Plant Ecology
https://doi.org/10.1007/s11258-024-01414-9

How do plants reduce erosion? An Eco Evidence assessment

A. C. Dahanayake[1] · J. A. Webb[1] · J. Greet[2] · J. D. Brookes[3]

Received: 20 November 2023 / Accepted: 19 March 2024

Abstract
Soil erosion adversely impacts natural and human environments globally. Vegetation is often used as a sustainable approach to mitigate erosion. Although using vegetation to reduce erosion is a widely accepted concept, how different plant traits mitigate different mechanisms of erosion, and the generality of these mechanisms has not been well demonstrated. We developed ten hypotheses on how different plant traits (roots, leaves, and stems) act to reduce erosion through different mechanisms (binding soil particles, promoting suspended sediment deposition and reducing the energy of waves, runoff, and wind). We then conducted a rapid evidence assessment of the scientific literature using the Eco Evidence method. We found strong evidence to support our overarching hypothesis—an increase in plant abundance reduces erosion. We also found support for the specific hypotheses that plant roots bind soil particles and that greater plant stem density and leaf area reduce surface run-off and promote sediment deposition. There was insufficient evidence to support the hypotheses that an increase in stem density or leaf area reduces wave or wind energy. None of our hypotheses were rejected. Species with higher root and stem densities and greater leaf area will be the most effective in mitigating erosion. Our review highlights that there is insufficient evidence regarding some potentially important mechanisms between vegetation and erosion, making these prospective areas for further research. Our results have the potential to aid environmental engineers when designing schemes to reduce erosion and ecologists and managers who are concerned about the conservation and restoration of erosion-prone environments.

Keywords Eco Evidence · Erosion · Rapid evidence assessment · Systematic literature review · Vegetation

Introduction

Erosion and deposition of soil particles shape the form of land, coastlines, rivers, and lakes. During soil erosion, particles detach from the soil mass and are transported by erosive agents such as flowing water and wind. When there is insufficient energy to transport the soil particles, they settle into depositional zones. Soil erosion adversely impacts natural and human environments globally (Burylo et al. 2011b; Pimentel et al. 1995). Erosion in agricultural land causes redistribution and loss of soil, breakdown of soil structure and a decrease in soil organic matter and nutrients, which reduces soil fertility and cultivable soil depth (Li et al. 2019). The loss of soil fertility has flow-on impacts on food production land values and may promote the abandonment of agricultural land (Sartori et al. 2019). The loss of soil organic matter can reduce the water-holding capacity of soils, ultimately reducing soil moisture and increasing the susceptibility of plants to water stress. Sedimentation of eroded particles can reduce the capacity of reservoirs, rivers, and drainage canals, increasing the risk of flooding (Obialor

Communicated by Michelle Tedder.

✉ A. C. Dahanayake
amali.dahanayake@student.unimelb.edu.au

J. A. Webb
angus.webb@unimelb.edu.au

J. Greet
greetj@unimelb.edu.au

J. D. Brookes
justin.brookes@adelaide.edu.au

[1] Department of Infrastructure Engineering, Faculty of Engineering and Information Technology, University of Melbourne, Parkville Victoria 3010, Australia

[2] School of Food, Agriculture, Forest and Ecosystem Sciences, Faculty of Science, University of Melbourne, Burnley, Victoria 3121, Australia

[3] School of Biological Sciences, Faculty of Sciences, Engineering and Technology, University of Adelaide, Adelaide, South Australia 5005, Australia

Published online: 13 April 2024

et al. 2019; Uri 2000). Nitrogen and phosphorus from eroded soil contribute to eutrophication globally. Furthermore, soil erosion has a considerable impact on the global economy, with an estimated cost of eight billion US dollars to the global GDP annually (Sartori et al. 2019; Telles et al. 2011).

There are natural and artificial techniques to mitigate erosion and safeguard soil integrity. These can be categorised as agronomic measures, soil management, and mechanical methods (Morgan 2005). Agronomic measures use vegetation to protect soil against erosion and build organic content. Soil management techniques include preparing the soil to promote plant growth and improving its structure, making the soil more resilient to erosion. Mechanical methods involve engineering structures to alter the surface topology to control the flow of water and air. Mechanical methods are often ineffective on their own, as they cannot prevent the detachment of soil particles. Many mechanical methods, such as terraces, are also costly to install and maintain and may create difficulties for farmers (Verstraeten and Poesen 1999). However, mechanical methods are often useful complementary measures to agronomic measures.

Using vegetation to mitigate the effects of soil erosion in embankments, riverbanks, lakeshores, and coastal areas is seen as a more sustainable, aesthetically pleasing and cost-effective solution than constructing artificial erosion reduction barriers (such as breakwaters on a beach), or conventional slope stabilisation methods (such as shotcrete on an embankment) (Cao et al. 2015; Herbst et al. 2006). Additionally, agronomic measures of soil conservation may be readily incorporated into existing farming systems and more useful for maintaining or restoring biodiverse plant communities (Morgan 2005).

The ability of plants to reduce soil erosion is generally accepted as a broad concept (Burylo et al. 2011b; Cao et al. 2015; De Baets et al. 2009). Plants may reduce erosion in multiple ways such as vegetation canopy and litter intercept raindrops and reduce their kinetic energy (Truman and Bradford 1990); plants increase water infiltration into the soil by intercepting runoff at the soil surface by acting as a roughness element, and by reducing the velocity of runoff water (Bochet and García-Fayos 2004; Styczen and Morgan 1995); and they increase soil cohesion by binding soil particles (Bochet and García-Fayos 2004; Truman and Bradford 1990).

The efficiency of soil stabilisation by plants may be affected by plant architecture and mechanical properties (Bochet et al. 2006; Morgan 2005). The physical attributes of plants such as the dimensions of the roots and stems, their spatial distribution on a plant, how plants are distributed (e.g. plant density), the strength characteristics (tensile strength and flexibility) of plant stems and roots to withstand the forces of erosion, may all determine the efficacy of the plants for preventing erosion (De Baets et al. 2009).

However, while the general concept of plants being able to reduce erosion is well accepted, and there are individual studies demonstrating how specific plant traits mitigate the different mechanisms of soil erosion, the generality of these specific mechanisms has not been well demonstrated. In short, we do not know which plant traits are most effective for reducing erosion and how. In this review, we aimed to synthesise existing evidence on how the above- and below-ground parts of plants mitigate erosion. With this understanding, the selection of plants and plant distribution may be optimised so that plants can be more effectively used for erosion reduction.

We reviewed evidence from previously published literature on how various plant traits help to reduce different mechanisms of erosion. Instead of a conventional narrative literature review, we systematically assessed the extent of evidence for causal relationships between different plant traits and erosion mechanisms using the Eco Evidence method (Norris et al. 2012).

Methods

Eco Evidence approach

To assess the evidence within the scientific literature we conducted a rapid evidence assessment using the Eco Evidence method (Norris et al. 2012). Eco Evidence uses evidence available in the published ecological literature to transparently assess the level of support for cause–effect hypotheses in environmental investigations (Norris et al. 2012). This method tests pieces of evidence against a series of criteria and can be used to build an argument for causality through the collective strength of a number of pieces of otherwise weak evidence (Greet et al. 2011). Since this method weighs each piece of evidence according to its study design, stronger studies contribute more to the assessment of causality, but weaker evidence is not discarded (Nichols et al. 2011). The analysis provides a congruous, unbiased and logical method to identify likely causes of observed or hypothesised effects (Suter et al. 2010). The method can be reproduced, and the results are less dependent on the reviewer than those of narrative reviews (Miller et al. 2013; Webb et al. 2017).

The Eco Evidence method is an 8-step process (Fig. 1), in which the user synthesises the evidence for one or more cause–effect hypotheses (Norris et al. 2012).

Developing the hypotheses (steps 1–4)

We developed a conceptual model of our hypotheses on how different plant traits potentially mitigate the different mechanisms of soil erosion (Fig. 2). For this model, the

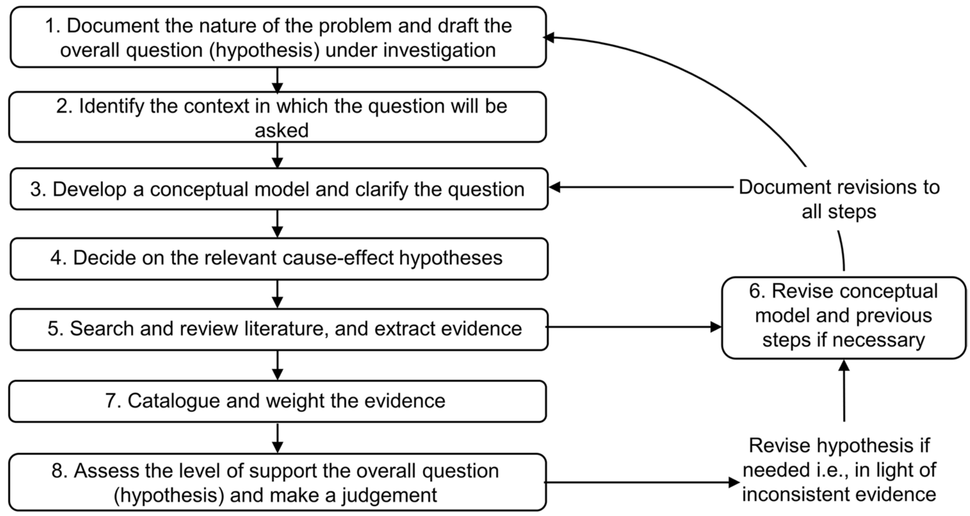

Fig. 1 Eight-step process of Eco Evidence method (reproduced from Norris et al. 2012)

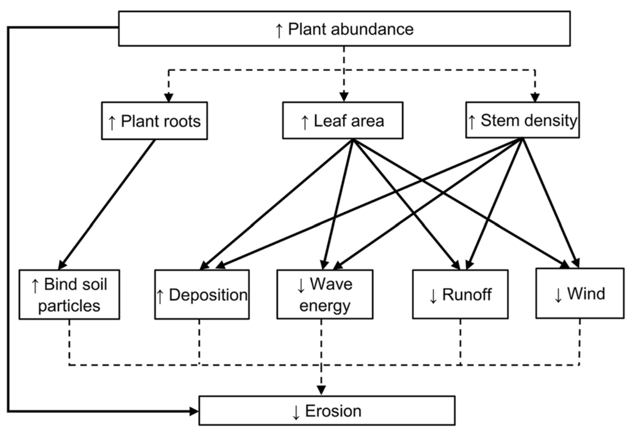

Fig. 2 Conceptual model illustrating the potential causal relationships between different plant traits and erosion mechanisms that we investigated via rapid evidence assessment. Every solid line shows a putative causal relationship that we tested in our analyses. Broken lines represent assumed relationships that were not tested

overarching hypothesis was that an increase in plant abundance would result in reduced soil erosion. This allowed us to include studies that considered plant abundance and its effects on erosion but did not assess the specific mechanisms contributing to the reduction.

For the context of the question, we limited our study to herbaceous plants and shrubs. We excluded trees because they act differently when it comes to soil conservation (De Baets et al. 2009). In addition, shrubs and herbaceous plants germinate quickly with favourable site conditions (Brindle 2003) and they can reduce concentrated flow erosion (i.e. rill and ephemeral gully erosion) in a shorter time (De Baets et al. 2009).

The Soil Science Society of America states that "soil is a natural body comprised of solids (minerals and organic matter), liquid, and gases that occurs on the land surface, occupies space, and is characterised by one or both of the following: horizons, or layers, that are distinguishable from the initial material as a result of additions, losses, transfers, and transformations of energy and matter or the ability to support rooted plants in a natural environment" (Soil Survey Staff 1999). Therefore, soil includes terrestrial sediments as well as littoral sediments. Although the properties of soils in different environments will vary, the intent of this study was to test for general causal relationships between plant traits and erosion mechanisms, regardless of such differences.

We derived ten specific hypotheses from our conceptual model (Table 1). We included the overarching hypothesis that an increase in plant abundance results in reduced erosion. We considered whether an increase in plant roots results in an increased binding of soil particles. In addition, we considered whether an increase in leaf area promotes suspended sediment deposition, reduces wave energy, reduces surface run-off, and reduces wind velocity at the soil surface. We also considered whether an increase in plant stems per unit area promotes suspended sediment deposition, reduces the energy in waves, reduces surface run-off, and reduces wind velocity at the soil surface. Splash detachment is a key mechanism of the erosion process; therefore, we included studies that discussed splash erosion under the two hypotheses that considered run-off.

For the definitions of plant traits included in this conceptual model, we considered that: an increase in plant abundance also includes increases in plant density or plant cover, an increase in plant roots includes increases in root characteristics such as root depth or diameter, an increase of leaf area include an increase in the dimensions of the leaves (contributing to the increase in the leaf area), and an increase in stem density will include an increase in either the material density of the stems or how densely the stems are located on the ground. For the complete list of search term definitions please refer to Table I in supplementary information.

Table 1 Causes, effects, and their trajectories (the hypotheses) that we investigated via rapid evidence assessment

Hypothesis number	Cause	Cause trajectory	Effect	Effect trajectory
1	Plant abundance	Increase	Erosion	Decrease
2	Plant roots	Increase	Bind soil particles	Increase
3	Leaf area	Increase	Deposition	Increase
4	Leaf area	Increase	Wave energy	Decrease
5	Leaf area	Increase	Run-off	Decrease
6	Leaf area	Increase	Wind	Decrease
7	Stem density	Increase	Deposition	Increase
8	Stem density	Increase	Wave energy	Decrease
9	Stem density	Increase	Run-off	Decrease
10	Stem density	Increase	Wind	Decrease

For the simplification of the study, we did not include an in-depth analysis of the individual mechanisms of how the species-specific traits of plants reduce the driver of erosion listed along with it in our hypotheses (for example, an in-depth analysis of different physicochemical interactions of different root traits and soil). Our aim instead was to develop a broader understanding of how these broad groups of plant traits mitigate the different drivers of soil erosion, by synthesising the existing evidence on how the above and below ground parts of plants mitigate erosion. This simpler conceptual model enabled us to extract pieces of evidence from multiple literature sources to assess the support or lack of support for our hypotheses, and to aggregate those pieces of evidence to form an objective conclusion about our general hypotheses.

Evidence extraction (steps 5–6)

Following the development of our conceptual model and individual hypotheses, we extracted evidence for the causal relationships from the scientific literature. To conduct the literature search, we first developed two limiting term searches (TS1 and TS2; Table I, supplementary information) to narrow the search to include only studies that investigated relationships between plants and erosion. Then we developed search terms related to the specific hypotheses regarding the various plant traits and the mechanisms of erosion (Table I, supplementary information). We used a previously published case study that employed Eco Evidence (Miller et al. 2013) to inform the development of these search terms. These search terms were combined using AND operators to capture the causes and effects of all the specific hypotheses (Table II, supplementary information).

We searched the Web of Science database for research papers published from January 2000 to October 2023. Then we extracted the search results (authors, title, keywords, abstract, and the year it was published) and tabulated them under the search term combination (i.e., hypothesis) under which they were identified. Some records can show up for multiple hypotheses (papers which would potentially give evidence to multiple hypotheses). The order of the list of papers returned for each hypothesis was then randomised to eliminate any bias potentially introduced by the age of the papers.

The listed papers were initially screened by reading their title and abstract and were marked as 'yes'/'no'/'maybe' according to their relevance to our hypothesis and whether they appeared to contain usable evidence for further analysis. All the abstracts of the papers that were marked as 'yes' or 'maybe' were then carefully read for a second time and were marked as either a 'yes' or a 'no'. If any abstract was identified as potentially contributing to other hypotheses than the one it was initially listed under, it was transferred to the lists of those hypotheses. Then, the full papers (of all the abstracts marked as 'yes') were read to extract the evidence. Upon reading the full papers, we found that some of them did not provide appropriate evidence to inform our hypotheses, as well as some papers that provided evidence for multiple hypotheses.

We initiated the evidence extraction process with hypothesis two, because of the overwhelming 10,560 search hits generated by hypothesis one. We proceeded through to hypothesis ten. Upon revisiting hypothesis one, we found that it had already amassed sufficient evidence to meet the threshold value (as outlined in Step 8), thereby supporting the hypothesis. Therefore, for hypothesis one, we only needed to read 75 randomly ordered papers for this first step. This decision was made to manage the workload while still obtaining a reasonable amount of unbiased evidence from the published literature. A table showing the number of abstracts and full papers which were read for this review is given in supplementary material (Table II, supplementary information).

Papers that did provide appropriate evidence for our hypotheses underwent evidence extraction according to the standard methods in Eco Evidence (Norris et al. 2012).

Evidence extraction involves recording information on whether the study findings support the hypothesis, the type of experimental or survey design used and the number of independent sampling units. This information is used to weigh the evidence in Step 7.

Evidence weighting (step 7)

For each study, the quality of (and thus weight given to) the evidence is evaluated in terms of three attributes:

1. Study design type (e.g., control vs impact with no before data, gradient design, before after control impact etc.)
2. The number of independent sampling units used as controls
3. The number of (potentially) impacted independent sampling units (e.g., impact sites, treatment locations)

In the case of studies with gradient response designs, the total number of sampling units is used in place of (2) and (3) above.

Certain study designs are more at risk of confounding effects than others, which thus weakens their inferential strength (Norris et al. 2012). Therefore, different types of study designs are allocated different weights according to their robustness. Studies in which error terms are well controlled (e.g., Before After Control Impact [BACI] designs) are given more weight than less rigorously controlled designs (e.g., when only impact locations are sampled) (Table 2).

Inferential power is increased by having one or more control sites in a study, as it better captures overall 'normal' behaviour, which is useful for assessing the variance from that norm (Downes et al. 2002). As a result, studies with control sites are allocated a greater weight in the Eco Evidence method, with more points allocated when controls are replicated (Table 2).

Similarly, a higher number of impact sites results in a better estimate of the variance and the range of dynamics experienced by the impact locations. Therefore, studies with more than one impact sites receive a higher weight (Table 2).

For a study type categorised as a gradient response design, its weight is increased with replication, such that the weight increases at a similar rate to factorial study designs. For studies that use a gradient response design, the total number of sites used is considered in weighting (Table 2).

For each piece of evidence, its total evidence weight is the sum of the study design weight and replication weight/s.

Making a judgement (step 8)

Lastly, we summed the total weight of evidence for and against support for each of our hypotheses. The default threshold value of 20 total evidence points was used to interpret the evidence for a causal relationship for our specific hypotheses (Table 3).

There are four possible outcomes using this method. "Support for hypothesis" means there likely exists a causal relationship between the cause and effect as predicted. "Support for alternate hypothesis" will include studies that show either a directional trajectory opposite to what we predicted or a failure to reject the null hypothesis of no causal relationship between the hypothesised cause and effect. "Inconsistent evidence" means that there is considerable evidence both in favour of and against the hypothesis and suggests that we might have to revise our conceptual model, the context of studies included (e.g., to a narrower range of environments), or refine the hypothesis to address this inconsistency. Both "support for alternate hypothesis" and "inconsistent

Table 2 Weights applied to study types and the number of control/reference and impact/treatment sampling units (Norris et al. 2012)

Study attribute	Weight
Study design type	
After impact only	1
Reference/control vs impact with no before data	2
Before vs after with no reference/control location(s)	2
Gradient response model	3
Before-after control-impact designs and variants	4
Number of reference/control sampling units	
0	0
1	2
> 1	3
Number of impact/treatment sampling units	
1	0
2	2
> 2	3
Replication of gradient response models	
< 4	0
4	2
5	4
> 5	6

Table 3 Interpretation of Eco Evidence total evidence weights (Norris et al. 2012)

Evidence in support of hypothesis	Evidence not in support of hypothesis	Conclusion
≥ 20	< 20	Support for hypothesis
< 20	≥ 20	Support for alternate hypothesis
< 20	< 20	Insufficient evidence
≥ 20	≥ 20	Inconsistent evidence

evidence" should be viewed as falsifications of the hypothesis according to Popper's theory of falsification, since both of these present conditions under which the original hypothesis does not hold true. "Insufficient evidence" might indicate an actual gap in the published literature, or this may be rectified by a more comprehensive literature review (Greet et al. 2011). However, given the comprehensiveness of our literature search, we are confident that any such results in this review indicate a true knowledge gap.

Results

We identified 41 appropriate studies from the literature, from which we extracted 57 evidence items. These studies, organised by the causal relationships (hypotheses) that they provided evidence for, were tabulated (Table III, supplementary information). Some studies provided evidence for multiple hypotheses. The majority of the studies supported our hypotheses. Of our ten hypotheses, six were supported by the evidence, and four had insufficient evidence. There were no hypotheses for which we found support for the alternate hypotheses or inconsistent evidence. The total weights of evidence for and against each of our hypotheses along with the outcome of the Eco Evidence assessments are tabulated in Table 4 and presented in Fig. 3.

We found strong evidence to support our overarching hypothesis that an increase in plant abundance decreases erosion. In addition, we found strong evidence to support the hypotheses that plant roots bind soil particles and increases in stem density and leaf area reduce surface run-off.

While we also found evidence to support the hypotheses that increases in stem density and leaf area promote suspended sediment deposition, these hypotheses were not as well supported by the literature. Although there was an overall conclusion of 'support for hypothesis' for these mechanisms, the evidence was only marginally above the threshold value of 20 evidence points.

For the remaining hypotheses, there was insufficient evidence to draw any general conclusions. This included two hypotheses for which we found no evidence at all. We did not find any studies with evidence either in support or against the hypotheses of an increase in leaf area reduces wave energy or an increase in stem density reduces wind velocity.

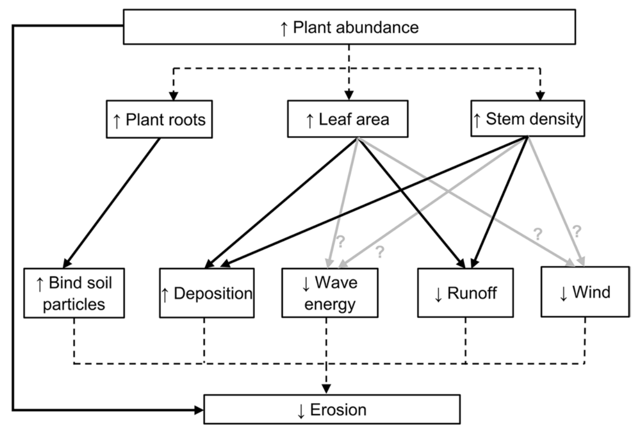

Fig. 3 Eco Evidence Results in the conceptual model. Every solid black line shows a causal relationship that we found evidence to 'support for hypothesis', and every solid grey line with a question mark shows a causal relationship for which we found 'insufficient evidence'. Broken lines represent assumed relationships that were not tested

Table 4 Total weight of evidence for and against support for the hypotheses, and the outcomes from the Eco Evidence assessments

Hypothesis (cause—effect)	Number of studies in support of hypothesis	Evidence in support of hypothesis	Number of studies not in support of hypothesis	Evidence not in support of hypothesis	Conclusion
↑ Plant abundance—↓ Erosion	10 studies	56	1 study	3	Support for hypothesis
↑ Plant roots—↑ Bind soil particles	19 studies	119	No studies	0	Support for hypothesis
↑ Leaf area—↑ Deposition	6 studies	26	No studies	0	Support for hypothesis
↑ Leaf area—↓ Wave energy	No studies	0	No studies	0	Insufficient evidence
↑ Leaf area—↓ Run-off	6 studies	36	No studies	0	Support for hypothesis
↑ Leaf area—↓ Wind	1 study	3	No studies	0	Insufficient evidence
↑ Stem density—↑ Deposition	5 studies	29	2 studies	10	Support for hypothesis
↑ Stem density—↓ Wave energy	1 study	7	No studies	0	Insufficient evidence
↑ Stem density—↓ Run-off	6 studies	42	No studies	0	Support for hypothesis
↑ Stem density—↓ Wind	No studies	0	No studies	0	Insufficient evidence

Discussion

Plants do reduce erosion

Our systematic assessment found strong evidence to support the overall research hypothesis that plants reduce erosion. This was manifested through many individual studies supporting the overarching hypothesis linking plant abundance with reduced erosion, and several of the more specific hypotheses regarding specific mechanisms. We found support for the specific hypotheses that plant roots bind soil particles, and that greater plant stem density and leaf area reduce surface run-off and promote sediment deposition. Most of the studies we reviewed provided evidence 'in support' of our hypotheses and only a handful of studies provided evidence 'not in support'. None of our hypotheses were rejected. We found insufficient evidence to reach a general conclusion for some of our hypotheses, highlighting prospective areas for further research.

Although some of the relationships that we tested are generally accepted as valid, and there are individual studies considering the mechanisms separately, there are no systematic studies which assess the available evidence for each of these relationships in a synoptic manner. To our knowledge, this is the first study that analyses and synthesises the evidence for these relationships. As a result, our study gives ecologists and water managers a comprehensive understanding of how important plant traits can be used to reduce multiple mechanisms of erosion.

Our review captured a wide range of research contexts. For example, this review included studies from riparian habitats (Hamidifar et al. 2018) and coastal environments (Maximiliano-Cordova et al. 2019), and from climates that varied from subtropical (Mo et al. 2019), mountainous sub-Mediterranean (Burylo et al. 2011a), semi-arid (Zhang et al. 2017) to alpine (Hudek et al. 2017). This suggests that the research findings are generally applicable to a wide range of contexts.

Only one study, Li et al. (2023), provided evidence that did not support the hypothesis that an increase in plant abundance reduces erosion. This could be because this study was conducted in the field, where the greater unexplained variation compared to a laboratory experiment, and limitations of the monitoring tools which may have led to low power to detect statistically significant effects.

How do plants reduce erosion?

Increasing soil cohesion

We found strong evidence from the literature to support the hypothesis that plant roots bind soil particles together, making the soil less susceptible to erosion. Roots contribute to this by increasing soil cohesion/root reinforcement (Burylo et al. 2011a; De Baets et al. 2009; Farhadi et al. 2018; Hamidifar et al. 2018; Hao et al. 2021; Li et al. 2014; Zegeye et al. 2018), reducing sediment loss/erodibility (Chau and Chu 2017; Ma et al. 2023; Zhang et al. 2017), increasing the shear strength of the soil (Chen et al. 2019), forming a mesh that binds soil particles (Chomczyńska et al. 2016), reducing the relative soil detachment rate (De Baets et al. 2007; Farhadi et al. 2018; Li et al. 2014; Vannoppen et al. 2016), and increasing aggregate stability (Hudek et al. 2021, 2017).

Promoting suspended sediment deposition

We found evidence to support the hypotheses that greater plant leaf area and stem density promote suspended sediment deposition. The increase in leaf area per unit of interception volume of a plant contributes to sediment deposition by increasing the mass of sediment trapped per unit volume (Burylo et al. 2011b), increasing vertical accretion (Bass et al. 2022), decreasing the erosion rates (Feagin et al. 2019), and by reducing the sediment yield and sediment concentration (Ma et al. 2016; Truman and Williams 2001; Zhang et al. 2011). An increase in stem density promotes suspended sediment deposition by decreasing erosion rates (Feagin et al. 2019), increasing vertical accretion (Bass et al. 2022), and increasing sediment trapping efficiency (Erktan and Rey 2013; Lambrechts et al. 2014; Mekonnen et al. 2016).

However, two studies, da Silva et al. (2016) and Horppila et al. (2013), provided evidence that did not support the hypothesis that an increase in stem density promotes suspended sediment deposition.

Da Silva et al. (2016) studied the influence of emergent vegetation (*Echinodorus macrophyllus*) on sediment transport in the Capibaribe River, Brazil. They calculated the vegetation resistance force using the diameter of stems and found that it did not have a statistically significant effect on the amount of suspended sediment discharged by the river. There could be multiple reasons why this study did not support our hypothesis. This could be due to the fact that this study was conducted in the field, where the greater unexplained variation compared to a laboratory experiment, may have led to low power to detect statistically significant effects. Moreover, the presence of dams along the Capibaribe watershed may have impacted the river hydraulics, potentially disrupting the effects of vegetation on deposition (da Silva et al. 2016).

Horppila et al. (2013) experimentally studied the effects of different stem densities of the emergent macrophyte *Phragmites australis* on water turbulence, bottom shear velocity and water turbidity. They found that stem density had no significant effect on critical shear velocity at the sediment surface. The potential reasons that this study did not support our hypothesis are the range of shear velocity that they studied, as well as the effects of other plant traits which were not included in this study. They found that when the shear velocity reached 0.0035 m/s–0.0055 m/s, water turbidity increased greatly, and sediment erosion occurred regardless of the stem density. Furthermore, the effects of emergent plants on sediment resuspension and erosion were not only due to their effects on hydrodynamics but also due to the stabilising effect of their roots and rhizomes, which were not considered in the study (Horppila et al. 2013).

Reducing surface runoff

We found strong evidence to support the hypotheses that increases in leaf area and stem density reduce surface runoff. Increases in leaf area and stem density decrease the energy dissipation per unit time and per unit weight of the flow (unit stream power) (Kervroëdan et al. 2018). Surface runoff is exponentially related to the Leaf Area Index (LAI), with decreasing runoff at higher leaf areas (Chau and Chu 2017; Ma et al. 2016; Truman and Williams 2001). The increase in stem density reduces surface runoff by increasing the sediment obstruction potential (De Baets et al. 2009; Farhadi et al. 2018) and increasing the runoff trapping efficiency (Mekonnen et al. 2016). The reduction in surface runoff is attributable to direct (interception) and indirect (infiltration) effects of plants (Garcia-Estringana et al. 2013; Raya et al. 2006).

Knowledge gaps and recommendations for future research

For four of our hypotheses, we found insufficient evidence to reach a conclusion. This included two hypotheses for which we found only a few relevant studies and two hypotheses for which we found no evidence at all. Given the very small number of studies that were found, we are confident that expanding the bounds of our literature search to include years before 2000 would not have led to a sufficient increase in evidence to reach a general conclusion, and therefore these findings indicate true knowledge gaps.

For all of our hypotheses concerning wave energy and wind, there was insufficient evidence to reach a conclusion. This could be due to the difficulties of measuring these mechanisms along with relevant plant traits in the field, given that field studies provide limited control over parameters such as wind and waves. Flume experiments in a laboratory could be a good solution for this research gap. Artificial wave flumes and wind tunnels could be used to study the effects of plant traits on these erosion mechanisms. It is worth noting that anthropogenic factors, such as the position of dams in a river and breakwaters in coastal areas, can affect the characteristics of waves, inhibiting the accurate measurement of the driving factors necessary for testing these hypotheses (da Silva et al. 2016). However, this could be mitigated by modelling the observed data and assigning appropriate coefficients for the effects of dams and breakwaters, and through validating the models using multiple years of monitoring data.

We acknowledge that there is a propensity to publish only the significant results and that studies with no correlation or a failure to falsify null hypotheses are more difficult to publish (Koricheva 2003). Thus, there is a bias in the studies published. However, Eco Evidence is less affected by publication bias than other systematic review methods such as meta-analysis. Eco Evidence has the capacity to incorporate evidence even in the absence of summary statistics that are essential for a meta-analysis. It is common for authors to denote certain factors in their analyses as non-significant without providing summary statistics, but they usually provide complete summary statistics for results that are significant. In an Eco Evidence analysis, both types of results can be included, but in a meta-analysis, only the results that are significant can be included (Greet et al. 2011; Norris et al. 2012).

Implications for management: best ways to use plants to reduce erosion

Our results can inform water managers, ecologists, and engineers aiming to mitigate the effects of erosion on riverbanks, lakeshores, and coastal areas. It is evident that plants with denser root structures are more efficient at binding soil particles together. Therefore, when considering revegetation and restoration of an eroding lakeshore or riverbank (for example), the use of plants with a denser root structure would be preferable.

The use of artificial methods to control erosion is often ineffective on their own as they cannot prevent the detachment of soil particles (Morgan 2005). Therefore, managers could combine plants with dense root systems with other erosion prevention methods such as the use of sandbags to yield better results. Juvenile plants could be planted in bags made from biodegradable material (such as hessian sacks) containing a growing medium rich in the nutrients necessary for plants to establish. These sandbags may keep the lakeshore or riverbank from eroding until the plants are established. Once the plants are established, their roots will bind the soil particles together and stabilise the shoreline or riverbanks. This method has proven to be effective in reducing lakeshore erosion at Lake Victoria, NSW, Australia by using Spiny Sedge (*Cyperus gymnocaulos*) (pers. obs.) and in reducing coastal erosion by promoting seagrass (*Zostera marina*) (Unsworth et al. 2019).

In addition, our review found that plants with higher stem density and larger leaf area will reduce surface runoff and promote deposition of suspended sediments. Such plants would be particularly useful in areas receiving high amounts of rainfall since it is runoff that needs to be controlled to prevent erosion. Even on a lakeshore where large trees may be sparse, dense growth of understory vegetation (hence high stem density) and plants with larger leaf area could help to reduce runoff-induced soil erosion. For example, sedge and rush species (*Juncus* spp.) with their high stem densities could be very effective for this purpose. In addition, grass species with high stem densities and dense fine root networks could be very effective in preventing topsoil from being eroded by concentrated flow by preventing soil detachment, reducing runoff velocity, filtering soil particles and promoting suspended sediment deposition (De Baets et al. 2009).

However, some grass and rush species with high stem densities and leaf areas such as *Juncus* spp. and *Phragmites australis*, although having excellent erosion reduction potential, can only grow in moist environments and prefer gently sloping areas (De Baets et al. 2009). This limits the use of these plants to restore an eroding lakeshore or riverbank if certain elevations are dry for most of the year, or if the slopes are too steep. Using drought-resistant plants could be a solution in such conditions. The use of *Cyperaceae* spp. (sedges) for erosion control has been found to be applicable in many environments (Bryson and Carter 2008; Simpson and Inglis 2001) and some sedge species, such as *Cyperus gymnocaulos*, are also relatively drought-tolerant and suitable for locations prone to drying.

In restoration practice, revegetation is often implemented with multiple objectives, and it is important to consider biodiversity implications (e.g. through the use of species-rich native planting mixes) as well as potential to mitigate erosion when selecting appropriate plants. For example, species mixtures with plants with greater leaf area and higher stem densities can be complimented by having an understory of grass species which have denser root structures.

Critical appraisal of the Eco Evidence approach

There are many advantages of the Eco Evidence approach that we used. The systematic analytical framework of Eco Evidence reduces bias and improves reproducibility (the result depends less on the reviewer). Since the eight-step method is an iterative process, we were able to refine our conceptual model and define clear hypotheses that could be tested by searching the literature. The clearly defined hypotheses led to efficient searching of literature, enabled us to identify knowledge gaps and prevented us from making conclusions based on insufficient evidence. The conclusions made from this Eco Evidence approach are therefore more transparent and less prone to bias than from a narrative review. We believe this method gives us the ability to conduct comprehensive and efficient reviews in ecology.

The Eco Evidence method mainly depends on the causal criterion 'consistency of association', where the repeated observation of an association between the plausible cause and effect under different conditions and assessed using different methods. In order to achieve this, the summation of study weights for and against the hypothesis are compared. We used the standard study weights and the default threshold value of 20, as suggested by Norris et al. (2012). These standard weights and the 20-point cut-off were established through a series of tests and in-depth discussions with ecologists based around questions of how many good quality or poor quality studies showing the same result need to be seen before one is satisfied that causality is demonstrated. The weights and thresholds can be modified as long as it is justified (Norris et al. 2012). A study on floodplain geomorphological processes (Grove et al. 2011) adjusted the study weights, arguing that it is impractical to have 'before' data due to the long timescales involved in floodplain formation (i.e., thousands of years). The standard 20-point cut-off implies that a minimum of three independent, extremely high-quality studies are enough to determine the existence (or non-existence) of a cause-and-effect relationship. On the other hand, at least seven low-quality studies may be required to arrive at the same conclusion (Norris et al. 2012). This cut-off serves as a handy way to split a continuous score, similar to the widely accepted convention of 0.05 as a significant p-value. However, like significance levels, it should not be applied thoughtlessly.

However, there were a few difficulties that we encountered while using the Eco Evidence method. Some of the study designs were not straightforward and clear in the research papers and it consumed a lot of time to identify the specific information required to weigh those studies. In addition, for some studies, it was difficult to determine the study type as one of the few study types defined in the Eco Evidence method. Therefore, this method has the potential to be improved by including more detailed classifications of study designs. The framework does not differentiate between observational studies and actual experiments (i.e., studies where treatments were randomised). Nonetheless, experiments offer stronger evidence for causality.

In addition, the method does not address the scenario of inconsistent pieces of evidence found from a single study

(Norris et al. 2012). However, in general, we believe the advantages outweigh the disadvantages of this method.

Conclusion

Overall, there is strong evidence to conclude that greater plant abundance reduces soil erosion, with a number of specific mechanisms also being supported through our review. Plants with denser root structures, more stems per unit area and larger leaf area, reduce erosion by binding soil particles together, reducing surface runoff and promoting suspended sediment deposition. Therefore, plants with these traits should be considered in erosion management and restoration of environments. Water managers could combine plants with denser root systems with other artificial erosion prevention methods, as well as promote a dense growth of understory vegetation (high stem density) of plants with a large leaf area, in the restoration of erosion-prone environments. Lastly, the research gaps identified through our review regarding the role of stem density and leaf area in reducing wave or wind energy, highlight suitable avenues for future research.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s11258-024-01414-9.

Acknowledgements This work was funded by the Murray Darling Basin Authority (MDBA) and A. C. Dahanayake is funded by a Melbourne Research Scholarship from the University of Melbourne. The authors wish to acknowledge A/Prof. Chris Walsh for reviewing this manuscript prior to its submission to the journal. Authors wish to extend their gratitude to the two anonymous reviewers and editors for reviewing the manuscript which helped to improve this manuscript to its present level.

Author contributions Conceptualisation: A.C.D., J.A.W., J.G., J.D.B. Developing methods: A.C.D., J.A.W., J.G., J.D.B. Conducting the research: A.C.D. Data analysis: A.C.D. Data interpretation: A.C.D., J.A.W., J.G., J.D.B. Preparation figures and tables: A.C.D. Writing: A.C.D., J.A.W., J.G., J.D.B. All authors contributed to the study conception and design. Literature review and analysis were performed by A. C. Dahanayake. The first draft of the manuscript was written by A. C. Dahanayake, and all authors contributed to the review and improvement of the manuscript. All authors read and approved the final manuscript.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions. This work was funded by the Murray Darling Basin Authority (MDBA) and A. C. Dahanayake is funded by the Melbourne Research Scholarship from the University of Melbourne.

Data availability Data are available from the authors upon reasonable request.

Declarations

Competing interests The authors declare no competing interests.

References

Bass J, Granse D, Hache I, Jensen K, Karius V, Minden V, Stock M, Suchrow S, Kleyer M (2022) Plant traits affect vertical accretion of salt marshes. Estuar Coast Shelf Sci 276:108010

Bochet E, García-Fayos P (2004) Factors controlling vegetation establishment and water erosion on motorway slopes in Valencia, Spain. Restor Ecol 12:166–174

Bochet E, Poesen J, Rubio JL (2006) Runoff and soil loss under individual plants of a semi-arid mediterranean shrubland: influence of plant morphology and rainfall intensity. Earth Surf Proc Land 31:536–549

Brindle FA (2003) Use of native vegetation and biostimulants for controlling soil erosion on steep terrain. Transp Res Rec 1819:203–209

Bryson CT, Carter R (2008) The significance of Cyperaceae as weeds. In: Naczi RFC, Ford BA (eds) Sedges: uses, diversity, and systematics of the cyperaceae. Missouri Botanical Garden Press, St Louis, MO, Monographs in Systematic Botany from the Missouri Botanical Garden, pp 15–101

Burylo M, Hudek C, Rey F (2011a) Soil reinforcement by the roots of six dominant species on eroded mountainous marly slopes (Southern Alps, France). CATENA 84:70–78

Burylo M, Rey F, Bochet E, Dutoit T (2011b) Plant functional traits and species ability for sediment retention during concentrated flow erosion. Plant Soil 353:135–144

Cao L, Zhang Y, Lu H, Yuan J, Zhu Y, Liang Y (2015) Grass hedge effects on controlling soil loss from concentrated flow: a case study in the red soil region of China. Soil Tillage Res 148:97–105

Chau NL, Chu LM (2017) Fern cover and the importance of plant traits in reducing erosion on steep soil slopes. CATENA 151:98–106

Chen Y, Thompson C, Collins M (2019) Controls on creek margin stability by the root systems of saltmarsh vegetation, Beaulieu Estuary, Southern England. Anthr Coasts 2:21–38

Chomczyńska M, Soldatov V, Wasąg H, Turski M (2016) Effect of ion exchange substrate on grass root development and cohesion of sandy soil. Int Agrophysics 30:293–300

da Silva YJAB, Cantalice JRB, Singh VP, CruzSouza CMCAWLdS (2016) Sediment transport under the presence and absence of emergent vegetation in a natural alluvial channel from Brazil. Int J Sedim Res 31:360–367

De Baets S, Poesen J, Knapen A, Galindo P (2007) Impact of root architecture on the erosion-reducing potential of roots during concentrated flow. Earth Surf Proc Land 32:1323–1345

De Baets S, Poesen J, Reubens B, Muys B, De Baerdemaeker J, Meersmans J (2009) Methodological framework to select plant species for controlling rill and gully erosion: application to a mediterranean ecosystem. Earth Surf Proc Land 34:1374–1392

Downes BJ, Barmuta LA, Fairweather PG, Faith DP, Keough MJ, Lake PS, Mapstone BD, Quinn GP (2002) Monitoring ecological impacts: concepts and practice in flowing waters. Cambridge University Press, Cambridge, U.K.

Erktan A, Rey F (2013) Linking sediment trapping efficiency with morphological traits of Salix tiller barriers on marly gully floors under ecological rehabilitation. Ecol Eng 51:212–220

Farhadi A, Ahmadi H, Soufi M, Motamedvaziri B, Moeini A (2018) Assessment of the potential of semi-arid plants to reduce soil erosion in the Konartakhteh watershed, Iran. Arab J Geosci 11:518

Feagin RA, Furman M, Salgado K, Martinez ML, Innocenti RA, Eubanks K, Figlus J, Huff TP, Sigren J, Silva R (2019) The role of beach and sand dune vegetation in mediating wave run up erosion. Estuar Coast Shelf Sci 219:97–106

Garcia-Estringana P, Alonso-Blazquez N, Marques MJ, Bienes R, Gonzalez-Andres F, Alegre J (2013) Use of mediterranean legume shrubs to control soil erosion and runoff in central Spain. a large-plot assessment under natural rainfall conducted during the stages of shrub establishment and subsequent colonisation. CATENA 102:3–12

Greet J, Webb JA, Cousens RD (2011) The importance of seasonal flow timing for riparian vegetation dynamics: a systematic review using causal criteria analysis. Freshw Biol 56:1231–1247

Hamidifar H, Keshavarzi A, Truong P (2018) Enhancement of river bank shear strength parameters using vetiver grass root system. Arab J Geosci 11:611

Hao H-X, Qin J-H, Sun Z-X, Guo Z-L, Wang J-G (2021) Erosion-reducing effects of plant roots during concentrated flow under contrasting textured soils. CATENA 203:105378

Herbst M, Roberts JM, Rosier PTW, Gowing DJ (2006) Measuring and modelling the rainfall interception loss by hedgerows in southern England. Agric for Meteorol 141:244–256

Horppila J, Kaitaranta J, Joensuu L, Nurminen L (2013) Influence of emergent macrophyte (Phragmites australis) density on water turbulence and erosion of organic-rich sediment. J Hydrodyn 25:288–293

Hudek C, Putinica C, Otten W, De Baets S (2021) Functional root trait-based classification of cover crops to improve soil physical properties. Eur J Soil Sci 73:13147

Hudek C, Stanchi S, D'Amico M, Freppaz M (2017) Quantifying the contribution of the root system of alpine vegetation in the soil aggregate stability of moraine. Int Soil Water Conserv Res 5:36–42

Kervroëdan L, Armand R, Saunier M, Ouvry J-F, Faucon M-P (2018) Plant functional trait effects on runoff to design herbaceous hedges for soil erosion control. Ecol Eng 118:143–151

Lambrechts T, François S, Lutts S, Muñoz-Carpena R, Bielders CL (2014) Impact of plant growth and morphology and of sediment concentration on sediment retention efficiency of vegetative filter strips: flume experiments and VFSMOD modeling. J Hydrol 511:800–810

Li Q, Liu G, Zhang Z, Tuo D, Xu M (2014) Effect of root architecture on structural stability and erodibility of topsoils during concentrated flow in hilly loess plateau. Chin Geogra Sci 25:757–764

Li T, Zhang H, Wang X, Cheng S, Fang H, Liu G, Yuan W (2019) Soil erosion affects variations of soil organic carbon and soil respiration along a slope in Northeast China. Ecol Process 8:28

Li X, Zhang F, He Q, Yang M (2023) Correspondence analysis between vegetation cover and sheet erosion rate on an abandoned farmland slope based on 7Be measurement. CATENA 222:106886

Ma B, Li C, Li Z, Wu F (2016) Effects of crops on runoff and soil loss on sloping farmland under simulated rainfall. Clean: Soil, Air, Water 44:849–857

Ma J, Ma B, Li Z, Wang C, Shang Y, Zhang Z (2023) Determining the mechanism of the root effect on soil detachment under mixed modes of different plant species using flume simulation. Sci Total Environ 858:159888

Maximiliano-Cordova C, Salgado K, Martínez ML, Mendoza E, Silva R, Guevara R, Feagin RA (2019) Does the functional richness of plants reduce wave erosion on embryo coastal dunes? Estuaries Coasts 42:1730–1741

Mekonnen M, Keesstra SD, Ritsema CJ, Stroosnijder L, Baartman JEM (2016) Sediment trapping with indigenous grass species showing differences in plant traits in northwest Ethiopia. CATENA 147:755–763

Miller KA, Webb JA, de Little SC, Stewardson MJ (2013) Environmental flows can reduce the encroachment of terrestrial vegetation into river channels: a systematic literature review. Environ Manage 52:1202–1212

Mo M, Liu Z, Yang J, Song Y, Tu A, Liao K, Zhang J (2019) Water and sediment runoff and soil moisture response to grass cover in sloping citrus land, Southern China. Soil Water Res 14:10–21

Morgan RPC (2005) Soil Erosion and Conservation. Blackwell Publishing Ltd

Nichols S, Webb A, Norris R, Stewardson M (2011) Eco evidence analysis methods manual a systematic approach to evaluate causality in environmental science. Canberra, eWater CRC

Norris RH, Webb JA, Nichols SJ, Stewardson MJ, Harrison ET (2012) Analyzing cause and effect in environmental assessments: using weighted evidence from the literature. Freshw Sci 31:5–21

Obialor CA, Okeke OC, Onunkwo AA, Fagorite VI, Ehujuo NN (2019) Reservoir sedimentation: causes, effects and mitigation. International Journal of Advanced Academic Research 5:92–109

Pimentel D, Harvey C, Resosudarmo P, Sinclair K, Kurz D, McNair M, Crist S, Shpritz L, Fitton L, Saffouri R, Blair R (1995) Environmental and economic costs of soil erosion and conservation benefits. Science 267:1117–1123

Raya AM, Zuazo VHD, Martínez JRF (2006) Soil erosion and runoff response to plant-cover strips on semiarid slopes (SE Spain). Land Degrad Dev 17:1–11

Sartori M, Philippidis G, Ferrari E, Borrelli P, Lugato E, Montanarella L, Panagos P (2019) A linkage between the biophysical and the economic: assessing the global market impacts of soil erosion. Land Use Policy 86:299–312

Simpson DA, Inglis CA (2001) Cyperaceae of economic, ethnobotanical and horticultural importance: a checklist. Kew Bull 56:257–360

Soil Survey Staff (1999) Soil taxonomy: a basic system of soil classification for making anf interpreting soil surveys. United States Department of Agriculture-Natural Resources Conservation Service.

Styczen ME, Morgan RPC (1995) Engineering properties of vegetation. In: Morgan RPC, Rickson RJ (eds) Slope stabilization and erosion control: a bioengineering approach. E&FN Spon, London, pp 5–58

Suter GW, Norton SB, Cormier SM (2010) The science and philosophy of a method for assessing environmental causes. Hum Ecol Risk Assess Int J 16:19–34

Telles TS, Guimarães MF, Dechen SCF (2011) The cost of soil erosion. Rev Bras Ciênc Solo 35:287–298

Truman CC, Bradford H (1990) Antecedent water content and rainfall energy influence on soil aggregate breakdown. Soil Sci Soc of Amer J 54:1385–1392

Truman CC, Williams RG (2001) Effects of peanut cropping practices and canopy cover conditions on runoff and sediment yield. J Soil Water Conserv 56:152–159

Unsworth RKF, Bertelli CM, Cullen-Unsworth LC, Esteban N, Jones BL, Lilley R, Lowe C, Nuuttila HK, Rees SC (2019) Sowing the seeds of seagrass recovery using hessian bags. Front Ecol Evol 7:00311

Uri ND (2000) Agriculture and the environment—the problem of soil erosion. J Sustain Agric 16:71–94

Vannoppen W, Poesen J, Peeters P, De Baets S, Vandevoorde B (2016) Root properties of vegetation communities and their impact on the erosion resistance of river dikes. Earth Surf Proc Land 41:2038–2046

Verstraeten G, Poesen J (1999) The nature of small-scale flooding, muddy floods and retention pond sedimentation in central Belgium. Geomorphology 29:275–292

Webb JA, Schofield K, Norton SB, Nichols SJ, Melcher A (2017) Weaving common threads in environmental causal assessment methods: toward an ideal method for rapid evidence synthesis. Freshw Sci 36:250–256

Zegeye AD, Langendoen EJ, Tilahun SA, Mekuria W, Poesen J, Steenhuis TS (2018) Root reinforcement to soils provided by common ethiopian highland plants for gully erosion control. Ecohydrology 11:1940

Zhang C, Liu GB, Song ZL, Qu D, Fang LC, Deng L (2017) Natural succession on abandoned cropland effectively decreases the soil erodibility and improves the fungal diversity. Ecol Appl 27:2142–2154

Zhang W, Yu D, Shi X, Wang H, Gu Z, Zhang X, Tan M (2011) The suitability of using leaf area index to quantify soil loss under vegetation cover. J Mt Sci 8:564–570