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Estimating nutrient transport associated with water and wind erosion across New South Wales, Australia

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ABSTRACT

Nutrient transported from soils to water bodies not only threatens agricultural productivity and food security but also causes the degradation of water quality and the environment in many parts of the world. However, nutrient transport through soil erosion is often ignored in nutrient cycle studies; there is little understanding of how much nutrient is lost through water and wind erosion. In this study, we attempted to assess soil nutrient transport due to both water and wind erosion and its spatial and temporal variability across New South Wales (NSW), Australia. We estimated the mass fraction (%) of total nitrogen (N), total phosphorus (P) and soil organic carbon (SOC) in the eroded soil, and the total nutrient stock of the soil layer down to 200 cm using water and wind erosion models and digital soil mapping. The estimated average N, P and SOC stocks in NSW topsoils (0–5 cm) are 160, 43, and 2970 kg ha^{-1} respectively. There are great variations in the transport of nutrients by erosion in space and time, ranging from near zero in the Western region to 395 kg ha^{-1} yr^{-1} in the North Coast region. The average total nutrient transport rate is about 2.4 % of the surface soil (0–5 cm) total stock in NSW due to both water and wind erosion. The total cost of nutrient transport is estimated at 4.2 billion Australian dollars for the entire state of NSW and 0.2 billion dollars from the cropping lands per year. The areas with the highest nutrient transport rates are the North Coast and Hunter regions due to the relatively high water erosion and nutrient content of the soils. On average, water erosion contributes up to 98 % of the total nutrient transport across the state as a whole, but wind erosion can contribute up to 12 % of the total transport in Spring (i.e., September). This study is the first attempt to investigate nutrient transport from both water and wind erosion in Australia. The methodology and findings contribute to the knowledge of nutrient transport due to erosion in broad nutrient cycle studies.

1. Introduction

Soil nutrient transport through soil erosion is a major driver of soil fertility decline and soil quality degradation. Nutrient transport refers to the movement or mobilisation of nutrients from their original place. Nutrient loss often refers to the nutrient lost or transported to endpoints such as rivers or lakes (Mutema et al., 2015). These two terminologies are often used interchangeably in most studies. This study is more focused on nutrient transport or nutrient loss potential within a given location or a pixel (e.g., 90 m by 90 m) in raster based spatial modelling.

Soil erosion not only causes soil degradation and nutrient transport but also negatively impacts ecosystem services, the environment (clean air and water), carbon storage and biomass production. Nutrient transport of fertile topsoil through surface runoff and sediment transport not only threatens agricultural production (den Biggelaar et al., 2003; Strohmeier et al., 2016) it also pollutes waterways and receiving water bodies (Bui et al., 2011; Leys and McTainsh, 1999; Vaezi et al., 2017). For example, too much nutrient transported into surface waters can cause algal blooms and associated de-oxygenation of water bodies (Lal, 2006; Munodawafa, 2007).

There are also economic losses associated with soil degradation and nutrient losses (Jónsson and Davíðsdóttir, 2016). The loss of soil organic carbon (SOC) and the primary nutrients including nitrogen (N), phosphorus (P) and potassium (K) by erosion has a significant effect on the

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nutrient sustainability and productivity of the soils (Leys and McTainsh, 1994; Müller-Nedebock and Chaplot, 2015).

The estimated nutrient transport rates (normally measured in kilograms per hectare per year or kg ha^{-1} yr^{-1}) vary greatly for different regions and land uses (Li et al., 2017; Napoli et al., 2017; Me et al., 2018). The amount of soil and nutrients transported depends on the prevailing land uses and land management practices (Bashagaluke et al., 2018). Bertol et al. (2003; 2017) studied nutrient transport by water erosion under a range of land management systems and they quantified available nitrogen, phosphorus, potassium, calcium, and magnesium losses with simulated rainfall on field plots (3.5 m by 11 m) with different land management systems including bare soil, soybean, and natural pasture with and without tillage. Martínez-Menaa et al. (2020) studied the long-term effectiveness of sustainable land management practices to control runoff, soil erosion, and nutrient transport and the role of rainfall intensity in Mediterranean rainfed agroecosystems.

Up to 90 % of nitrogen and phosphorus could be transported by soil erosion and then accumulate within a sedimented area (Sharpley et al., 2001). Omuto and Vargas (2018) found that the average annual nutrient transport rates due to topsoil loss ranged 66–117 kg ha^{-1} of total N, 205–364 kg ha^{-1} of available P and 9–17 kg ha^{-1} of exchangeable K in their soil nutrient transport assessment in Malawi in 2017. However, estimates by Silvestri et al. (2017) in the flat land-reclamation district of Central Italy have much lower ranges with 0.9–3.5 kg ha^{-1} for N, 0.6–1.9 kg ha^{-1} for P losses. The results from Ma et al. (2016) indicated that the average loss ratio of N was 1.9 %, while that of P was 1.5 % in China's Three Gorges Reservoir Area.

Various modelling and field experimental techniques have been used to monitor nutrient transport. Munodawafa (2007) and Cilek (2016) estimated the depletion of SOC through soil erosion in the Mediterranean region using the Pan-European Soil Erosion Risk Assessment model, a physically based, regionally scaled soil erosion model. Bagarello et al. (2010; 2011) used statistical and empirical models to predict soil loss distribution and sediment concentration in Italy. Enrichment ratios (ER) were used to calculate the total N and P loss during wet seasons for major runoff events (Cogle et al., 2011; Tesfahunegn and Vlek, 2014); these studies found that the ER of the bare treatment was lower than that for other treatments with groundcover.

In Australia, Bartley et al. (2012) reviewed sediment and nutrient concentration data from Australia for use in catchment water quality models. Joo et al. (2012) estimated sediment and nutrient loads in 10 major catchments draining into the Great Barrier Reef (GBR) lagoon during 2006–2009. By examining the spatial distribution of SOC over two large (>500 km^2) catchments in relation to soil erosion and deposition, Hancock et al. (2019) found that SOC can be translocated by significant rainfall events, and the driver of the SOC change and soil movement corresponds with the largest rainfall. Holz and Augustin (2021) studied carbon redistribution within cultivated landscapes and found it is strongly controlled by soil erosion and sedimentation and that soil carbon is preferentially transported during erosion. McCloskey et al. (2021) estimated fine sediment and particulate nutrients delivered from 35 GBR catchments at a daily time-step and a sub-catchment scale. Their estimation was based on the eWater Source modelling framework and SedNet model and coupled with agricultural systems models. Catchment scale monitoring and historical data sets across GBR (e.g., Young et al., 1996; Carroll et al., 2012) were used to calibrate and evaluate the modelled sediment and nutrient loads linked to the sources.

The major forms of soil erosion include water and wind erosion and they are generally believed to be related to a specific climate zone: wind erosion is related to more arid regions (McTainsh et al., 1990), and water erosion is related to more humid regions (Visser et al., 2005). In semi-arid regions such as in Australia, both erosion processes contribute significantly to total soil erosion and can occur almost simultaneously (McTainsh et al., 1992). Loss of vegetation cover has been identified as one of the main causes of both water and wind erosion (Bui et al., 2011). For Australia as an example, it is the driest inhabited continent in the world with 70 % of its land in an arid or semi-arid climate zone and an average rainfall of less than 350 mm, wind erosion is widespread and the nutrient transport via wind erosion cannot be ignored in this country. Leys and McTainsh (1994) carried out a study at a cultivated paddock in far south-west NSW and found that the dust that was eroded had 16 times more total nitrogen and 11 times more organic carbon than the soil it was derived from. Larney et al. (1998) further confirmed that the windblown sediment was enriched in plant nutrients in Canada. The loss of topsoil due to wind erosion translated into a measurable effect on wheat yield. SOC and nutrient transport resulting from spring dust emissions have been investigated in Northern China (Song et al., 2019). Chappell et al. (2013) estimated the spatial and temporal variation in total monthly dust and SOC emissions between 2000 and 2011 in Australia. The estimated loss via dust emission was about 4 Tg SOC yr^{-1}, which represents a loss of about 2 % of the total carbon stock (0–10 cm) of Australia (Chappell et al., 2014). These studies imply that wind erosion cannot be ignored in Australia (Chappell and Webb, 2016; Chappell et al., 2019).

Despite the widespread research on water and wind erosion, studies on nutrient transport from both water and wind erosion and their relative contributions are very rare (Segovia et al., 2017). To better understand the soil and nutrient transport or deposition, especially in semi-arid areas, both water and wind erosion processes should be studied simultaneously. This improves our understanding of the amount, timing and form of soil constituents leaving a given land use. Further, the nutrients transported by the soil erosion process need to be expressed in economic terms to reflect the impact of erosion on fertilizer investment. The loss of soil nutrients through erosion indicates significant cost because of the need for replacement to enhance the sustainability of cropping systems (Bashagaluke et al., 2018). The magnitude of nutrient transport through soil erosion under different cropping systems and amendments needs to be quantified to inform agronomic practices (Martínez-Casasnovas and Ramos, 2006; van Beek et al., 2016; Bashagaluke et al., 2018; Nowsher et al., 2021).

Therefore, this study aims to estimate the total nutrient stock in the soil layers and the transport of the primary soil nutrients including total N, total P and SOC due to both water and wind erosion in the recent 20-year period (2001–2021). Further, the associated dollar cost is estimated based on the replacement of the total nutrients lost through erosion and the cost of additional fertilizers at present market prices (June 2022). It is the first attempt in Australia to use both water and wind erosion models, along with soil nutrient and physical properties, to predict potential soil and nutrient transport.

This study will provide monthly soil erosion and nutrient transport information which will inform how prevailing land use practices affect soil erosion and nutrient transport. With the erosion and nutrient time-series data, we will further analyse the variations in nutrient transport by erosion in space and time across NSW within natural resource management (NRM) regions, called Local Land Service (LLS) regions in NSW, and land use types (e.g., Yang et al., 2018; Yang et al., 2020b).. The findings from this study are expected to help improve our understanding of the amount, timing, and form of nutrient transport through erosion from a given land use. The methodology developed in this study could be modified and built upon by other users to meet local requirements and data availability elsewhere in the world, therefore, contributing to broad carbon and nutrient cycle studies.

2. Methods and materials

This study used RUSLE (Renard et al., 1997) to model water erosion and RWEQ (Fryrear et al., 1998) to model wind erosion for the period from 2001 to 2021. We used these models because they have similar modelling frameworks to those developed by the United States Department of Agriculture over the last 40 years, and they have been widely used internationally and in Australia (Yang et al., 2022; Zhang et al., 2022). The general procedure is illustrated in Fig. 1.

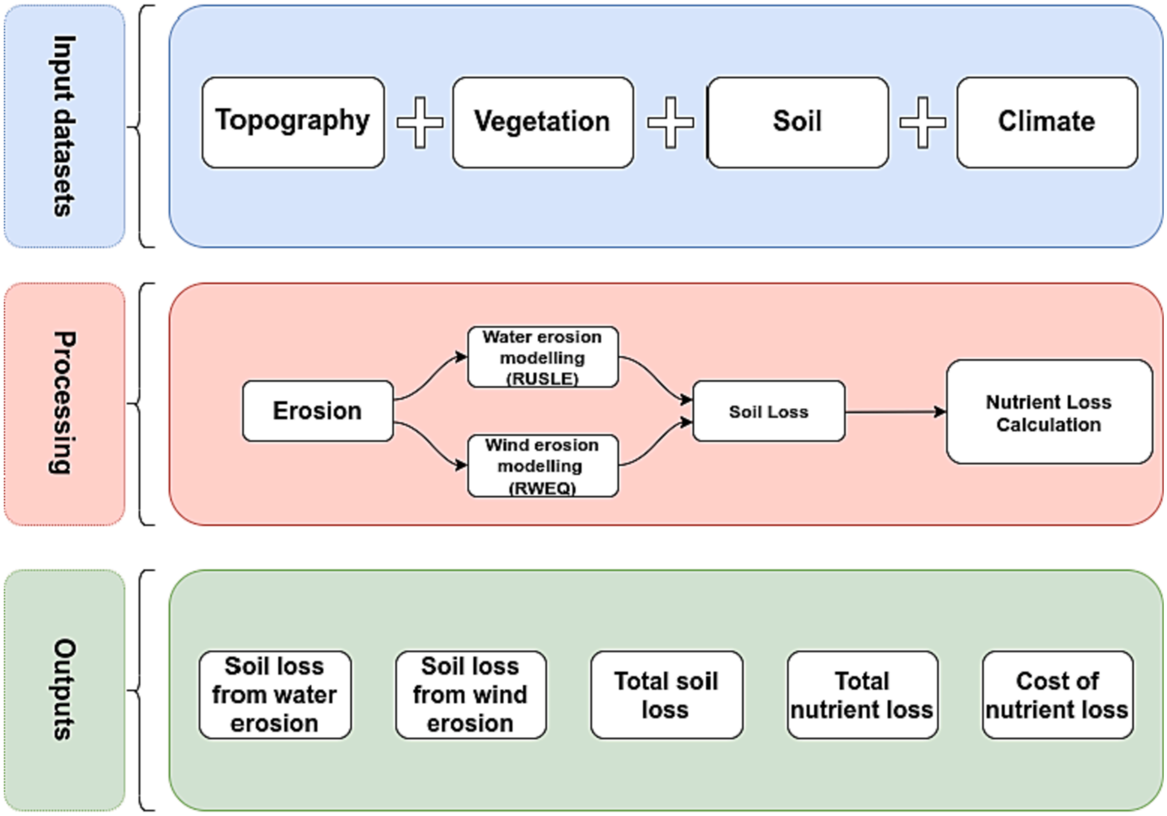

Fig. 1. The general procedure on soil erosion and nutrient transport estimation across New South Wales, Australia for the period 2001–2021.

2.1. Datasets

The dominant datasets used in this study include land use, Soil and Landscape Grid of Australia (SLGA) comprising digital soil maps (DSM) with soil nutrient content (N, P, SOC), digital elevation models (DEM), satellite (MODIS and Landsat) derived fractional vegetation cover (30–500 m), the NSW Soil and Land Information System (SALIS) with soil property and profile information, DustWatch datasets (dust concentration, wind erosion), and rainfall data (radar rainfall, gauge rainfall and BoM rainfall gridded data). All these input datasets have been re-projected to the same coordinates (Geocentric Datum of Australia 1994, i.e., GDA94) and resampled to the same spatial resolution (~90 m). These datasets are summarised in Table 1.

Table 1
Major datasets used in this study and their sources.

Datasets	Source	Resolution	Web link
SLGA	TERN	~90 m	https://www.tern.org.au/news-soil-data
DEM	GA	30 m	https://www.ga.gov.au/
Vegetation cover	CSIRO	500 m	https://eo-data.csiro.au/remotesensing/v310/
SALIS	DPE	Polygon	https://www.environment.nsw.gov.au
Land use	DPE	Polygon	https://datasets.seed.nsw.gov.au/
DustWatch	DPE	Point	https://www.environment.nsw.gov.au
Climate	BoM	5000 m	http://www.bom.gov.au/jsp/awap/rain/

SLGA: Soil and Landscape Grid of Australia; SALIS: New South Wales Soil and Land Information System (SALIS); TERN: Terrestrial Ecosystem Research Network of Australia; GA: GeoScience of Australia; CSIRO: Commonwealth Science and Industry Research Organisation of Australia; DPE: New South Wales Department of Planning and Environment; BoM: Bureau of Meteorology of Australia.

2.2. Water erosion modelling using revised universal soil loss equation (RUSLE)

The water erosion, dominantly hillslope erosion, in NSW was estimated based on the revised universal soil loss equation (RUSLE, Renard et al., 1997) and well documented in our previous publications (Yang, 2020; Yang et al., 2020a). RUSLE is expressed as a product of these five factors:

$$A = R \times K \times LS \times C \times P \quad (1)$$

where A is the predicted soil loss (kg ha^{-1} yr^{-1}); R is the rainfall erosivity factor (MJ mm ha^{-1}h^{-1} yr^{-1}); K is the soil erodibility factor (kg h MJ^{-1} mm^{-1}); LS is the slope-length and steepness factor (dimensionless); C is the cover and management factor (0–1, dimensionless); and P is the conservation support-practices factor (0–1, dimensionless) which is not considered in this study.

Briefly, the R factor was estimated monthly from long-term gridded daily rainfall records sourced from the Australian Bureau of Meteorology using a daily rainfall erosivity model (Yang and Yu, 2015). The K factor was derived from the SLGA datasets (Grundy et al., 2015) using the content of soil organic matter, soil texture, soil structure and the soil profile permeability class (Yang et al., 2017). The LS factor was estimated from the hydrologically corrected DEM on a catchment basis using an overland-flow length algorithm as described in Yang (2015), then merged to form a seamless LS layer for the entire State. The C factor was derived from the MODIS fractional vegetation cover products following the method outlined in Yang (2014) and Yang (2020). This approach considers the role of non-photosynthetic vegetation in addition to photosynthetic vegetation which is considered to give more meaningful estimate of cover than the traditional methods (Yang et al., 2022).

In this study, all RUSLE factors have been updated using the most recent datasets available for NSW, and time series water erosion have been produced for the period of 2001–2021.

2.3. Wind erosion modelling using revised wind erosion equation (RWEQ)

The Revised Wind Erosion Equation (RWEQ) model estimates soil erosion and transport (or sediment flux) by wind for certain times of the year (Fryrear et al., 1998). It was used in this study to estimate soil wind erosion as it's relatively simple, computationally efficient, and suitable for large-scale environmental studies (Zhang et al., 2022).

The horizontal sediment flux (Q, kg m^{-1}) and vertical sediment flux (S_L, kg m^{-1}) are estimated with the following equations:

$$Q = Q_{max}\left(1 - e^{(Z/S)^2}\right) \tag{2}$$

$$S_L = \frac{2 \bullet Z}{S^2} Q_{max} \bullet e^{-(Z/S)^2} \tag{3}$$

where Q_{max} is the maximum transport capacity (in kg m^{-1}), Z is the downwind distance (m), and S is the critical field length (m).

$$Q_{max} = 109.8[WF \bullet EF \bullet SCF \bullet K \bullet C] \tag{4}$$

$$S = 150.71(WF \bullet EF \bullet SCF \bullet K \bullet C)^{-0.3711} \tag{5}$$

where WF is the weather factor (kg m^{-1}); EF is the erodibility factor (dimensionless); SCF is the soil crust factor (SCF, dimensionless); K is the surface roughness factor (dimensionless); and C is the vegetation factor (dimensionless).

The WF integrates the effects of various meteorological factors on wind erosion. It is calculated as:

$$WF = W_f \bullet \frac{\rho}{g} \bullet SW_f \bullet SD \tag{6}$$

$$W_f = \sum_{i=1}^{i-n} U_2(U_2 - U_t)^2 \frac{N_d}{500} \tag{7}$$

$$SW_f = 1 - SW \tag{8}$$

$$SD = 1 - P \tag{9}$$

where W_f is the wind factor (kg m^{-1}), ρ is air density, g is gravity acceleration, SW_f is the soil moisture factor, SW represents soil moisture, SD is the snow cover factor and P is the probability that the snow cover depth is > 25.4 mm in the simulation period. U_2 is the wind velocity at 2 m; U_t is the wind velocity threshold, generally set as 5 m s^{-1}; N_d the number of days in the simulation period (1 day in this study).

The soil erodibility factor (EF) and soil crust factor (SCF) are expressed by the aggregation of soil particles (especially clay, silt and SOC) as follows:

$$EF = \frac{29.09 + 0.31S_a + 0.17S_i + \frac{0.33S_a}{C_l} - 2.59(SOC*1.72) - 0.95CaCO_3}{100} \tag{10}$$

$$SCF = \frac{1}{1 + 0.0066(C_l)^2 + 0.021(SOC*1.72)^2} \tag{11}$$

where, S_a is the sand grain proportion; S_i is the soil silt proportion; C_l is clay proportion; SOC is soil organic carbon proportion; and $CaCO_3$ is calcium carbonate proportion.

The calculation of surface roughness factor (K) is based on an approximation of soil roughness (K'):

$$K' = cos\alpha \tag{12}$$

where α represents slope gradient and is calculated from a hydrologically corrected DEM (30 m).

The vegetation cover factor (C) is estimated from fractional vegetation cover (FVC, in %) as below:

$$C = e^{-0.0438FVC} \tag{13}$$

The above calculations have been implemented in a Google Earth Engine (GEE) environment to enable large-scale spatio-temporal soil loss simulations and the detailed methods are presented in Zhang et al. (2022).

2.4. Estimation of nutrient stock and transport rates

The soil nutrient data from SLGA were used to calculate the "stock" of nutrient. SLGA combines historical and current data generated from sampling, laboratory sensing, modelling and remote sensing. It contains the world's first comprehensive and continental soil raster datasets (approximately 90 m by 90 m resolution) down to a depth of two metres below the surface (Grundy et al., 2015). The datasets include total mass fraction (%) for N, P and SOC. The SLGA and other sources of datasets used in this study are summarised in Table 1.

The soil nutrient stock for N, P and SOC was calculated for each of the soil layers of 0–5 cm (thickness = 5 cm), 5–15 cm (thickness = 10 cm), 15–30 cm (thickness = 15 cm), 30–60 cm (thickness = 30 cm), 60–100 cm (thickness = 40 cm) and 100–200 cm (thickness = 100 cm):

$$S_i = C_i{*}BD_i{*}D_i{*}100000 \tag{14}$$

where S_i is the soil nutrient stock (kg ha^{-1}) in layer *i*, C_i is the nutrient content (%) in layer *i*, BD_i is the bulk density (g cm^{-3}) in layer *i*, D_i is the soil thickness (cm) of layer *i*, and 100,000 is the unit conversion factor to convert from g cm^{-2} to kg ha^{-1} (1 g cm^{-2} = 100000 kg ha^{-1}). The nutrient considered in this study only includes N, P and SOC.

For example, the amount of SOC stock in the topsoil layer (0–5 cm) with a SOC content of 2.0 % (or 0.02) and bulk density of 1.3 g cm^{-3} is:

$$SOC_1 = 0.02x1.3gcm^{-3}x5cm \ = 0.13gcm^{-2} = 13000kg\,ha^{-1} \tag{15}$$

Note that for soils with gravel, the nutrient stock calculation was adjusted by taking out the gravel content. So, if SOC was 2.0 % as used in the above calculation, but the soil had 20 % gravel (by volume) then the SOC content was adjusted:

$$SOC_1 = 2.0 - (2.0x0.2) = 1.6\% \tag{16}$$

The NSW land use map (available online on SEED, https://datasets.seed.nsw.gov.au/dataset/nsw-landuse-2017-v1p2-f0ed) has information of surface rock content with six classes (nil, less than2%, 2–10 %, 10–20 %, 20–50 % and > 50 %). This was the only rock dataset available and it was used to adjust the calculation for soil nutrient stock.

The total soil nutrient stock (*S*) per unit area (kg ha^{-1}) was calculated as the sum of all nutrients at each soil layer (S_i) from 0 to 200 cm:

$$S = \sum_{i=1}^{n} S_i or S = \sum_{i=1}^{n} C_i{*}BD_i{*}D_i \tag{17}$$

As most erosion only happens at the topsoil layer (0–5 cm), nutrient transport (kg) from soil erosion of the surface layer was estimated from the total soil transport rate from both water and wind erosion (kg ha^{-1} yr^{-1}), the nutrient content (%) of the soil, and the field size (ha):

$$Nut_{t(i)} = Soil_{t(i)}{*}Nut_{conc(i)}{*}Area \tag{18}$$

where $Nut_{t(i)}$ is the nutrient transport rate by water and wind erosion from the topsoil for a given area (e.g. a pixel or a LLS region) in a given period (kg yr^{-1}), $Soil_{t(i)}$ is the total estimated soil loss rate from the topsoil by both water and wind erosion (kg ha^{-1} yr^{-1}), $Nut_{conc(i)}$ is the nutrient content (%) of the topsoil layer, and *Area* is field size (ha). The nutrient transport rates were calculated monthly (kg $month^{-1}$) and annually (kg yr^{-1}) from 2001 to 2021 based on a pixel (the smallest unit), a region (e.g. LLS) and the entire state.

The relative rate of nutrient loss ($Nut_{t(i)}\%$) for each of the three nutrients at each soil layer (*i*) is calculated by:

$$Nut_{t(i)}\% = \frac{Meanannualrateofnutrienttransportperunitarea}{Totalsoilnutrientstockperunitarea} \quad (19)$$

An index of total nutrient transport (Nut_t) for water and wind erosion is calculated by combining the relative nutrient transport rates for all the nutrient components under consideration (McKenzie et al., 2017):

$$Nut_t = \sum_{i=1}^{j} Nut_{t(i)}\% \quad (20)$$

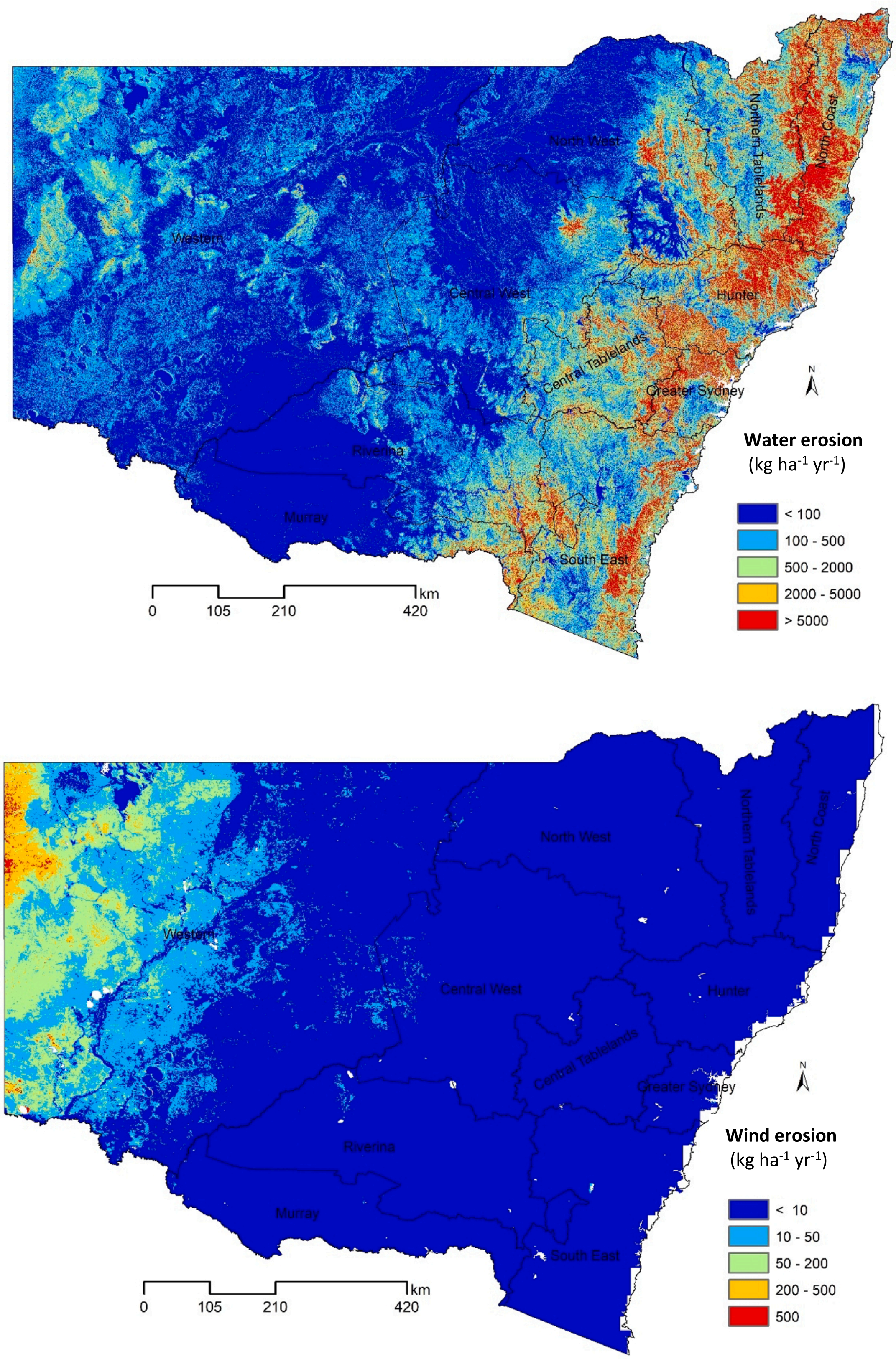

Fig. 2. The estimated average water erosion rate (above) and wind erosion rate (bottom) across New South Wales, Australia for the period 2001–2021.

where i is the individual nutrient type of concern, j is the number of types of nutrient considered including N, P and SOC.

2.5. Estimating cost of nutrient transport

In this study, the replacement cost method was used to estimate the cost of fertility erosion as it has been used in many previous studies (e.g. Gunatilake and Vieth, 2000; Bashagaluke et al., 2018). This involved converting nutrient transport to existing fertilizer forms to assess the monetary value of the nutrients lost through erosion under the different soil and crop management practices (Gulati and Rai, 2014; Erkossa et al., 2015; Bashagaluke et al., 2018). The prevailing local market price of each fertilizer was used to compute monetary value of soil fertility erosion. In this study, we only consider total nitrogen, total phosphorus, and organic carbon. The nutrient transport cost was estimated as:

$$Nut_{cost} = \sum_{1}^{n}(Nut_{i_{loss}} * Nut_{i_{price}}) \tag{21}$$

where Nut_{cost} is the nutrient transport cost (in Australian dollars) through soil erosion, $Nut_{i_{loss}}$ is the nutrient transport rate from the topsoil in a given period for nutrient component i (e.g., N, P) in kg ha^{-1} yr^{-1}, $Nut_{i_{price}}$ is the market price for nutrient i in Australian dollars, n is the total nutrient components considered (N, P and SOC in this study). Based on Fertilizer Australia (2022) the market price is \$1.30 kg^{-1}N, \$1.48 kg^{-1}P. The cost of SOC was estimated at \$1.20 kg^{-1} based on Tozer and Leys (2013).

3. Results and discussion

3.1. Estimated water erosion and wind erosion across New South Wales

The average water erosion in NSW is estimated 1023 kg ha^{-1} yr^{-1} based on RUSLE for the period from 2001 to 2021. The average wind erosion in NSW is estimated at 15 kg ha^{-1} yr^{-1} based on RWEQ for the same period (2001–2021). The modelling indicates that water erosion is the dominant form of erosion which is about 90 times higher than wind erosion on average, considering the state as a whole. Fig. 2 shows the average water and wind erosion rates across NSW over the subject period.

The water erosion rate is much higher in the eastern parts of NSW than the state average. The North Coast region has the highest water erosion rate (about 7000 kg ha^{-1} yr^{-1}) among all the LLS regions. It is followed by the Hunter region with an average erosion rate of about 4000 kg ha^{-1} yr^{-1}. In comparison, wind erosion is concentrated in the western parts of NSW where the soil is drier, and vegetation is sparser. There is negligible wind erosion estimated by the model in the eastern parts of NSW when averaged over the 20 years of this study.

There is a strong seasonality in both water and wind erosion. Water erosion is much higher in summer (December to February) than in other seasons, being the highest in February (Fig. 3). Wind erosion prevails in spring (September to November), being the highest in September especially in drier western regions. The raitos of water erosion to winter erosion range from 7 in September to 400 in February across NSW. More details on the state and trends of water and wind erosion across NSW and the seasonality have been presented in our previous publications (Yang, 2020; Zhang et al., 2022).

3.2. Nutrient stocks in New South Wales soils

The average nutrient contents in NSW topsoils are 0.12 % total N, 0.03 % total P, 2.24 % SOC and they decrease to 0.03 %, 0.02 % and 0.26 % respectively at the bottom of soil profile (up to 200 cm). With these nutrient contents and soil bulk densities (BD), the average nutrient stock in the topsoil layer (0–5 cm) is estimated to be 161 kg ha^{-1} total N, 43 kg ha^{-1} total P, and 2979 kg ha^{-1} SOC, and 3183 kg ha^{-1} for all the three components. Total nutrient stocks below the topsoil gradually decrease to 2181, 1431, 865, 598 and 446 kg ha^{-1} for the depths of 5–15 cm, 15–30 cm, 30–60 cm, 60–100 cm and 100–200 cm respectively (Table 2). The nutrient stock in the topsoil layer (0–5 cm) is about three times higher than the other layers below (5–200 cm). This result agrees with other studies (e.g. Bashagaluke et al., 2018) that the eroded topsoil contains about three times more nutrients per unit weight than are left in the remaining soil.

The soil nutrient stock is generally higher in the east coastal areas compared to the Western regions with the highest levels in the South East (26292 kg ha^{-1}), North Coast (252853 kg ha^{-1}), Central Tablelands (24964 kg ha^{-1}) and Northern Tablelands (24211 kg ha^{-1}) regions, while the Western region has the lowest nutrient stock (8026 kg ha^{-1}). The NSW wheat cropping areas (or wheatbelt) including the Murray, Central Tablelands and Riverina regions also have relatively high nutrient stock, in the order of 1000 kg ha^{-1} or higher. The spatial distribution of SOC showed higher carbon contents in the low relief areas, which may be related to sediment deposition. However, it is complex to determine the destination of the eroded carbon since it depends on several factors, including the type and stage of erosion and the fractions removed (e.g. Lal, 2019). Fig. 4 shows the estimated total nutrient stocks (total N, P and SOC) in the topsoil layer (0–5 cm) across NSW. Table 3 lists the estimated nutrient stocks (total N, P and SOC) in the topsoil layer (0–5 cm) across NSW LLS regions.

3.3. Soil nutrient transport due to water and wind erosion across NSW

The estimated average annual nutrient transport rates in NSW are

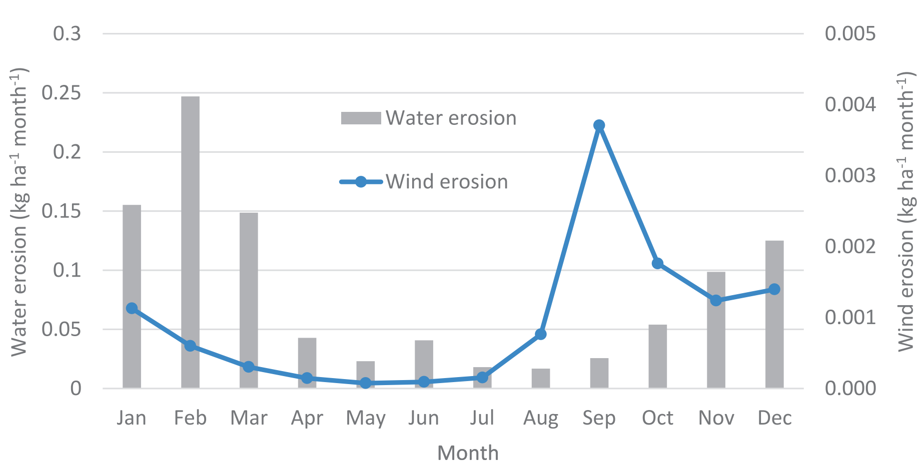

Fig. 3. The estimated average monthly water and wind erosion rates across New South Wales, Australia for the period 2001–2021.

Table 2
The average nutrient mass fraction and stock in NSW soils.

Layer	Thickness (cm)	Depth (cm)	BD (g cm^{-3})	N (%)	P (%)	SOC (%)	Total (%)	N (kg ha^{-1})	P (kg ha^{-1})	SOC (kg ha^{-1})	Total (kg ha^{-1})
1	5	0–5	1.34	0.12	0.03	2.22	2.37	161	43	2979	3183
2	10	5–15	1.41	0.10	0.03	1.41	1.54	143	43	1995	2181
3	15	15–30	1.47	0.07	0.03	0.88	0.98	96	39	1297	1431
4	30	30–60	1.46	0.04	0.02	0.53	0.59	63	34	769	865
5	40	60–100	1.48	0.03	0.02	0.35	0.40	45	34	519	598
6	100	100–200	1.51	0.03	0.02	0.25	0.29	38	30	377	446

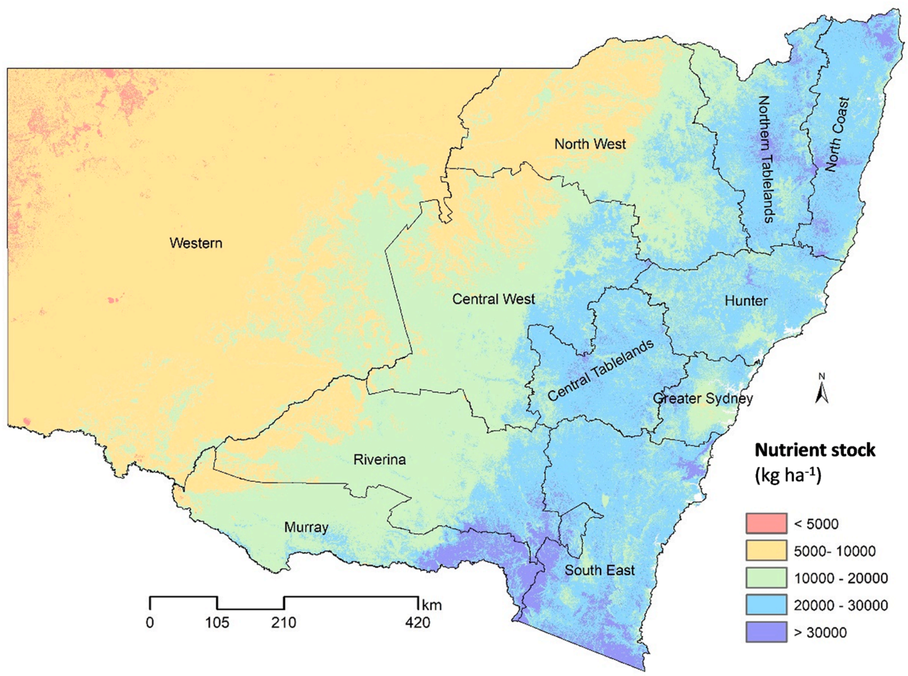

Fig. 4. The estimated total soil nutrient (N, P and SOC) stock in the topsoil layer (0–5 cm) across New South Wales, Australia.

Table 3
The estimated nutrient stocks in the topsoil (0–5 cm) across NSW Local Land Service (LLS) regions.

LLS	BD (g cm^{-3})	N (%)	P (%)	SOC (%)	Total (%)	N (kg ha^{-1})	P (kg ha^{-1})	SOC (kg ha^{-1})	Total (kg ha^{-1})
Central Tablelands	1.24	0.17	0.03	3.79	3.99	1065	187	23,712	24,964
Central West	1.40	0.12	0.03	2.03	2.18	828	235	14,394	15,457
Greater Sydney	1.15	0.20	0.03	3.45	3.68	1172	169	19,960	21,301
Hunter	1.15	0.20	0.04	3.73	3.97	1143	212	21,574	22,928
Murray	1.35	0.15	0.04	2.77	2.95	992	246	17,999	19,238
North Coast	1.08	0.22	0.04	4.53	4.80	1204	250	24,399	25,853
North West	1.31	0.12	0.04	1.94	2.10	801	283	12,784	13,868
Northern Tablelands	1.18	0.17	0.03	3.89	4.09	978	207	23,026	24,211
Riverina	1.38	0.14	0.03	2.34	2.51	940	223	15,821	16,984
South East	1.18	0.20	0.03	4.22	4.46	1207	188	24,896	26,292
Western	1.44	0.06	0.03	1.00	1.09	460	203	7363	8026

total N: 2.2, total P: 0.3 and SOC: 41.6 kg ha^{-1} yr^{-1}. There is great variation in soil nutrient-transport across NSW (Fig. 5). The total nutrient transport rates through erosion ranged from 2 kg ha^{-1} yr^{-1} in the Western region to 395 kg ha^{-1} yr^{-1} in the North Coast region. The values estimated are close to those found by Roose and Bartches (2006), who compared data from numerous experiments in the United Kingdom concerning the contribution of water erosion to carbon losses in different climatic, relief, soil type, and management conditions. The estimated SOC transport in NSW falls in the lower range compared to the global studies (e.g., Mutema et al., 2015; Müller-Nedebock and Chaplot, 2015) in which less than 50 kg ha^{-1} yr^{-1} is considered low.

The nutrient transport rates also vary greatly over the 20-year study period (Table 4). The lowest nutrient transport (15.7 kg ha^{-1} yr^{-1}) was found in 2019 as there was a prolonged period of drought and there was little runoff or water erosion. The highest nutrient transport rate (78.0 kg ha^{-1} yr^{-1}) was in 2020 as there were a lot of storm events after the dry period and bushfires of the previous years, which significantly reduced the vegetation cover leaving little soil protection.

The seasonal variation in nutrient transport follows the same pattern as that of water erosion. The average monthly nutrient transport is estimated 2.0 kg ha^{-1} month^{-1}. Minimum monthly nutrient transport rate is estimated at 0.42 kg ha^{-1} month^{-1} in August and the maximum is

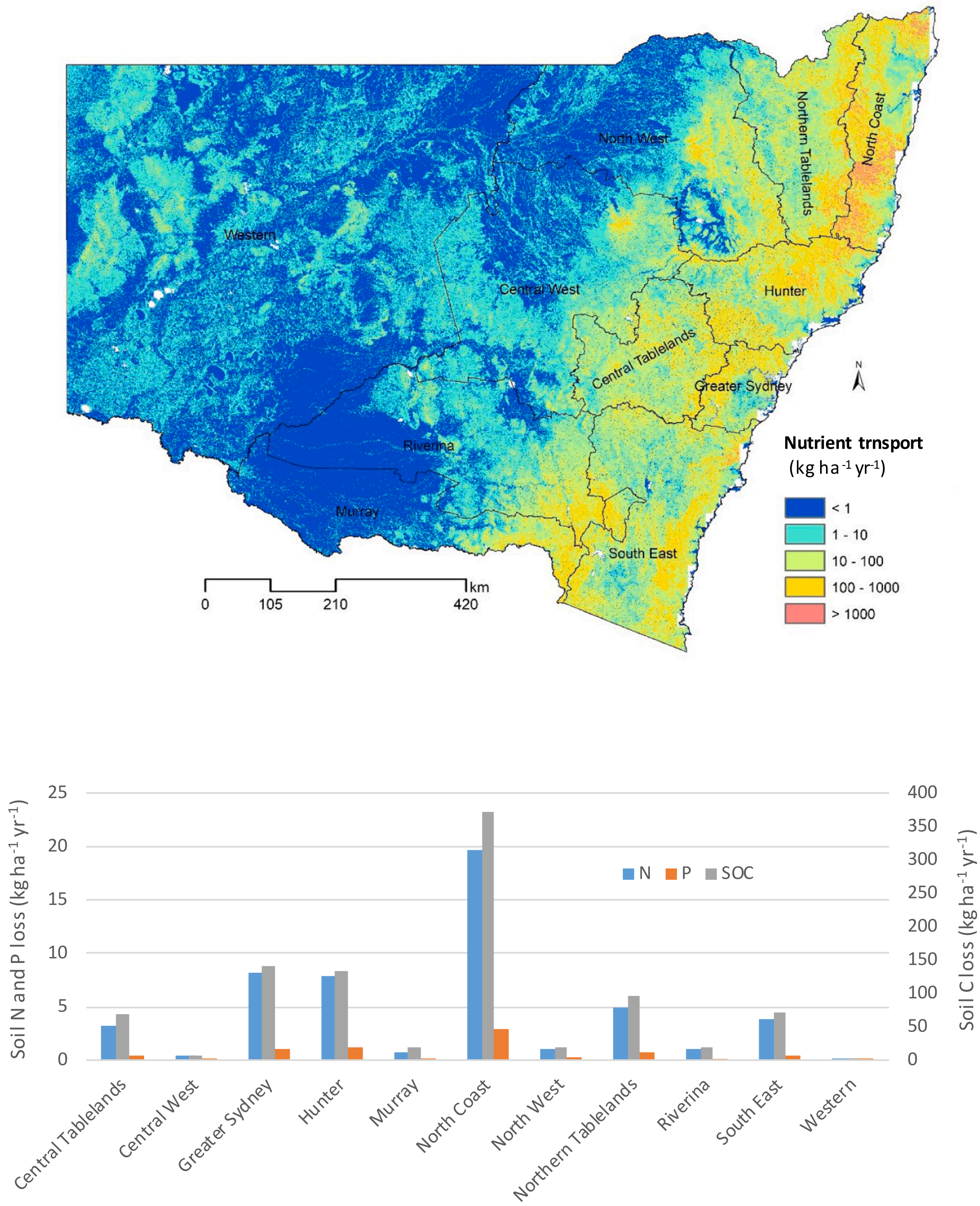

Fig. 5. The estimated average annual nutrient transport rate (2001 to 2021) from water and wind erosion across New South Wales (top) and the average annual nutrient transport rate at each Local Land Service (LLS) region (bottom).

estimated 5.94 kg ha^{-1} month^{-1} in February. Nutrient transport in summer is about 14 times higher than that in winter due to higher rainfall intensities over summer.

Losing just 1 mm of soil via water or wind erosion, over a hectare, is approximately equivalent to losing 10 tonnes of soil. It is the topsoil that erodes, and this soil layer generally has the highest levels of organic matter and plant nutrients like nitrogen, potassium and phosphorus. While the loss of 1 mm of soil seems trivial, this represents losing 240 kg ha^{-1} of organic carbon, 12 kg ha^{-1} of total N and 3 kg ha^{-1} of total P on average from NSW soils. This loss comes from the native and hard-won organic pool built up over time and from good land management practices which support soil structure and on-going nitrogen mineralisation. While most nutrients can be replaced by fertiliser (although it can be costly), organic carbon is much harder to build up.

Nutrient transport rates vary significantly among land uses. Nutrient transport rates are significantly higher for production forestry (9.6, 1.4 and 179.3 kg ha^{-1} yr^{-1} for N, P and SOC respectively) and nature conservation (8.3, 1.1 and 153.8 kg ha^{-1} yr^{-1} for N, P and SOC respectively). In contrary, cropping land has low nutrient transport rates (0.2, 0.1 and 3.9 kg ha^{-1} yr^{-1} for N, P and SOC respectively) as it's generally located in flat area (slope < 2 %) with little soil loss. Results also show a relatively lower nutrient transport rate in grazing and pasture lands with a total nutrient transport rate less than 36 kg ha^{-1} yr^{-1} (Table 5). Though these results reveal the impact of land use on nutrient transport in general, more detailed analysis is needed to consider contributions from other factors such as slopes, soil conditions and the management practices.

3.4. *Estimated cost of nutrient transport across NSW*

On average, the annual amount of soil eroded from the NSW is estimated to be 80 million tonnes. The total cost of the nutrient transported (N, P and SOC) is estimated at $4.21 billion Australian dollars based on the market price of these fertilisers in 2022. The cost of nutrient transported within individual LLS regions was estimated between $0.06 (Western) and $1.53 (North Coast) billion Australian dollars. Table 6

Table 4
Annual nutrient transport rates (kg ha^{-1} yr^{-1}) from New South Wales topsoil due to water and wind erosion from 2001 to 2021.

Year	Rainfall (mm)	Erosivity (MJ mm ha^{-1}h^{-1} yr^{-1})	Erosion (kg ha^{-1} yr^{-1})	N (kg ha^{-1} yr^{-1})	P (kg ha^{-1} yr^{-1})	SOC (kg ha^{-1} yr^{-1})	Total (kg ha^{-1} yr^{-1})
2001	480	1145	1264	3.0	0.5	56.1	59.5
2002	317	681	754	1.5	0.2	27.8	29.5
2003	491	964	950	1.9	0.3	36.3	38.5
2004	490	1147	1141	2.4	0.4	45.0	47.7
2005	509	918	894	1.9	0.3	35.2	37.4
2006	353	680	693	1.5	0.2	29.1	30.9
2007	554	1183	1095	2.2	0.4	41.5	44.1
2008	526	1144	1086	2.3	0.4	43.3	46.0
2009	502	1246	1313	3.1	0.5	58.3	61.8
2010	818	1803	1320	2.6	0.4	50.4	53.5
2011	675	1654	1160	2.4	0.4	46.0	48.9
2012	572	1425	1056	2.4	0.4	44.6	47.4
2013	473	1239	1466	3.3	0.5	61.8	65.5
2014	432	808	688	1.4	0.2	26.2	27.8
2015	472	848	781	1.6	0.3	30.8	32.7
2016	669	1092	839	1.8	0.3	33.4	35.4
2017	446	811	754	1.7	0.3	31.2	33.1
2018	342	551	623	1.4	0.2	26.6	28.2
2019	258	410	418	0.8	0.1	14.8	15.7
2020	642	1518	1813	3.9	0.6	73.4	78.0
2021	738	1709	1541	3.3	0.5	62.6	66.5
Mean	512	1094	1031	3.0	0.5	41.6	44.2

Table 5
Annual erosion and nutrient transport rates (kg ha^{-1} yr^{-1}) from different land uses in New South Wales.

Land use	Slope (%)	Erosion	N	P	SOC	Total
Production forestry	14.2	2951	9.6	1.4	179.3	190.3
Nature conservation	19.2	3450	8.3	1.1	153.8	163.2
Perennial horticulture	15.3	3221	6.4	1.1	128.0	135.5
Plantation forestry	9.2	981	2.0	0.4	44.9	47.3
Grazing modified pastures	6.3	919	1.8	0.3	35.9	38.1
Grazing native vegetation	3.5	506	0.8	0.2	15.5	16.5
Cropping	1.5	164	0.2	0.1	3.9	4.2

summarises the estimated soil nutrient stock, transport and costs across NSW LLS regions.

The costs of nutrient transport can also be estimated based on land use (e.g. cropping). NSW has a total cropping area of 11.6 million hectares, and the average erosion rate in the cropping area is 0.2 kg ha^{-1} yr^{-1}. The total cost of nutrient transport for the NSW cropping area is $0.23 billion dollars per year from NSW cropping area, including $0.07 billion for N, $0.11 billion for P and $0.05 billion for SOC. With the information on nutrient transport at a given specific area and a time, it's possible to locate the high risk areas needed for land management improvement and monitoring. For example, the production forestry land use areas in the North Coast and Hunter regions in NSW need some land management actions to reduce soil erosion and nutrient transport.

The calculations in this study are simply an estimate of the nutrient transport and the replacement costs. This is the immediate cost of fertility transport from soil erosion, however the long-term cost to society in terms of water quality and other environmental risks can also be significant (Bertol et al., 2017). In addition, soil organic matter transported by soil erosion contains not only the primary nutrients (e.g. N, P), but also soil microbial communities that need to be considered in the cost calculation for SOC loss as a nutrient source. Considering all these factors is not feasible for studies over large areas (e.g. state-wide as in this study), however, we plan to consider and analyse the long-term impacts on soil productivity and the off-site impacts (e.g. water quality) on a catchment basis in our future studies.

4. Conclusion

This study presents a first attempt to assess soil nutrient transport from both water and wind erosion and its spatial and temporal variability across NSW, Australia. We estimated the mass fraction (%), stock, transport and the costs of total nitrogen, total phosphorus and soil organic carbon in the eroded soil. The average annual total nutrient transport (N, P and SOC) from soil erosion in NSW is estimated 90 kg ha^{-1} yr^{-1}, ranging from near zero in the Western region to 395 kg ha^{-1} yr^{-1} in the North Coast region. The average total annual nutrient transport rate due to both water and wind erosion is estimated at approximately 2.4 % of the surface soil (0–5 cm) total stock in NSW. The total annual cost of nutrient transported is estimated at $4.21 billion Australian dollars for the entire state and $0.2 billion dollars from cropping areas. Nutrient transport by water erosion is estimated at approximately 90 times higher, on average, than by wind erosion, considering the state as a whole, however, wind erosion is more significant in the dry Western region in Spring (e.g. September). The areas with the highest nutrient transport are in the North Coast, Greater Sydney and Hunter regions due to the relatively high water erosion and nutrient content of the soils.

The results of this study highlighted priority areas being the North Coast and Hunter regions that are most likely to be susceptible to soil erosion with high potential nutrient transport rates, off-site costs and high capacity for improvement and recovery. Identifying these critical nutrient transport areas can help identify where conservation efforts can potentially be more beneficial and efficient. The estimates on nutrient stock, transport rates and costs, though not fully evaluated, were reasonable and comparable with other Australian and international studies as the water and wind erosion models are well developed and the best available data sets were used. Through this study, we also developed integrated and automated sequences of workflows with repeatable spatial analysis tools so that the results can be updated as more accurate and higher resolution input data (e.g. vegetation cover, and digital soil maps) become available. The differences in soil and nutrient transport

Table 6
Estimated annual soil nutrient transport and costs across New South Wales Local Land Service (LLS) regions.

LLS Name	Area (ha)	TotalStock (kg ha^{-1})	Erosion (kg ha^{-1} yr^{-1})	N (kg ha^{-1} yr^{-1})	P (kg ha^{-1} yr^{-1})	SOC (kg ha^{-1} yr^{-1})	Total (kg ha^{-1} yr^{-1})	Cost ($ billion)
Central Tablelands	3,128,969	198,976	1381	3.2	0.5	68.3	71.9	0.27
Central West	9,150,734	248,368	296	0.4	0.1	7.7	8.2	0.09
Greater Sydney	1,247,414	251,120	3272	8.2	1.0	141.0	150.2	0.23
Hunter	3,295,470	288,582	3672	7.9	1.2	133.7	142.8	0.57
Murray	4,188,377	183,096	337	0.8	0.1	18.0	18.9	0.10
North Coast	3,212,218	208,578	5435	19.6	2.9	372.8	395.3	1.53
North West	8,255,405	215,755	638	1.0	0.3	18.1	19.3	0.19
Northern Tablelands	3,957,423	101,194	3073	4.9	0.8	97.0	102.7	0.49
Riverina	6,699,410	142,599	461	1.0	0.2	19.2	20.3	0.16
South East	5,562,503	128,651	1686	3.9	0.5	71.5	75.9	0.51
Western	31,442,872	142,036	165	0.1	0.0	1.5	1.7	0.06

among NSW LLS regions were due to the differences in rainfall intensity, slope gradient, soil nutrient contents and vegetation cover or land management. The average annual total nutrient transport rates vary greatly among land uses, ranging from 4.2 to over 300 kg ha^{-1} yr^{-1}. This demonstrates the importance of land use and management in controlling nutrient transport. As other factors, such as slope and rainfall are difficult to control, it is essential that land management changes that maximise soil vegetation cover are used to ensure the long-term sustainability of agricultural systems and to avoid irreversible losses.

Our method addresses some limitations of previous nutrient transport estimation studies which only focused on either water or wind erosion at an annual interval or longer. By incorporating monthly time series data, our method is more suitable for the assessment of spatial and seasonal variability of soil erosion and nutrient -transport, and ultimately guiding improved land management practices.

Nevertheless, there remain several shortcomings and sources of uncertainty in our approach, and further development and validation of the method are needed. Nutrient transport in this study only considered the movement due to erosion from its original location or on a pixel basis. Nutrient transported to water bodies or redistributed downslope to other lower parts of the landscape need to be considered in future studies. Field-based studies are needed in the high priority areas to determine the actual level of nutrient transport and the impact on downstream water quality. This study only considered three major nutrients; other important soil nutrients such as potassium (K), sulfur (S), magnesium (Mg) or calcium (Ca) also need to be considered in future studies.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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