}} - \mathrm{TVC_{m1}} \tag{6}$$

2.3.7 | Derive annual sustainable land management indices (SLMI)

Adding the number of months in a calendar year with positive net *effective vegetation cover* gave the annual SLMI for each pixel (Equation 7). This indicates the number of months in the year with *effective vegetation cover*, an indicator of sustainable land management.

$$\mathrm{SLMI}_{\mathrm{Yr}(i)} = \sum_{m=1}^{12} \mathrm{EVC}_m, \mathrm{EVC}_m = \begin{cases} 0, \mathrm{EVC}_m < 0 \\ 1, \mathrm{EVC}_m \geq 0 \end{cases} \tag{7}$$

2.3.8 | Present and interpret results considering relative rainfall index (RRI)

SLMI results across the State and over different years are displayed in raster maps (100 m resolution). They are further stratified by NRM region and land use classes, i.e., (i) cropping, (ii) grazing, (iii) nature conservation/forestry and (iv) all uses, and presented in charts and tables. In addition to the annual SLMI, it was useful to derive proportions of the State or an NRM region with SLMI values greater than a benchmark level, for example, areas where SLMI > 9, indicating areas where land is being managed sustainably for at least 10 months (more than ¾) of the year.

The influence of recent rainfall conditions over the preceding 12 months of any subject month was considered important in the final interpretation of results, as maintaining adequate vegetation cover can be challenging in dry periods, even under normally effective land management regimes.

For this purpose, a relative rainfall index (RRI) was created (Equation 8). This represents the total rainfall over the preceding 12 months compared with the long-term average rainfall (2001–2021 period).

$$\mathrm{RRI} = \left(\mathrm{R_{preceding\ 12\ months}} / \mathrm{R_{long-term\ average}}\right) \tag{8}$$

Thus, for example, if an area had received 400 mm year^{-1} over the preceding 12 months, and the long-term average annual rainfall was 600 mm year^{-1}, the RRI would be 400/600 or 0.67. At this stage in the development of our scheme, the RRI is considered only on a qualitative basis when interpreting trends of SLMI. All rainfall data were sourced from the gridded data of the Australian Bureau of Meteorology (BoM, 2021).

3 | RESULTS

The method is demonstrated with three case studies over (i) localized sites in the Central Tablelands LLS; (ii) the entire Central Tablelands LLS; and (iii) all NSW, focusing on the year 2020. Results for all 11 LLS regions are presented in Supplementary Information.

3.1 | Case study 1: Two localized sites in the Central Tablelands LLS

The potential of the method to identify apparently non-sustainable land management is demonstrated by the examination of two sites in the Central Tablelands LLS for April 2020 and that entire year (Figures 5a–f). The two sites, A and B, are both predominantly cropping enterprises on gently undulating land (3%–10% slope) within broader areas of similar land use and form (Figure 5a,b).

Both sites have prevailing vegetation cover (PVC) lower than the surrounding areas during the subject month (April 2020), as revealed by the MODIS fractional vegetation cover image (Figure 5c). These cover levels are compared with the target vegetation cover (TVC, Figure 5d), ie, the cover required to prevent erosion beyond the tolerable erosion target applicable for April of any normal year. The net effective vegetation cover (EVC) (ie, PVC-TVC) of Figure 5e reveals predominantly negative values over the two sites for the subject month, indicating there was insufficient vegetation to prevent intolerable erosion in these areas for that month.

The results for each month of 2020 were combined to give the Sustainable Land Management Index (SLMI) for that year (Figure 5f). Relatively low yearly SLMI values are evident for Sites A and B, ranging from 4–8, compared with most surrounding areas with values 9–12. This indicates the two sites had fewer months in that year with sufficient vegetation to ensure tolerable erosion, suggesting less sustainable land management than surrounding lands, especially in site B where most pixels achieve the vegetation cover target in only 4 months or less of that year.

3.2 | Case study 2: Central Tablelands LLS

The operation of our method is now demonstrated at coarser scale for the entire Central Tablelands LLS over

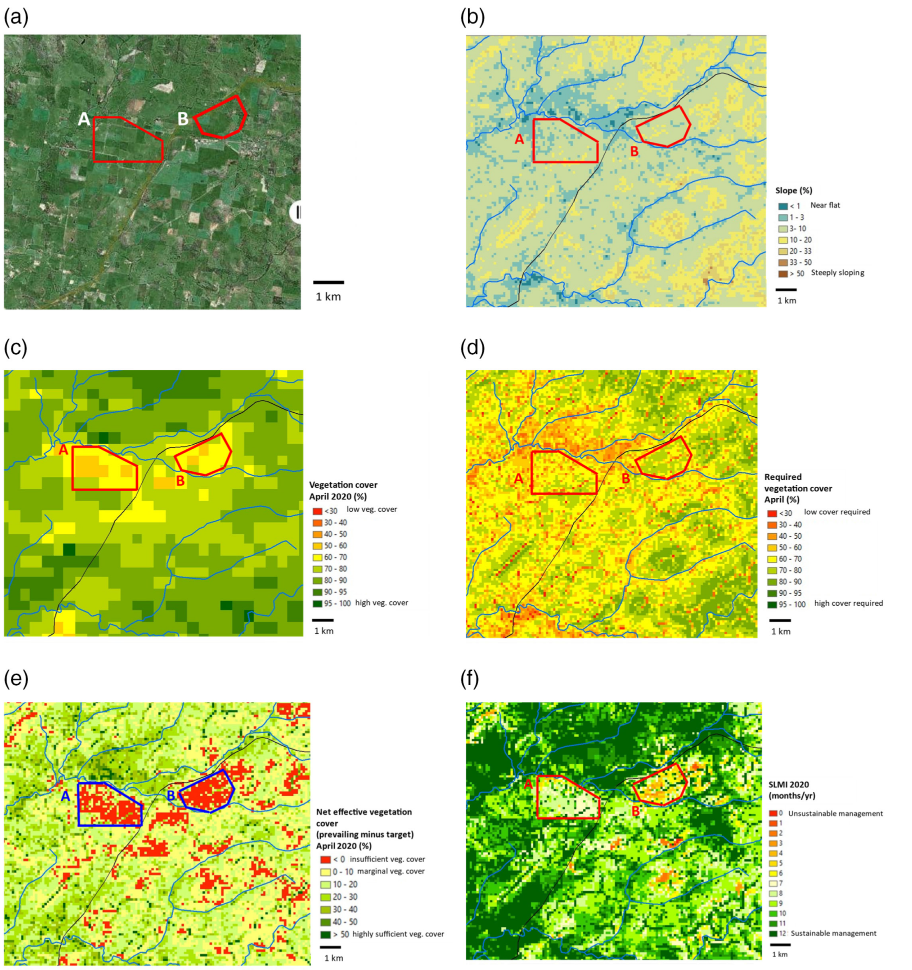

FIGURE 5 Demonstration of method over two sites in Central Tablelands LLS. (a) Satellite imagery, unspecified date. (b) Slope (%). (c) *Prevailing vegetation cover (PVC)*, April 2020 (%). (d) *Target vegetation cover (TVC)*, April (all years). (e) Net *effective vegetation cover (PVC-TVC)*, April 2020. (f) *Sustainable Land Management Index (SLMI)*, 2020 (months with sufficient vegetation cover for tolerable erosion)

April 2020 and the whole year (Figures 6a–h). The topography and land use of the region, as broadly described in s.2.1, are presented in Figures 6a,b, respectively.

Figures 6c,d, respectively, present the *prevailing vegetation cover* for April 2020 (from MODIS) and the *target vegetation cover* for April of any year. The difference between these cover levels is presented in the 'net *effective vegetation cover*' images (Figure 6e,f). The latter uses two classes only, indicating vegetation cover levels as either sufficient or insufficient to prevent erosion beyond the tolerable level. Both images reveal a moderate area with insufficient vegetation cover for the subject month, particularly in the higher relief areas in the central north and the east of the region, mainly associated with grazing, forestry and nature conservation.

The results for each month of 2020 were combined to give the Sustainable Land Management Index (SLMI) for that year (Figure 6g), revealing the number of months for each pixel where land management was broadly sustainable. A generally similar spatial pattern to that displayed for the single month of April is evident, but the areas of concern are less widespread.

A broad indication of rainfall patterns influencing the subject year is presented through the relative rainfall index (RRI) in Figure 6h. It is evident that most of the LLS received slightly less than average rainfall over the preceding 12-month periods throughout 2020. This is important to consider when comparing results with other years, as maintaining adequate vegetation cover under dry conditions can be challenging for all land managers. Results may have also been influenced by the extensive bushfires that impacted the eastern part of this region from late 2019 to early 2020.

Further data, trends and insights into the land management performance of the Central Tablelands LLS are evident from the charts presented in the following section, dealing with results for all NSW.

3.3 | Case study 3: Results for all NSW

The final map of the yearly SLMI across NSW for 2020 is presented in Figure 7. This indicates widespread areas of concern over the tableland regions of eastern NSW and the rangelands of far western NSW. Widespread areas are demonstrated to have nonsustainable vegetation cover for 4 or more months of the year, with some areas having unsustainable cover for almost the entire year. The majority of the state is revealed to have at least one or more months with unsustainable vegetation cover. The vegetation cover was frequently less than that required to prevent intolerable erosion under normal conditions for each month. However, a large belt in the central and central west part of the State does display sustainable vegetation cover for all 12 months of the year.

These results should be considered in conjunction with the prevailing recent rainfall conditions. Figure 8 presents the relative rainfall index (RRI) for 2020 and reveals that throughout this year, the preceding 12 months were typically drier than average for much of the State. This at least partly accounts for the lower-than-required prevailing vegetation cover that contributed to the relatively low SLMI values over much of the State. The temporal trends in SLMI and RRI across the State over the preceding decade are discussed below.

The charts of Figures 9 and 10 present SLMI results for the Central Tablelands LLS and all NSW over the period 2010–2021. These charts also stratify results by the land use categories of cropping, grazing, nature conservation/forestry and all uses.

The trends over the 12-year period for the LLS and all NSW are notably similar, reflecting our contention that the Central Tablelands LLS is a suitable representative of the whole State. Values are typically slightly lower for the LLS than for all NSW, indicating slightly less sustainable vegetation cover levels, except for the nature conservation/forestry use where values are slightly higher.

Figure 9 reveals that for NSW the average SLMI values are typically high. For all uses combined (Figure 9d), values were typically approximately 11.5, but dropping down to approximately 10 in 2018 and 2019, before rising to over 11 in 2021. Cropping land use has the highest values, followed by grazing, with nature conservation/forestry having the lowest values.

Similar high magnitudes and trends over the period are revealed for the proportion of area with SLMI > 9, i.e., 10, 11 or 12 months (Figure 10). For all uses combined (Figure 10d), this proportion was close to 95% between 2010 and 2017, before dropping down to 80% in 2019, then rising back to 90% in 2021. Again, the proportions are highest for cropping land use, followed by grazing, with nature conservation/forestry having the lowest values.

These state-wide results reveal that in terms of our sustainable land management index (SLMI), cropping land use performed best, followed by grazing use, then nature conservation/ forestry land use. This ordering represents the degree to which each land use maintained sufficient vegetation cover to prevent intolerable water erosion. This should be interpreted in light of the fact that cropping typically occurs on flat or very gently sloping land, where it appears to be relatively easy for the land manager to maintain sufficient vegetation cover levels to prevent erosion. Conversely, nature conservation/forestry lands typically occupy steep parts of the landscape, subject to high erosion risk, where it appears to be more difficult for the land manager to maintain vegetation cover levels

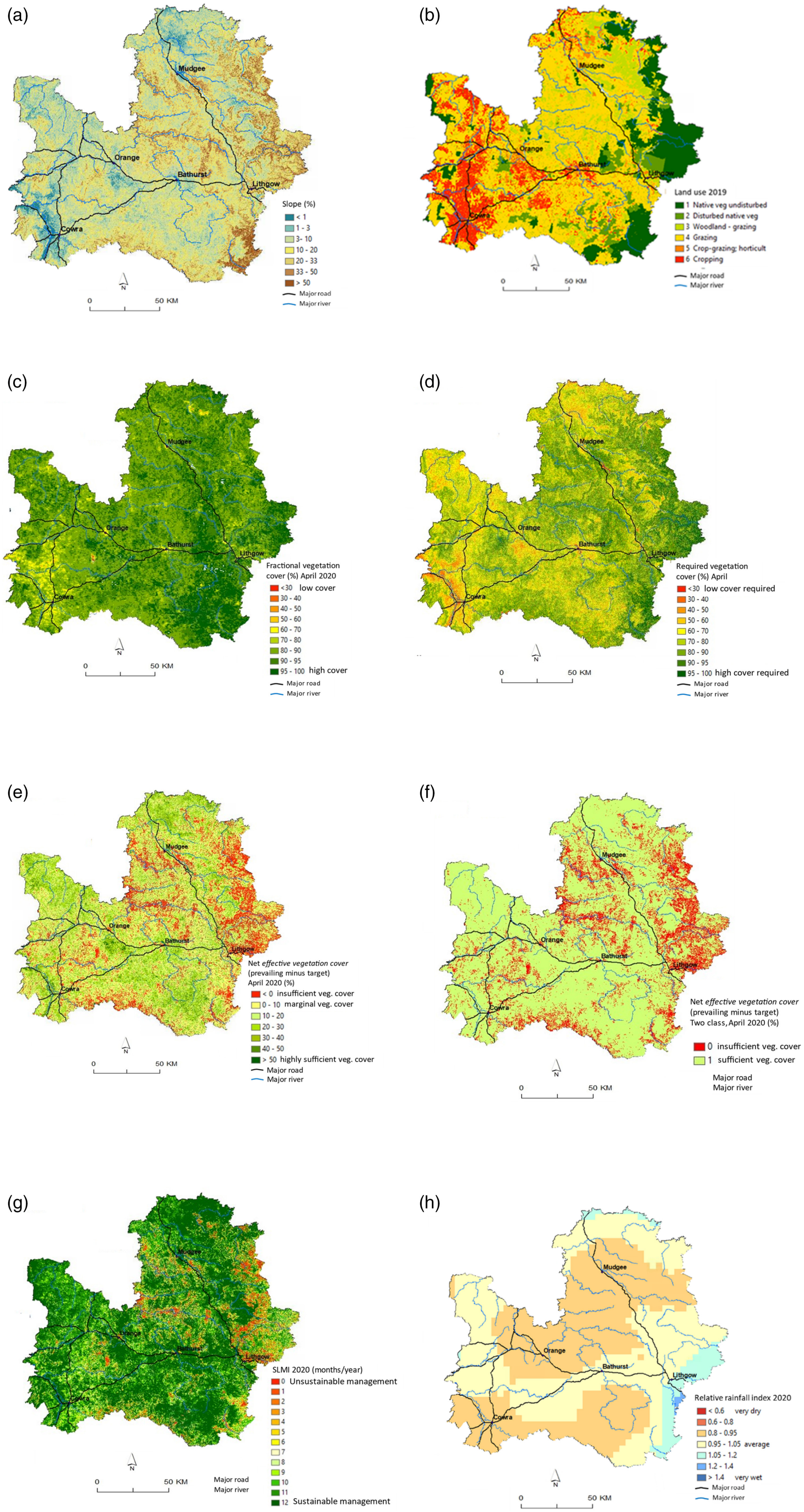
(a)
Mudgee
Orange
Bathurst
Lithgow
Cowra
Slope (%)
< 1
1 - 3
3- 10
10 - 20
20 - 33
33 - 50
> 50
Major road
Major river
0
50 KM
N
(b)
Mudgee
Orange
Bathurst
Lithgow
Cowra
Land use 2019
1 Native veg undisturbed
2 Disturbed native veg
3 Woodland - grazing
4 Grazing
5 Crop-grazing; horticult
6 Cropping
Major road
Major river
0
50 KM
N
(c)
Mudgee
Orange
Bathurst
Lithgow
Cowra
Fractional vegetation cover (%) April 2020
<30 low cover
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 95
95 - 100 high cover
Major road
Major river
0
50 KM
N
(d)
Mudgee
Orange
Bathurst
Lithgow
Cowra
Required vegetation cover (%) April
<30 low cover required
30 - 40
40 - 50
50 - 60
60 - 70
70 - 80
80 - 90
90 - 95
95 - 100 high cover required
Major road
Major river
0
50 KM
N
(e)
Mudgee
Orange
Bathurst
Lithgow
Cowra
Net effective vegetation cover (prevailing minus target) April 2020 (%)
< 0 insufficient veg. cover
0 - 10 marginal veg. cover
10 - 20
20 - 30
30 - 40
40 - 50
> 50 highly sufficient veg. cover
Major road
Major river
0
50 KM
N
(f)
Mudgee
Orange
Bathurst
Lithgow
Cowra
Net effective vegetation cover (prevailing minus target) Two class, April 2020 (%)
0 insufficient veg. cover
1 sufficient veg. cover
Major road
Major river
0
50 KM
N
(g)
Mudgee
Bathurst
Lithgow
SLMI 2020 (months/year)
0 Unsustainable management
1
2
3
4
5
6
7
8
9
10
11
12 Sustainable management
Major road
Major river
0
50 KM
N
(h)
Mudgee
Orange
Bathurst
Lithgow
Cowra
Relative rainfall index 2020
< 0.6 very dry
0.6 - 0.8
0.8 - 0.95
0.95 - 1.05 average
1.05 - 1.2
1.2 - 1.4
> 1.4 very wet
Major road
Major river
0
50 KM
N

FIGURE 6 Demonstration of method over the Central Tablelands LLS. (a) Slope (%) Central Tablelands LLS. (b) Land use, Central Tablelands LLS (2019). (c) *Prevailing vegetation cover*, April 2020. (d) *Target vegetation cover* required for final tolerable erosion, April (2001–2021) (%). (e) Net *effective vegetation cover* (prevailing minus target vegetation cover), April 2020. (f) 2 class net *effective vegetation cover* (prevailing minus target vegetation cover), April 2020. (g) Yearly *Sustainable Land Management Index (SLMI)*, 2020. (h) *Relative rainfall index (RRI)*, 2020

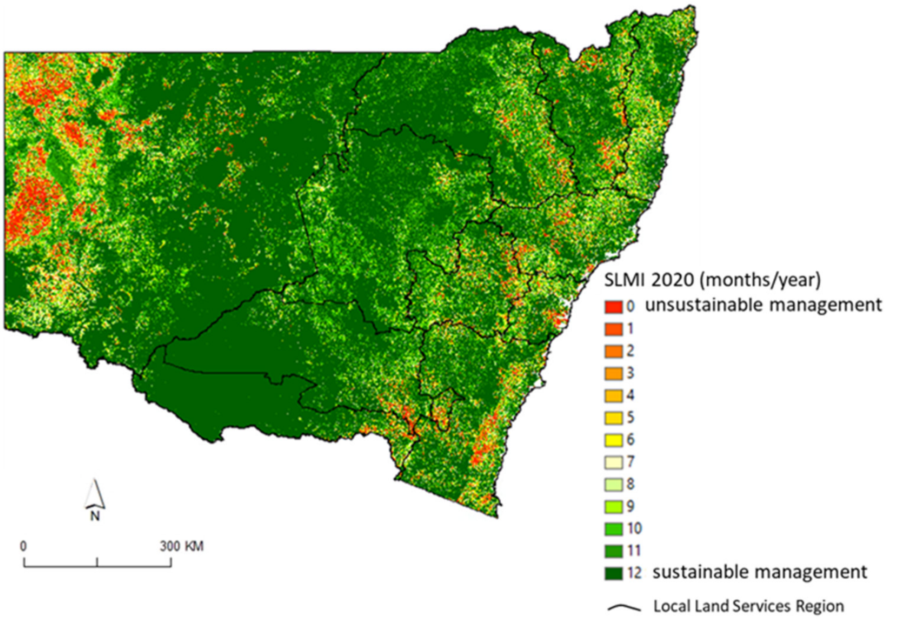

FIGURE 7 Yearly *Sustainable Land Management Index (SLMI)*, NSW 2020

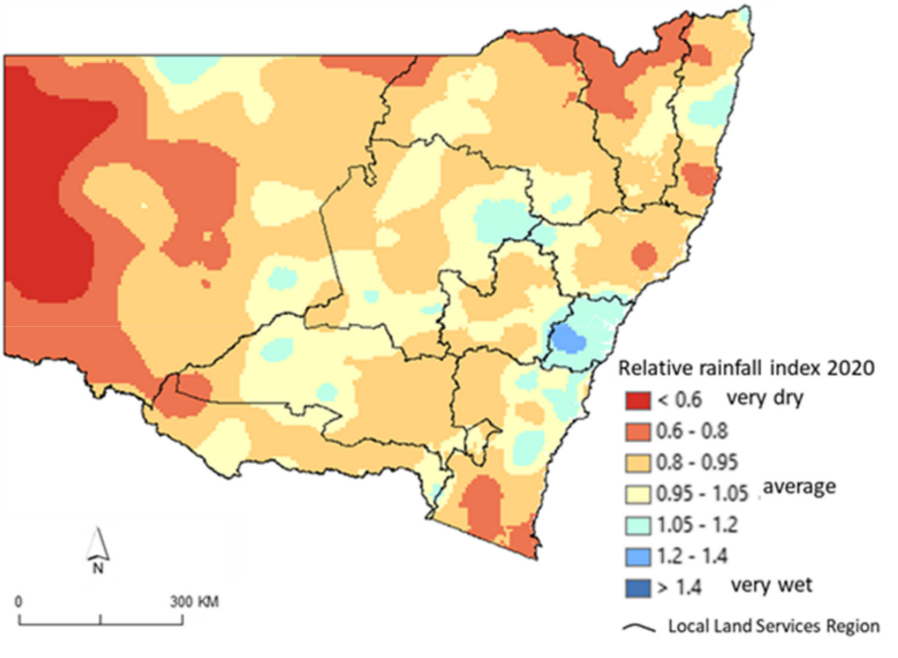

FIGURE 8 *Relative rainfall index (RRI)*, NSW 2020

sufficient to prevent erosion, even without intentional human disturbance.

However, all land uses revealed a significant drop in sustainable vegetation cover levels over the 2018–2019 years, being the most pronounced in relative terms for the cropping and grazing uses. These years coincide with the driest period as revealed by the relative rainfall index in Figure 11, in which this rainfall indicator dropped to only 65% of normal levels. Noteworthy is the lack of a strong relationship evident from a visual comparison between the SLMI and RRI trends (Figures 10 and 11) for the years 2010–2017, at least for cropping and

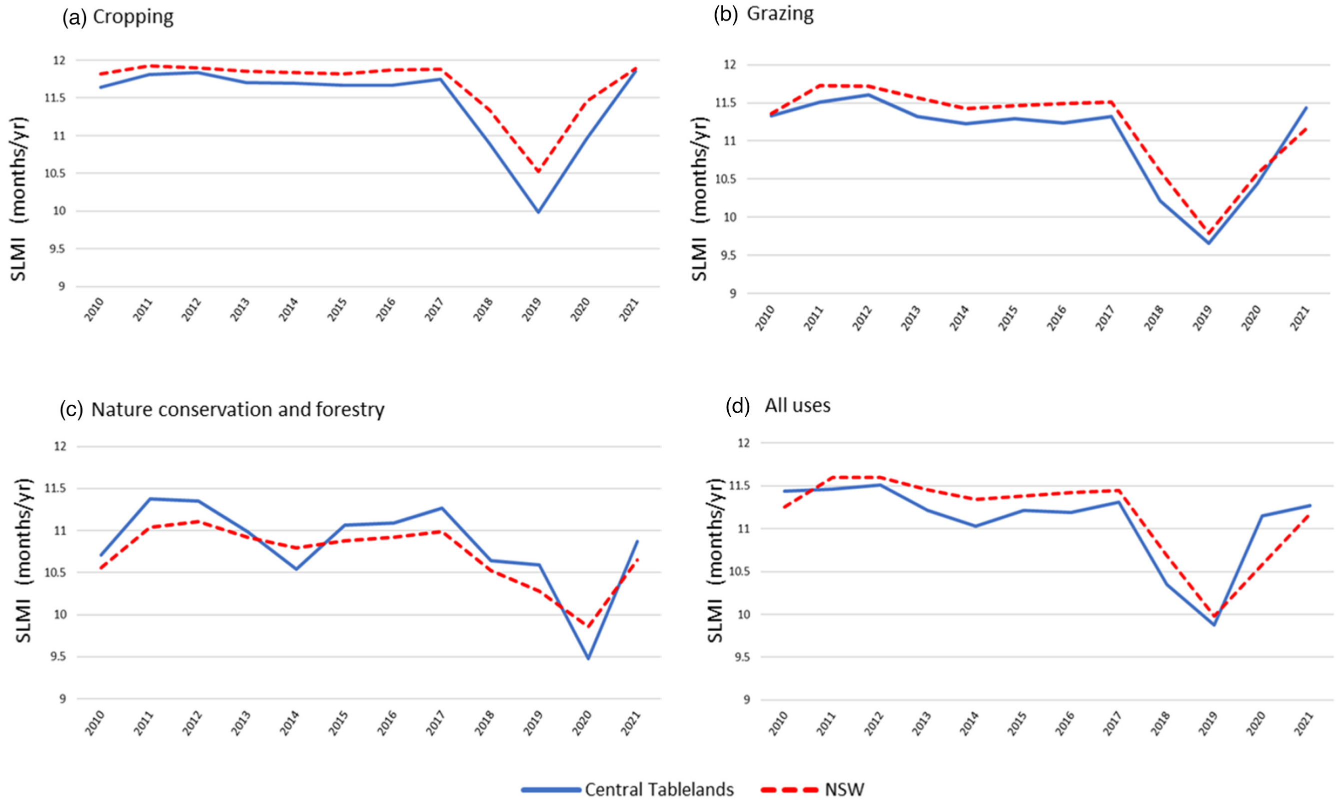

FIGURE 9 *Mean sustainable land management index (SLMI)* for (a) cropping, (b) grazing, (c) nature conservation and forestry and (d) all uses, for Central Tablelands LLS and NSW, 2010–2021

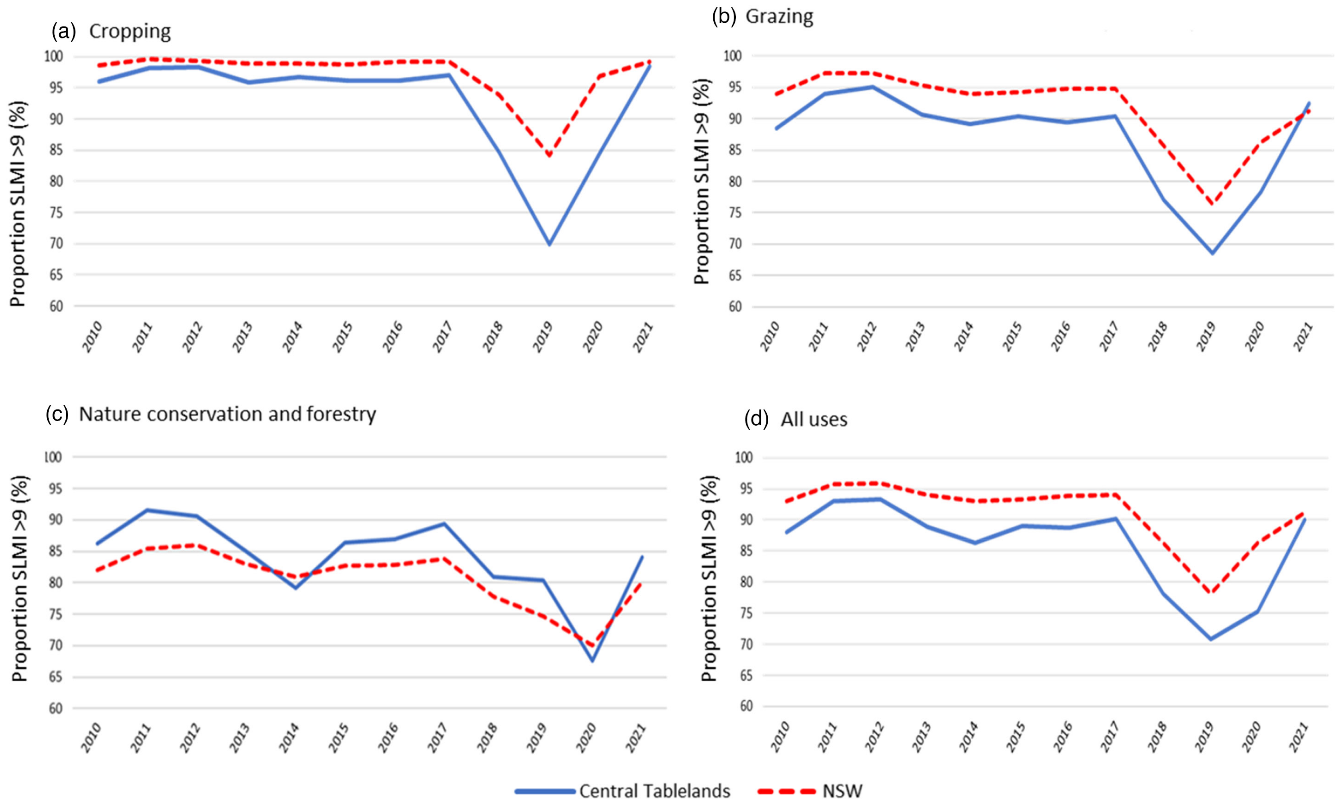

FIGURE 10 Proportion of area with *SLMI* >9 months/year for (a) cropping, (b) grazing, (c) nature conservation and forestry and (d) all uses for Central Tablelands LLS and NSW, 2010–2021

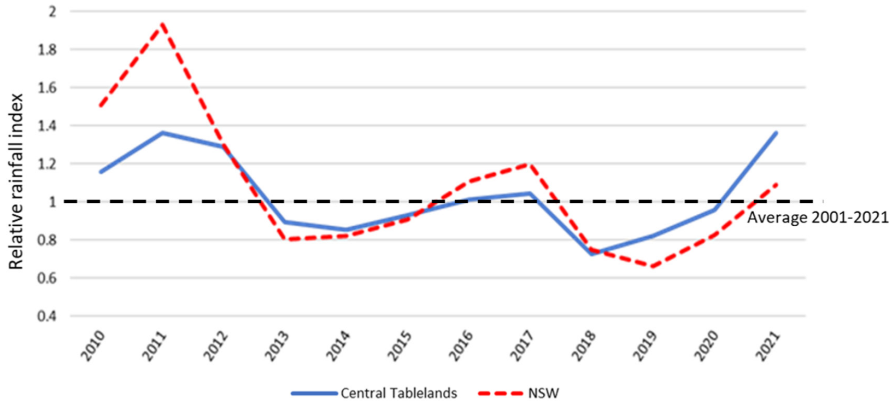

FIGURE 11 *Relative rainfall index (RRI)* for Central Tablelands LLS and NSW, 2010–2021

grazing use. Despite the significant fluctuation in the RRI, the SLMI indices remain relatively steady for those two land uses, until a rapid response after the cumulative effect of ongoing drier conditions in 2018. However, nature conservation/forestry use does follow the RRI trend quite closely.

The results for nature conservation and forestry use for both the Central Tablelands LLS and all NSW appear to reflect a partial influence of the severe bushfires that impacted much of eastern NSW during late 2019 and early 2020. Whereas cropping and grazing use demonstrate the maximum decline in SLMI indices in 2019, for nature conservation and forestry the maximum decline occurs in 2020, suggesting it was the loss of vegetation cover during the bushfires that most markedly influenced their results.

The trends in SLMI for all LLS regions of NSW over the 2010–2021 period are presented in Supplementary Information, Figures S1 and S2. The associated RRI is presented in Figure S3. Similar trends to those identified above are all evident. Considering all uses, the overall best-performing LLSs are Murray, Riverina and Central West, with SLMI indices between 11.5 and 12 for most of the period, while the lowest-performing LLSs are North Coast, Hunter and Greater Sydney, with SLMI indices between 10.0 and 10.5 for most of the period.

4 | DISCUSSION

4.1 | Potential usage of the scheme

We have explored and demonstrated a new approach to the monitoring of sustainable land management using widely available remote-sensed vegetation cover data. It provides an alternative approach to previous schemes that attempt to use remote-sensed data for vegetation and land management monitoring purposes, and we believe overcomes some of their limitations as we discuss in the following section.

Results are based on the extent of vegetation cover, as revealed by the MODIS-derived FVC products of Guerschman and Hill (2018) and viewable through online sources (GEOGLAM, 2021). Where the physical environmental conditions of two adjoining properties are the same, then the property with the higher vegetation cover is less susceptible to soil erosion. It is thus considered to have more effective and sustainable land management, and this will be reflected in higher *sustainable land management indices.*

The scheme reveals modelled spatial and temporal patterns in the effectiveness of vegetation cover management across landscapes. It identifies property scale locations and broader scale regions where vegetation cover, soil erosion and ultimately land management practices are of concern and may require attention. The results may encourage land managers to promote and adopt practices that lead to greater vegetation cover and greater protection of soil resources.

Results should be of particular interest to land and natural resource management agencies operating at regional levels such as NRM regional bodies, like the LLSs in NSW. They are also important for Governments at state and national levels. They help to identify locations and regions where increased educational and extension resources should be allocated. Recognition of persistent problems can lead to appropriate changes in policy at local, state and national levels.

As in our previous paper, we are promoting the overall concept of using vegetation cover to monitor tolerable soil erosion and from this, sustainable land management. Our precise approach as presented in these papers can be modified to suit the specific requirements and data availability of different potential users.

4.2 | Merits of the method

Our method is one of the relatively few schemes reported for the monitoring of sustainable land management

(Cowie et al., 2011, 2018; FAO, 1993; Gray et al., 2015; McNeil & MacEwan, 2007; Schwilch et al., 2011). The method adopts the strategy of monitoring vegetation cover with respect to tolerable soil erosion to assess land management performance, using readily available remotely sensed data. The target vegetation cover required to avoid erosion over the tolerable levels is primarily based on long-term natural erosion rates for each pixel and varies continuously depending on site physical and climatic conditions.

Our method provides continuous rather than categorical output as applied in most previously published land management monitoring schemes. It avoided categorical rules and datasets that often lead to marked boundary effects where abrupt changes occur. Being based on remote sensing data, such as MODIS-derived fractional vegetation cover, the method avoids the need for expensive and resource-intensive field visits and landholder surveys. Results are easily updateable and repeatable. Once an initial framework has been established with the required digital datasets, the method can be easily updated with more recent data.

We believe our scheme has advantages over methods that solely use changes in remotely sensed vegetation cover as a surrogate for land management, even the more recent innovative schemes that apply relative benchmarking as a means to distinguish land management components from natural climatic and land condition causes of changes in vegetation cover (Bastin et al., 2012, 2014; Donohue et al., 2022; Hobbs et al., 2018; Nauman et al., 2017). These schemes would seem to be hindered by difficulties in identifying sufficient reference areas with equivalent climatic, topographic and soil conditions to allow meaningful interpretation of changes in vegetation changes in the target areas of interest. In our current scheme, there is no requirement to identify specific reference areas; the varying climatic and physical conditions are effectively accounted for by variation in the dynamic tolerable erosion rating. Our scheme goes further than just monitoring ground cover, it monitors ground cover with respect to the potential for erosion, which more directly introduces a land management component into the monitoring framework.

Our scheme overcomes limitations in using soil erosion monitoring as a surrogate for land management monitoring as has been undertaken in Australia and other countries (Teng et al., 2016; McKenzie et al., 2017; Leys et al., 2017; Yang, 2020; Jeanneau et al., 2021, Zhang et al., in press; Panagos et al., 2014; Karydas et al., 2020). The occurrence of significant soil erosion does not by itself always mean poor or ineffective land management, as some factors may be beyond reasonable expectations for the land manager to control. Likewise, a period of low erosion does not necessarily imply good land management, as it may be entirely due to the absence of erosive rainfall events. Our method does not monitor erosion itself or whether actual tolerable erosion has been exceeded. It only monitors the land management, that is, whether the prevailing vegetation cover was sufficient to prevent intolerable erosion under conditions normally expected for that calendar month.

Our method avoids the unrealistic setting of specific numeric vegetation cover targets to assess land management performance, such as 50% to avoid wind erosion and 70% to avoid water erosion, as has been applied in other applications (Leys et al., 2020; McKenzie et al., 2017). Similarly, our method avoids the application of a uniform tolerable erosion rate, such as 0.2 or 0.5 Mg ha^{-1} year^{-1} (Bui et al., 2011; Edwards & Zierholz, 2000; Montgomery, 2007; Verheijen et al., 2009). Such numerically constant targets have shortcomings as they do not consider spatial variations in soil, topographic, climatic and land use conditions.

Our method presented here overcomes a drawback of our recently published approach (Yang et al., 2022), whereby the erosion target for each pixel was simply set as the median of that pixel for each calendar month over the 2001–2020 period. This means that a site (pixel) that had been poorly managed, with low vegetation cover over that period would effectively have a lower target than an adjoining site that had been well managed with high vegetation cover. Thus, the results were only relative for each pixel. The new method presented here allows a comparison of the vegetation cover and level of sustainable management of adjoining sites on a more absolute basis. However, the former approach has the benefit of inherent simplicity.

The semi-quantitative format of the results allows the presentation of the monitoring results within the System of Environmental and Economic Accounting (SEEA) as is being introduced widely across Australia and globally (BoM, 2013; UN, 2014). This allows formal accounting procedures to be implemented in the assessment of change and facilitates the application of economic principles into natural resource management. It may promote further inclusion of important soil and land management issues into broader Government policy.

4.3 | Weaknesses and uncertainties of the method

MODIS, the source of the vegetation cover data has a 500 m resolution, which is coarser than many paddocks; thus, there are limitations in applying the results to individual paddocks. Other sources of remotely sensed vegetation cover data such as Landsat or Sentinel have finer resolution, but the former has a lower temporal resolution, meaning there are frequent data gaps due to cloud cover.

The current method only considers hillslope water erosion and does not include gully or wind erosion. The difficulty of modelling wind erosion and its complex relationship with vegetation cover (Chappell & Webb, 2016) precluded its use in the current project.

Similarly, the method does not directly consider other soil and land hazards such as acidification, organic carbon decline, nutrient decline or salinity, that also influence vegetation cover requirements. Nor does it consider other land management practices such as the frequency of tillage, use of traffic control, the application of fertilizers and conditioners or irrigation practices, which are all important components of sustainable land management. Nevertheless, the concept of avoiding soil erosion does provide an indirect consideration of many of these factors. Prevention of soil erosion is associated with high-ground vegetation cover, which is directly or indirectly connected to many forms of soil and land degradation (Chappell et al., 2019; McKenzie et al., 2017).

There is considerable uncertainty in our assessment of long-term natural erosion, which was derived by assuming vegetation cover equivalent to protected reserve status as extrapolated from existing reserves across the state.

Our modelling of monthly soil loss incorporated rainfall erosivity (R) derived on a monthly basis using daily rainfall analysis. However, storm events occur on an hourly time scale, meaning the R factor, and thus, total soil loss may be underestimated. The fractional vegetation cover data used to estimate C in the RUSLE equation for water erosion do not distinguish between vegetation on the ground surface and canopy cover of shrubs and trees, which behave somewhat differently in terms of protecting the soil surface from erosion, thus creating further uncertainty in the final soil loss estimates (Trevithick et al., 2014).

No formal quantitative validation of results has been undertaken to date. However, a visual, qualitative comparison of vegetation cover with final SLMI ratings, particularly where vegetation cover differed over adjoining areas with apparently similar soil-terrain character, as shown in Case Study 1 (Figure 5), demonstrated encouraging performance of the method.

4.4 | Future improvements

Further trialling and development of the method are proposed to improve its reliability in reflecting the degree of sustainable land management across landscapes. Attempts will be made to overcome the limitations outlined above. Incorporating the influence of wind erosion and the level of vegetation cover required to control it is a high priority for further development of the method. Accessing higher spatial resolution vegetation cover products such as Landsat or Sentinel into the method would enhance the potential for assessment and monitoring at individual paddock scale. Improvements to the method may also involve modifying and adjusting rules and finer details of the method, for example, the process for determining long-term natural water erosion and the magnitude of the additional tolerable erosion component (ATEC), currently set at 0.1 $Mg\,ha^{-1}$ $year^{-1}$. The inclusion of the relative rainfall index (RRI) as a quantitative rather than a qualitative component of the approach will be explored. A process of qualitative review and feedback of preliminary results by local land management experts, such as in the local NRM regions, is proposed.

The impacts of wildfires, with the associated major loss of vegetation cover, also need to be formally incorporated into the method. This represents another factor that is largely beyond the control of the landholder. The resulting low vegetation cover will contribute to higher erosion, but it would be unreasonable to suggest this was due to ineffective land management.

Other NRM researchers or agencies interested in applying this broad concept and approach may find it necessary to modify the process as presented here to better suit their specific conditions, available data and land management requirements.

5 | CONCLUSION

We have presented a new method for monitoring sustainable land management using widely available remote-sensed data, such as MODIS fractional vegetation cover data. The method assesses the prevailing vegetation cover relative to target levels required to prevent intolerable erosion under normal conditions for that calendar month of the year. Long-term natural erosion rates plus a small constant were used to derive spatially variable and meaningful tolerable erosion targets and indices of sustainable land management. Results in the form of yearly sustainable land management indices (SLMIs) were presented over NSW for the years 2010–2021, with further stratification based on land use category and natural resource management region.

The method has several merits and addresses some limitations of previous approaches to monitor vegetation cover and sustainable land management, including those that have relied on remote-sensed data alone. Our approach more successfully considers differences in vegetation cover with respect to variability in soils, slope and rainfall conditions and isolates the land management influences.

Nevertheless, there remain several shortcomings and sources of uncertainty in our approach, and further development of the method is warranted. The approach is offered as an example of the potential use of readily available vegetation cover data for monitoring sustainable land management across regions. Other users are invited to adapt and build on the overall approach to meet their local requirements and data availability. Monitoring of levels of sustainable land management through approaches such as this is important for the ongoing protection of our vital soil resources and the broader environment into the future.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in SEED, the NSW environmental data portal at https://www.seed.nsw.gov.au/.

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SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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