Manaaki Whenua
Landcare Research

Bio-physical performance of erosion and sediment control/mitigation techniques – an international comparison to common practices in New Zealand

Prepared for: MBIE as part of STEC

November 2020

Bio-physical performance of erosion and sediment control/mitigation techniques – an international comparison to common practices in New Zealand

Contract Report: LC3891

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Summary

Project and Client

- This report forms part of the deliverables for the MBIE programme 'Smarter targeting of erosion control' (STEC), specifically Milestone 1.2.2-1.

Objectives

- To 'benchmark' current erosion and sediment control (ESC) methods in New Zealand by comparing practices to those in our respective countries.
- To provide recommendations on practices for consideration to be used in New Zealand for controlling erosion and reducing sediment delivery to waterways.
- To produce a report to meet Critical Step Milestone 1.2.2-1 of the STEC programme

Methods

- We read the Phillips et al. (2020) review of current ESC practices in New Zealand.
- We assessed current ESC practices in our respective countries to determine practices currently not commonly used in New Zealand that might be useful in future.
- Recommendations were made of practices and processes deemed to be useful for New Zealand to investigate in the future.

Results – key findings/recommendations for New Zealand

- Although the general concepts of integrated adaptive ESC management are formulated in the literature, their full implementation in practice is lacking (both in New Zealand and internationally). The development of quantitative assessment methods are key to overcoming this issue.
- Aerial and satellite remote sensing offers remarkable opportunities to assess, map, and monitor different erosion processes and coupled with machine learning offers great potential.
- In general, controlling sheet and rill erosion rates has received most attention, whereas controlling gully erosion and particularly subsurface erosion by water received limited research interest.
- More attention is needed to evaluate the performance of ESC/mitigation techniques in the long term. Many lessons can be learned from successes and failures of the implementation of such control measures installed in various types of environments.
- Upscaling of erosion processes and quantifying the sediment connectivity at different spatial and temporal scales is a challenge that limits the usefulness of models at regional scales. In addition, improving the understanding and modelling of the interactions of erosion processes is also a challenge for research. In particular, the interaction between hillslope processes such as surface erosion and shallow landslides and the link to sediment transport in channels and streams is still difficult to quantify. Understanding this chain of processes is important for defining the effectiveness of ESC interventions at the catchment scale.

- Programmes for monitoring ESC measures are important for evaluating their effectiveness and also to aid planning of maintenance costs to ensure they maintain their functionality.

Conclusions

- The formulation and application of an "adaptive ESC management concept" is a useful tool for the effective and efficient implementation of ESC measures at different administrative levels (national, regional, and local).
- Improvements in remote sensing techniques are important for the assessment of processes and ESC measure effectiveness.
- The application of different types of models and datasets can improve the effectiveness of ESC measures when used during several management phases such as assessment, planning, and evaluation.
- At national scale, empirical and semi-quantitative models can be used to define hotspots of processes with high intensity ('susceptibility maps'). At regional scales event-based (probabilistic) physically based models can be used to quantify the intensity of processes considering different scenarios, based on the probability of occurrence. These approaches are needed for cost-benefit analysis of ESC measures.
- Effectiveness of bioengineering ESC measures changes drastically (0 to almost 100%) depending on the type of process and set of local conditions.
- Communication and training and passing on of knowledge about ESC measures at the local scale are important to optimise resources needed in the planning and implementation phases.
- In the future, management of established ESC measures (e.g. spaced-planted trees or protection forests) can be a challenge to guarantee the resistance and resilience of such ecosystems to climate changes and disturbances.
- Building of georeferenced cadasters for event documentation and measures can improve the efficiency in the management and effectiveness of ESC measures.
- Monitoring programmes are fundamental activities for the evaluation of implemented ESC measures, as well as for the calibration/validation of models that should be considered in New Zealand.

1 Introduction

Manaaki Whenua – Landcare Research has received funding from MBIE for a research programme called 'Smarter targeting of erosion control' (STEC). The programme aims to enable a breakthrough in erosion and sediment control (ESC), which is crucial for meeting proposed national water quality targets (MfE 2019a, b). The programme is directed at both the physical performance of ESC measures (the right treatment in the right place with enduring effectiveness) and their cost effectiveness.

Within the STEC programme there are several key areas of innovation to improve understanding and management of erosion and sediment in New Zealand. These include:

- improved spatial and temporal resolution of data
- characterisation of sediment quality
- linking erosion source to sediment quality
- enabling a leap in erosion modelling and prediction of the effects of erosion control at scales from hillslope to large catchments.

One research aim (RA1.2) is focused on assessing the biophysical performance of erosion mitigation measures to provide confidence in their use by land managers and in erosion models. A secondary aim is to link the biophysical performance to an assessment of the benefit–cost of measures to reduce sediment in water to improve catchment management to meet catchment water quality targets when they are introduced. It is not the specific aim of this report to cover the economic aspects here, as a parallel work stream within STEC (RA 1.4) is focused on the economic impacts of erosion and the benefits of mitigation.

This report is part of the RA 1.2 activities of the STEC programme and builds on the information summarized in the report of Phillips et al. (2020). We aim to extend the contents of that document to consider practices and methods for ESC that might be useful in New Zealand from a broader international point of view.

As mentioned by Phillips et al. (2020), a wide variety of well-established ESC practices are used in New Zealand. New challenges for the improvement of ESC, as in other countries, are mostly related to:

- improving quantitative approaches to assess the effectiveness of ESC techniques, considering the spatio-temporal variability of conditions and scales (e.g. triggering events, growth dynamics of vegetation, and disturbances)
- implementing multiple ESC approaches in an integrated-adaptive ESC management concept.

This report, like Phillips et al. (2020), also considers the most relevant processes in New Zealand (surface erosion, shallow landslides, streambank erosion, wind erosion), and focuses on extensive biological measures in the rural environment (e.g. afforestation), rather than specific local technical measures (e.g. cribwalls), which tend to be universally used.

The contents of this report are based solely on the knowledge of the authors rather than via a systematic search of the published and 'grey' literature.

2 Objectives

- 'Benchmark' current ESC methods in New Zealand by comparing practices with those in the authors' respective countries.
- Discuss the international knowledge on ESC in relation to the New Zealand situation as documented in the report 'Bio-physical performance of ESC techniques in New Zealand: a review' (Phillips et al. 2020).
- Identify ESC concepts, measures, tools, and techniques not common in NZ that might have potential for future implementation.
- Provide recommendations on practices for consideration to be used in New Zealand for controlling erosion and reducing sediment delivery to waterways.
- Produce a report to meet Critical Step Milestone 1.2.2-1 of the STEC programme.

3 Assessment of effectiveness: process understanding and scaling

To quantify an ESC measure's effectiveness, there is a need to understand and to model the erosion processes, as well as to obtain sufficient detail for the spatio-temporal characterization of model parameters (e.g. soil properties, rainfall data, vegetation cover, etc.).

To better understand the processes and discuss the effectiveness of measures in this report, we briefly describe a three-dimensional framework to categorize factors and processes related to ESC. It includes:

1 time dimension (duration of triggering hydrological processes),

2 spatial extent/dimensions of the processes, and

3 spatial zonation of the processes (contribution, process, and runoff/runout zones).

Figure 1 conceptually describes the three zones where factors and subsequently control measures may influence processes related to soil erosion and sediment transfer in the case of landsliding. These three zones are defined as 'contributing zone', 'process zone', and 'runoff/runout zone'.

Considering shallow landslide processes, the quantification of the effectiveness of measures is different depending on the zone considered. For instance, in the 'contributing zone', the regulation of the hydrological processes are fundamental to define the triggering condition of the landslide, whereas in the 'process zone' the mechanical properties of soil (including the effects of root reinforcement) are fundamental to determine the characteristics and triggering mechanisms of the landslide. Finally, the location and the morphological characteristics of the 'runoff/runout zone' (including the breaking effects of vegetation (Bettella et al. 2018)) define the connectivity of sediment sources that overall influence the sediment balance at the catchment scale. The processes and the effectiveness of ESC measures are discussed in this report considering these three zones of influence.

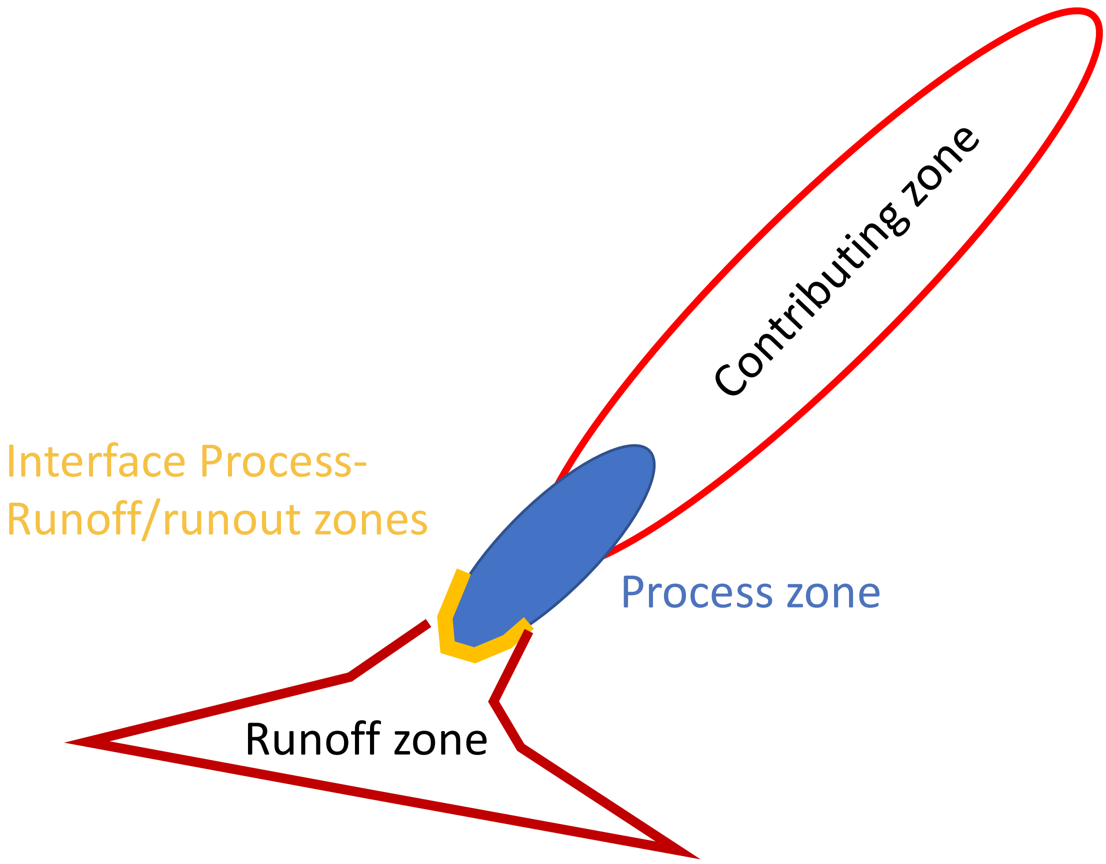


Figure 1. Conceptual visualization of the influencing “zones” related to an erosion process (source: M. Schwarz).

The categorization of the zones allows for a better understanding of the spatio-temporal characteristics of the processes and of the effects of factors/measures for erosion control. The conceptual visualization of the spatio-temporal dimensions of the processes discussed in this report is shown in Figure 2. As the review focuses mainly on bioengineering techniques, the magnitude of mechanical and hydrological effects of vegetation are sketched parallel to each axis. The values on the axes should be considered as general indications or orders of magnitude, and not as sharp limits. For example, sheet erosion involves single soil particle (< ca 1 mm diameter) disaggregated (splash effect) and mobilized by surface runoff during intense rainfall events (short duration); for this process vegetation contributes to reduce the splash effect, increasing soil aggregate stability, and reducing runoff quantity and velocity (micro-roughness). In steep eroded areas (typically in gully formations) shrub vegetation may considerably contribute to the stabilization of shallow soil creep (< 20 cm soil depth) through the mechanical effects of roots.

Rill erosion and gully erosion are driven by the flow shear stress generated through the water and sediment runoff derived from the drainage of areas larger than a few square meters during rainfall events with a duration sufficiently long to generate high peak runoff discharges. For these processes, vegetation influences both locally (process zone) the resistance of soil material to erosion (by both the above- and below-ground biomass), and the reduction of runoff generation in the contributing zone (storage and flow velocity). In the runout zone, vegetation may also trap sediments that cannot be transported in suspension and reduce the size of suspended particles through the reduction of flow velocity.

Shallow landslides are triggered by the combined effects of low soil suction (wet soil condition) and the build-up of positive pore water pressures along preferential flow paths during intense rainfall events (of relative short duration), typically in silty-sandy soils on slopes with inclinations between 20 and 45° (depending on the lithology). Vegetation may contribute considerably to shallow landslide stability through root reinforcement and evapotranspiration in the process zone, and through the regulation of runoff generation in the contributing zone. In the runout zone, vegetation contributes to reduce the runout distance (by trapping the failed soil mass), and thus reducing sediment connectivity to the stream network.

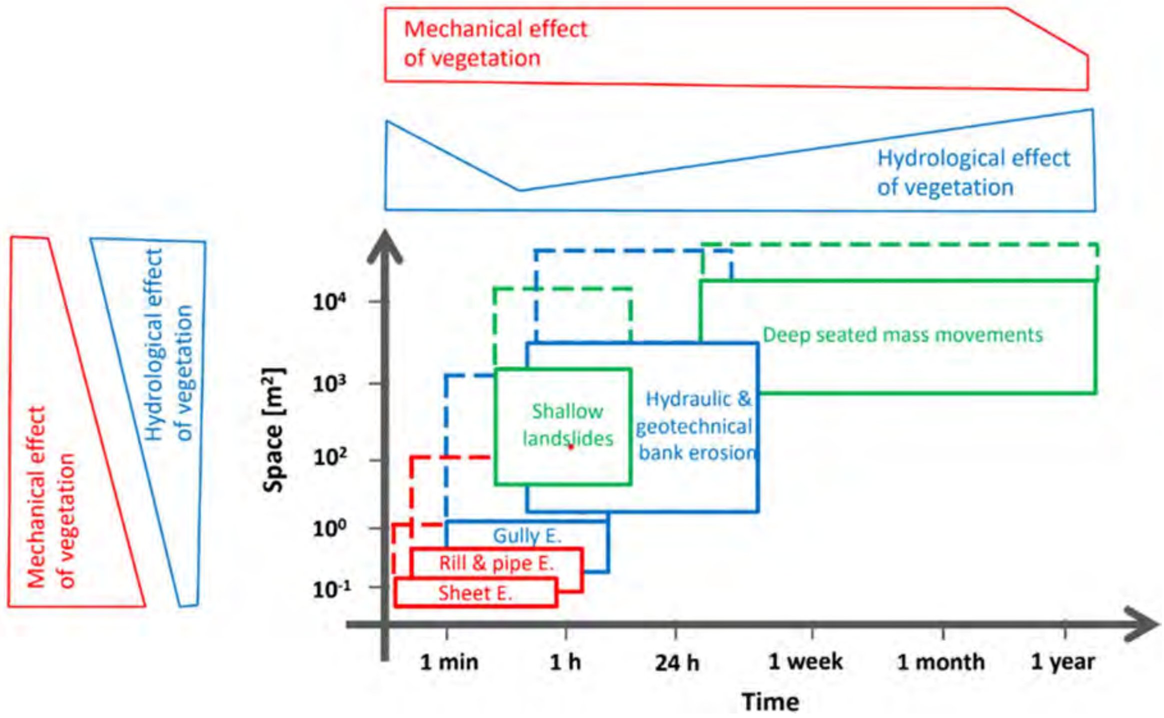


Figure 2. Conceptual visualization of the spatio-temporal dimensions of erosion processes triggered by hydrological events. On the top and left, the meaning of the effects of vegetation for different time and space scales are illustrated. Dashed lines indicate the extension of dimensions considering the contributing and runoff/runout zones. (Units on the X-axis: 10 min., 1 hour, 24 hours, 1 week, 1 month, 1 year) (source: M. Schwarz).

Riverbank erosion involves mainly two types of processes: hydraulic bank erosion (due to the effect of flow shear stress) and geotechnical bank erosion (driven by gravity). The two processes are often coupled in the sense that due to the modification of river cross section geometry caused by hydraulic bank erosion, the probability of geotechnical bank erosion is increased. Vegetation can reduce the magnitude of these processes in the process zone mainly through the mechanical effects (roots and flexible stems) up to a limited threshold value of river discharge. In the contributing zone, vegetation reduces runoff discharge, depending on the magnitude of the rain event. Depending on the characteristic of the stream morphology, vegetation may contribute to stabilize deposited sediments on banks in the runoff zone. In some types of stream (e.g. step-pool) the presence of large wood (LW) is a fundamental element for the stabilization of the stream bed.

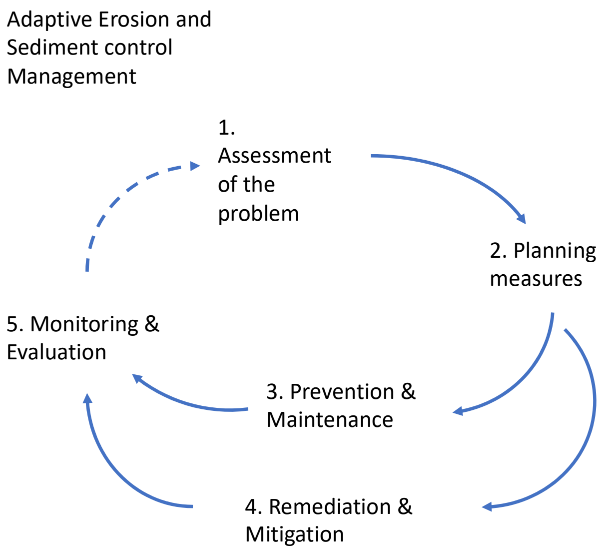
Deep-seated mass movements involve large soil masses where vegetation may contribute to mitigate deformation through the regulation of the hydrological balance in the contributing and process zones, in particular through the long-term effects of interception and evapotranspiration.

This general overview of vegetation's effects in the spatio-temporal interactions of coupled processes between the different zones (Fig. 2) helps inform a strategy for choosing the best combination of measures that may result in the greatest possible effectiveness for ESC at the catchment scale. Potential conflicting interactions of measures are highlighted too: for instance, drainage measures that increase slope stability may increase the regime of discharge magnitudes leading to an increase in bank erosion. Conversely, in some cases measures often have multiple benefits that should be considered in an integrated management strategy (e.g. mitigation of streambank hydraulic erosion may lead to the stabilization of slope mass movements). In this situation, the selected ESC measures outlined in this report are discussed considering their zone of application and the relative effectiveness depending on the magnitude of the triggering process, and thus considering the probability of the events.

Most studies on soil erosion by water have focused on surface processes, such as sheet (interrill), rill and gully erosion, although subsurface erosion by soil piping has been reported to be a significant and widespread process as well (Bernatek & Poesen 2018). The limited number of studies on this erosion process is explained by the fact that this soil degradation process is difficult to monitor as it operates below the soil surface without any indication at the surface, except when the pipe roof collapses and a sinkhole is formed. Yet, soil loss rates resulting from piping erosion are far from negligible in particular regions, as illustrated by some case studies from Europe (Poesen 2018). Factors controlling soil piping are not always fully understood. For instance, land-use changes may affect biological activity and this in turn may result in more biopore (macropore) formation which enhances subsurface flow and soil piping in areas with fluctuating water tables at shallow depth (e.g. Verachtert et al. 2013). Various reports point to the fact that piping also significantly interacts with other erosion processes such as gullying and shallow landsliding (Poesen 2018). Of all water erosion processes, piping erosion is perhaps the most difficult to control. Studies dealing with effective prevention and control measures of soil piping are scarce.

4 Integrated adaptive ESC management

To extend the implementation of measures in a wider framework of ESC strategies, an integrated adaptive management concept can be considered. Figure 3 shows the five phases of an integrated adaptive ESC management cycle. Extreme events are often needed to trigger the awareness of population and politicians about problems related to soil erosion and sediment control. Under this condition, the need for the "Assessment of the problem" (Phase 1) is given. In this phase, the aim is to define and quantify the extent and magnitude of ongoing or potential erosion processes.



1. Define and quantify the existing or potential erosion and sediment processes (e.g. using remote sensing technique, field measurements, model predictions), and also consulting stakeholders (e;g. farmers, local population suffering from the off-site effects of soil erosion (muddy floods), civil protection services).
2. Planning of measures at different scales (e.g. regional plans vs farm plans), using appropriate information (e.g. modelling results)
3. Application of spatial, technical or biological measures for the prevention of erosive processes and maintenance of measures (e.g. management of protection forest, restriction of forest operations)
4. Application of technical or biological measures for the recover or mitigation of erosion processes.
5. Set strategies for the regular monitoring and evaluation (effectiveness and efficiency) of the implemented measures in order to perform maintenance or pass to a re-engineering phase.

Figure 3. Illustration of a possible 'integrated adaptive erosion and sediment control management' cycle (source: M. Schwarz).

One of the most promising tools to facilitate the assessment of processes is through the use of remote sensing techniques, which have improved and become more accessible in recent years. Before these, field measurements (e.g. runoff plots, radionuclides) and modelling (e.g. RUSLE) were the mostly used approaches worldwide for soil erosion rate assessments. Also in this phase, a risk-based assessment of the problem that considers both frequency-magnitude of hazards/processes and the potential of damage/losses may be considered.

In the planning phase (Phase 2), the use of erosion process assessment, cost-benefit analysis, risk analysis, etc., may be used to define which measures may be implemented and to prioritise the investment at the catchment-communal-regional scales. In the case where the ongoing erosion rate is not critical but is considered to increase to a critical level in the near future, a 'prevention and maintenance' phase may be considered (Phase 3), where ESC measures are implemented to prevent erosion processes and maintain the equilibrium of the system, from the sediment balance point of view. In this phase, it may be decided to adopt conservation strategies (e.g. actively manage protection forests to maintain their mitigation effects). In the case where erosion rates are not sustainable, interventions to recover or improve the control of erosion need to be implemented (Phase 4). Depending on the extent and importance of the assessed problem (Phase 1), the need to obtain details for the parametrization and quantification of the processes may differ considerably. The detailed implementation of ESC measures needs to be adapted to the local conditions (considering the combination of local factors and processes, but also the actual status of knowledge and resources (socio-economic) for their implementation, as well as consideration of sustainability).

In the last few decades, the importance of monitoring and evaluating the status of the implemented past measures (Phase 5) has been recognized in order to adapt the system to possible changes of forcing and other factors. For example, due to climate change or changes in disturbance regimes (fire, drought, storms, etc.), or changes in population needs, the effectiveness of measures needs to be reconsidered and adapted. The empirical evidence of such changes is often the trigger for the acceptance of a new assessment phase. In some cases, it is the temporal evolution of the measures that does not fulfil the expected performance, and thus an adaptation is needed. A regular monitoring program based on a well-documented spatial record (cadaster) of measures is fundamental to plan adaptive intervention at the right time.

5 Selection of ESC topics

In considering the objectives of this report, the knowledge of the authors together with the contents of the report of Phillips et al. (2020 Bio-physical performance of erosion and sediment control techniques in New Zealand: a review), we defined specific ESC topics to be discussed in this document.

An overview of the selected topics (red text) within the context of the Adaptive ESC Management concept discussed in the previous section and by erosion process is listed in Table 1. Although the list is incomplete, the topics in black text give an idea of complementary techniques that are already well established in New Zealand, or that are well documented elsewhere.

Table 1. List of topics related to ESC organized relative to the phases of the adaptive management cycle and erosion process. Items in red text are suggested for New Zealand

	1. Assessment	2. Planning	3. Prevention & Maintenance (spatial, technical, and biological measures)	4. Remediation & Mitigation	5. Monitoring & Evaluation
Sheet erosion	• Field observation (exposition of stones, inorganic soil horizons and roots) • Pits • Field collectors (boxes) • Models: e.g. RUSLE, WATEM-SEDEM	• Erosion Prevention and Sediment Control Plan (EPSCP) (example in Belgium)	• **Spatial:** Hazards maps → Land use plans • **Technical:** o Mats for wheel tracks o SWCT (Meatens et al. 2012) • **Biological:** o Crop and vegetation management, o protection forest management	• Mechanical methods (e.g. terraces) • Geotextile (Meatens et al. 2012) • Poles along wheel tracks • Ectomycorrhiza inoculum • "Rough and Loose" technique	
Rill & gully erosion	• Remote sensing: data and methods (e.g. LiDAR, OBIA) • Field measurements	• Erosion Prevention and Sediment Control Plan (EPSCP) (example in Belgium)	• **Spatial:** Hazards maps → Land use plans • **Technical:** o drainage systems o minimal soil profile disturbance o check dams • **Biological:** o Reduce runoff at catchment scale o protection forest management	• **Ephemeral gullies:** o No tillage and reduced tillage o Topsoil compaction o Double drilling of crops o Live sediment traps/barriers o Grass buffer strips o Grassed waterways o Minimal soil profile disturbance • **Permanent gullies:** o Check dams o Revegetation	• Monitoring programmes for technical measures • Cadaster of measures

	1. Assessment	2. Planning	3. Prevention & Maintenance (spatial, technical, and biological measures)	4. Remediation & Mitigation	5. Monitoring & Evaluation
Shallow mass movements	• Remote sensing: ○ optical aerial and satellite data ○ manual and (semi-) automated methods ○ pixel- vs object-based methods • Field measurements • Models: ○ e.g. SOSlope (Schwarz et al. 2019a) for frequency-magnitude assessment	• Erosion Prevention and Sediment Control Plan (EPSCP)	• **Spatial:** Hazards maps → Land use plans • **Technical:** ○ drainage systems • **Biological:** ○ Reduce runoff at catchment scale ○ protection forest management	• Afforestation • Spaced-planted trees • Drainage • Reduce runoff	• Guidelines for the evaluation of ecosystem services • Monitoring programmes for technical measures • Cadaster of measures
Deep seated mass movements	• Remote sensing: ○ radar data /InSAR ○ image correlation ○ time series analysis • Field measurements		• **Spatial:** Hazards maps → Land use plans • **Technical:** ○ drainage systems • **Biological:** ○ Reduce runoff at catchment scale ○ protection forest management	• Drainage (above and below ground)	
Streambank erosion	• Models: ○ e.g. BankforNET (Gasser et al., 2020) • Field measurements		• **Spatial:** Hazards maps → Land use plans • **Technical:** ○ drainage systems • **Biological:** ○ Reduce runoff at catchment scale ○ protection forest management	• Management of riparian vegetation	• Guidelines for the evaluation of ecosystem services • Cadaster of measures

6 Assessment techniques

Several assessment techniques are used to define and quantify the extent and magnitude of ongoing or potential erosion processes. These include, for example, field surveys, observations and measurements, paleo-ecological studies, process modelling, and remote sensing-based assessments.

Combined modelling and survey approaches are used, for example, in Switzerland to assess the potential erosion for farmers (Bodenschutz in der Landwirtschaft (BAFU)). With the erosion risk map, the Federal Government provides a tool for assessing the potential risk of extensive soil erosion on arable land by water. The ERK2 enables competent authorities to efficiently monitor arable soils. The ability to compare this information across the entire country is possible because of the standardized information available for all cantons (in 2 × 2-metre raster = one pixel). The calculation of the potential risk of erosion in the ERK2 refers to so-called field blocks. Field blocks are clearly defined terrain units. However, the map does not distinguish whether the area is used for agriculture or as permanent green space.

While modelling is especially valuable for the prediction of process severity and frequency (see use of SOSlope in Schwarz et al. 2019a) and allows the consideration of the effects of climate change, remote sensing can be used to assess the current situation and to look back in time to derive information about the location, distribution, and patterns of erosion processes. Thus, information derived from remote sensing data can be of value in various aspects, for example, to get a better overview of the past erosion processes and patterns, to learn more about the behaviour of specific landslides (e.g. reactivation), to get an overview of direct impacts (e.g. affected infrastructure), and to better assess future risks (e.g. as input for modelling, spatial planning, risk zone identification, and hazard mitigation).

Remote sensing data from different sensors with increasing spatial and temporal resolution provides significant opportunity for the investigation of erosion processes, and for complementing existing assessment methods. Using remote sensing also allows remote and previously inaccessible areas to be investigated. At the same time, improvements in technology allow more advanced image analysis methods to be developed that can be applied for the assessment of different erosion processes.

6.1 Remote sensing

Aerial and satellite (and terrestrial) remote sensing offers remarkable opportunities to assess, map, and monitor different erosion processes such as surface erosion, mass movements (e.g. shallow landslides, deep-seated landslides, earthflows), gully erosion and bank erosion at different resolutions in space and time. All these erosion processes occur in New Zealand (Basher 2013). Appropriate remote sensing methods can also support assessment of ESC practices.

6.1.1 Landslides

Remote sensing plays a key role in studying landslides and provides an adequate and cost-effective source to derive information about landslide distribution and types (Metternicht et al. 2005; Joyce et al. 2009; Casagli et al. 2016). The value of remote sensing becomes more evident with the increasing amount of freely available Earth observation (EO) data, which provides new opportunities to map and monitor erosion processes.

A variety of different methods and techniques, such as visual image interpretation, pixel-based approaches, object-based image analysis (OBIA), machine-learning and deep learning, change detection and time series analysis, image correlation, Interferometric Synthetic Aperture Radar (InSAR), and optical, radar and digital elevation model (DEM) data from airborne and spaceborne sensors are globally used, though specific applications may vary depending on site characteristics (environmental, topographic, size, etc.).

The interpretation of optical EO data for erosion and landslide recognition can be conducted using manual, semi-automated, and automated approaches (Scaioni et al. 2014).

Visual interpretation of aerial photography and very high resolution (VHR) optical satellite imagery is still the most common method to recognize soil erosion features and mass movements. Manual interpretation of optical imagery has advantages for landslide mapping, especially where landslides led to significant changes in the land cover, as it is usually the case for shallow landslides. However, manual interpretation reveals several drawbacks: it is resource and time consuming, subjective and the quality of the resulting landslide maps strongly depends on the experience and skills of the investigator (Galli et al. 2008; Guzzetti et al. 2012; Hölbling et al. 2015).

Semi-automated techniques can limit the subjectivity in landslide mapping and can contribute to improving the reproducibility of landslide maps (Guzzetti et al. 2012).

Usually, image classification approaches can be split into two main categories, pixel-based and object-based (Moosavi et al. 2014). Pixel-based methods take into account the spectral information associated with each pixel without considering its actual neighborhood (Scaioni et al. 2014). Considering the resolution of data and the size and spatial distribution of landslides, pixel-based methods tend to be sensitive to errors (Martha et al. 2010), frequently resulting in salt-and-pepper classifications, with single pixels being demarcated as landslides (Hölbling et al. 2017).

Consequently, there has been a trend towards object-based mapping of erosion features and particularly landslides as demonstrated by a range of studies (e.g. Martha et al. 2010; Stumpf & Kerle 2011; Hölbling et al. 2012, 2016a; Heleno et al. 2016). Object-based approaches often achieve better results than pixel-based approaches (Moosavi et al. 2014; Keyport et al. 2018). Object-based image analysis (OBIA) provides a set of suitable tools for semi-automatically mapping erosion features based on EO data. In OBIA, both knowledge-based and statistical image analysis routines have been devised for the semi-automated extraction of landslides (Eisank et al. 2014). By working on the object-level instead of the pixel-level, OBIA allows considering spectral, spatial, textural, morphometric and hierarchical properties for the classification of landslides. Most often, a combination of optical imagery and derivatives from a DEM, such as slope and curvature, is used. Some OBIA studies also integrate SAR data (Plank et al. 2016; Hölbling et al. 2018; Dabiri et al. 2020), other studies apply LiDAR data (Van den Eeckhaut et al. 2012) or UAV data (Karantanellis et al. 2020) for landslide mapping.

Change detection and time series analysis are conducted both on pixel and object level using optical imagery from different sensors (Yang & Chen 2010; Lu et al. 2011; Mondini et al. 2011; Martha et al. 2012; Behling et al. 2014; Hölbling et al. 2015, 2020; Zhao et al. 2017; Ramos-Bernal et al. 2018; Lu et al. 2019), often considering the change in vegetation cover between pre- and post-event images as an indicator for mass movements. Zweifel et al. (2019) used OBIA for identifying spatio-temporal patterns of different erosion processes in the Swiss Alps.

Recently, machine learning (e.g. random forest (RF), support vector machine (SVM)) and deep learning (e.g. convolution neural network (CNN)) approaches were developed for landslide mapping (Bui et al. 2016; Mezaal et al. 2017; Ghorbanzadeh et al. 2019; Prakash et al. 2020; Wang et al. 2020). Lu et al. (2020) proposed a method for integrating OBIA and deep learning. However, a large number of training samples are required for the application of such approaches.

Image correlation methods are used to detect slow-moving landslides and to map, monitor, and quantify the surface displacement of active landslides. For example, Stumpf et al. (2017) developed a multiple pairwise image correlation (MPIC) technique using Pléiades satellite images. Lucieer et al. (2013) used Structure from Motion (SfM) and image correlation of UAV photography. UAV data was also used by Peppa et al. (2017) for estimating landslide motion. Raucoules (2018) combined sub-pixel correlation offset tracking techniques and differential SAR interferometry. Other studies for estimating the kinematics of landslides used SPOT-5 image pairs (Le Bivic et al. 2017) or Sentinel-2 images (Yang et al. 2020).

Satellite-based Interferometric Synthetic Aperture Radar (InSAR) has proved to be a valuable tool for detecting and monitoring subtle deformation of the ground surface at high spatial resolution and for velocity estimation, particularly of slow-moving landslides (Colesanti & Wasowski 2006; Cascini et al. 2010; Lauknes et al. 2010; Wasowski & Bovenga 2014; Casagli et al. 2016). Differential SAR Interferometry (DInSAR) and Multi-Temporal InSAR (MTI) techniques, such as Persistent Scatterer Interferometry (PSI) (Ferretti et al. 2001; Cigna et al. 2013; Crosetto et al. 2016) and Small Baseline Subset (SBAS) (Berardino et al. 2002; Lanari et al. 2004), allow measuring subtle surface changes based on images acquired at different times. Solari et al. (2020) developed a method based on satellite interferometric products to automatically extract the fastest moving areas.

6.1.2 Gullies

While the majority of remote sensing-based studies focus on the assessment of different types of landslides, several studies use aerial and satellite data for mapping erosion features, such as gullies. D'Oleire-Oltmanns et al. (2012) used UAV data for quantifying gully and badland erosion in 2D and 3D, other studies used satellite imagery to identify and map gully erosion with OBIA (Shruthi et al. 2011; D'Oleire-Oltmanns et al. 2014).

Furthermore, LiDAR (Johansen et al. 2012), UAV data (Liu et al. 2016), and DEM data (Vallejo Orti et al. 2019) are used for gully detection. Vrieling et al. (2007) used a pixel-based method, Wang et al (2016) mapped gullies by visual image interpretation. A CNN approach for automatic gully detection was developed by Gafurov and Yermolayev (2020); Shahabi et al. (2019) integrated OBIA with machine learning.

6.1.3 Streambank erosion

Several studies addressed stream bank erosion assessment with remote sensing. Payne et al. (2018) compared results from manual and automated bank erosion mapping based on time-series of high-resolution imagery and concluded that both approaches lead to comparable results. Hemmelder et al. (2018) used UAV derived DEMs to quantitatively assess bank erosion. Thomas et al. (2020) manually identified bank erosion and deposition based on multi-temporal Landsat images.

6.1.4 Surface soil erosion

Satellite-based spectral vegetation indices are mainly used to estimate soil erosion processes. Soil erosion within forests was identified by Zhang et al. (2014) and Xu et al. (2019) using different factors relate to the vegetation health and presence. Seutloali et al. (2017) assessed soil erosion with time series of Landsat data in combination with factors derived from the ASTER DEM such as slope stream erosivity and topographic wetness index. Sepuru and Dube (2018) conclude that sensors such as Sentinel-2 and Landsat 8 series, with improved spatial, spectral radiometric and temporal resolutions provide suitable sources for monitoring soil erosion.

6.1.5 Recommendations for New Zealand

Based on this brief review of remote sensing-based methods for erosion assessment, the following recommendations for New Zealand can be made.

To date, the majority of New Zealand landslide and erosion assessment studies have used manual mapping (e.g. Gao & Maro 2010; Dellow et al. 2017; Rosser et al. 2017; Betts et al. 2017; Basher et al. 2018; Massey et al. 2020) or a pixel-based classification approach (Dymond et al. 2007). Only a few studies have used semi-automated methods such as OBIA (e.g. Hölbling et al. 2016b; Spiekermann & Hölbling 2019; Hölbling et al. 2019). Hölbling et al. (2016a) identified spatio-temporal landslide hotspots on the North Island by analyzing historical and recent aerial photography.

Considering the advantages of semi-automated approaches compared to manual mapping, it is recommended that future work consider OBIA as a potential tool for mapping erosion features (particularly (shallow) landslides, but also gullies, etc.) and identifying erosion patterns, especially when larger areas are investigated or when time series of imagery are analyzed. Hölbling et al. (2016a) suggest the use of a hybrid approach that combines both semi-automated feature mapping and manual interpretation to improve the whole mapping process while reducing the time and effort needed for generating landslide inventories. For example, the initial delineation of areas of bare ground (as a result of erosion) could be automated, followed by a manual refinement by an experienced interpreter.

Also, machine learning and deep-learning approaches are not yet sufficiently explored for mapping erosion features in New Zealand. Considering the existing, manually created landslide inventories, sufficient training data for testing and validating such approaches should be available to implement these techniques and assess their performance.

Furthermore, studies that use SAR data for assessing slow-moving landslides/earthflows are lacking in New Zealand. Only a few studies have applied DInSAR/MTI methods for New Zealand erosion studies to date. An example is a study by Haghshenas Haghighi and Motagh (2016) who analyzed the slow displacement of Taihape landslide in the North Island with the SBAS technique using Envisat and TerraSAR-X data. InSAR techniques, while the analysis can be complex and results are influenced by several factors (e.g. topography, vegetation, sensor characteristics), the method could be suitable for monitoring slope movement and surface deformation over large scales. Information about movement rates derived from InSAR could also be coupled with feature delineation from optical data, for example, to assess earthflows. In doing this, information about moving rates and deformation measurements could be attached to spatially corresponding classified image objects. Such a combined interpretation of different remote sensing data (optical, SAR, DEM) offers possibilities for improved mapping of erosion features (Fig. 4).

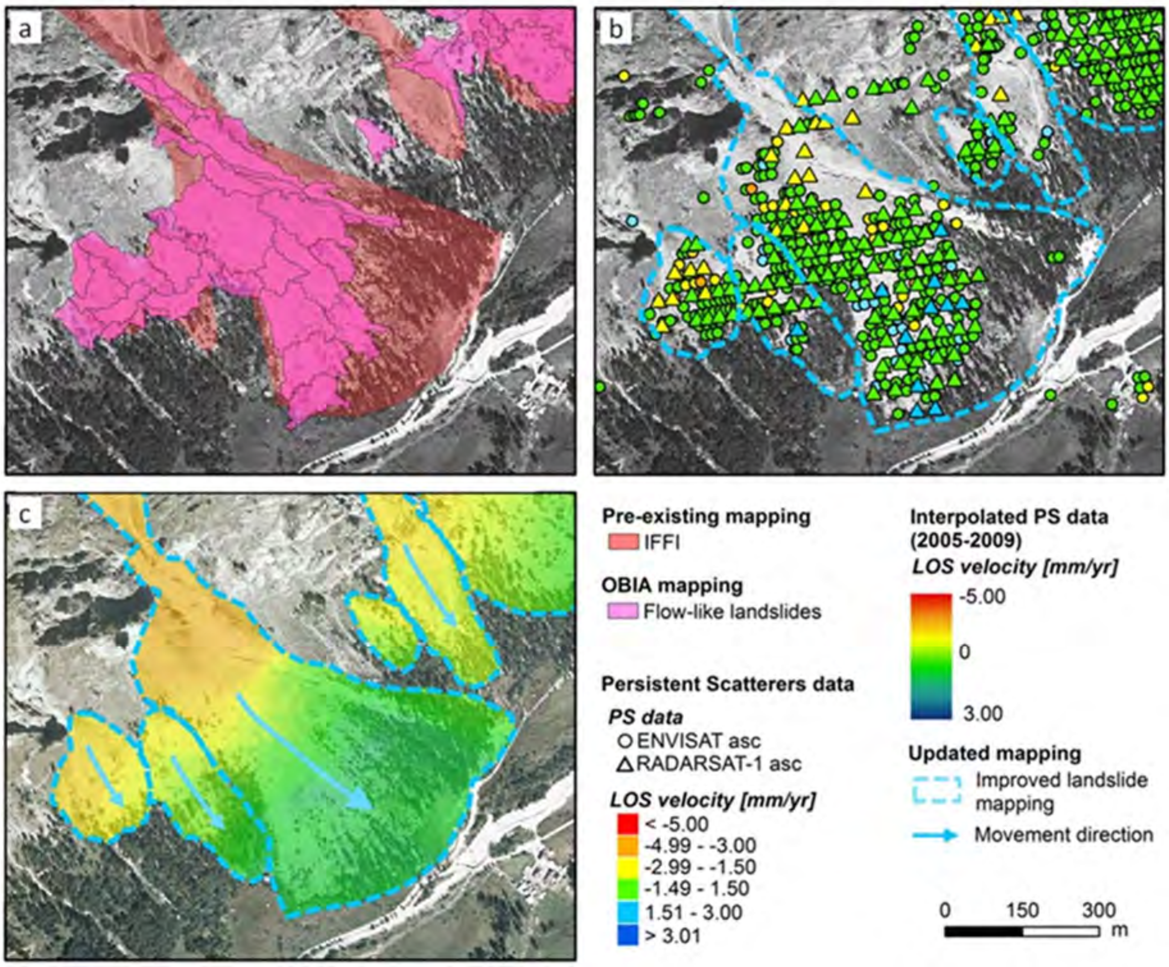


Figure 4. Combined interpretation of OBIA boundaries and SAR measures for refining the IFFI (Inventario dei Fenomeni Franosi) landslide inventory in Italy. The figure shows the pre-existing IFFI inventory and the OBIA mapping (a), the updated landslide boundaries and Persistent Scatterer Interferometry (PSI) results (b), and the interpolated Line of Sight (LOS) velocity of RADARSAT-1 persistent scatterers (PS) in 2005–2009 (c). Negative velocities for the identified PS show LOS movements away from the sensor, while positive values depict movements towards the sensor (from Hölbling et al. 2012).

While remote sensing per se is not an erosion control practice or mitigation measure, it can be used for example to identify spatio-temporal erosion patterns and hotspots. In addition, remote sensing results can serve as input for susceptibility and hazard modelling and assessing the effects of ESC practices. Semi-automated methods can reduce the subjectivity of mapping workflows, whereby particularly large-scale mapping tasks would probably benefit from a degree of automation (Hölbling et al. 2015). Guzzetti et al. (2012) argue that new remote sensing technologies will help improve the quality of landslide maps, with positive effects on all derivative products and analyses.

The increasing amount of remote sensing data offers significant opportunities for the assessment of erosion processes, but several limitations need to be considered. First, the spatial resolution may not be sufficient to detect very small erosion features or features that are not significant enough to be visible on the imagery used. Second, appropriate data, especially VHR optical imagery, might not be directly available after triggering events (e.g. due to cloud cover), and thus, not all features might be recognizable (e.g. due to already implemented restoration measures). Third, shadows can be a problem, especially in mountainous terrain. Ideally, different assessment methods, including remote sensing, should be used together to define and quantify erosion processes.

6.2 Planning

An Erosion Prevention and Sediment Control Plan (EPSCP) is considered the first step in ESC Management aiming to minimize the extent of disturbance by controlling the amount of soil that is being lost by various processes and by stabilizing exposed soil (USGS, Erosion Prevention and Sediment Control Plan Checklist, https://dec.vermont.gov/sites/dec/files/wsm/wetlands/docs/wl_vtepsc.pdf). Planning is more established in urban areas in the United States.

In their review, Fullen et al. (2006) give an overview of the erosion control instruments in Europe and other non-European countries. Although most countries in Europe do not have specific planning instruments, Belgium is one of the few exceptions. Here we provide, as an example from Europe, some information on Erosion Prevention and Sediment Control Planning as applied in Flanders (Belgium). Communities (towns) regularly affected by muddy floods (generated by various water erosion processes) and wanting to solve this problem are expected to request the Department Environment of the Flemish Government for support. This typically happens when inhabitants suffering regularly from the off-site effects of soil erosion put pressure on the local authorities to solve their problem. The Department Environment of the Flemish Government then provides expertise (by experienced erosion coordinators) as well as financial support (subsidies) to help them with the planning of erosion prevention and sediment control. The subsidies given cover a large fraction of the total costs (i.e. salary of an erosion coordinator, consumables and erosion control works). The remainder must be paid by the local (village) authorities (community). This planning typically follows the actions outlined below.

6.2.1 Assessment of the erosion problem.

A local erosion coordinator firstly makes an inventory of the erosion hotspots in the region, the various water erosion processes (sheet, rill, ephemeral and bank gullying, shallow landsliding on earth banks), their on-site and off-site impacts, and related damage costs. For this task, the coordinator relies on an erosion map with predicted mean annual soil loss rates by sheet and rill erosion (RUSLE-based) for every farmers' plot, information provided by technical services, civil protection, and all stakeholders involved. The end product of this task is an erosion hotspot map. This map is regularly updated to monitor the impact of soil conservation measures on soil loss reductions (Swerts et al. 2019, 2020).

6.2.2 Planning of erosion control measures.

In consultation with all stakeholders, an erosion control plan is then established that mainly focuses on the erosion hotspots. Such plans indicate where in the landscape measures should be taken and obviously also what type of measures. These measures range from biological control measures (e.g. grass buffer strips at the border of field parcels and grassed waterways in concentrated flow zones to trap sediments so that the sediments do not end up in the drainage network or on roads), to soil conservation measures (e.g. set aside cropland parcels suffering annually from excessive erosion, by growing grass on these plots, or subsidizing conservation tillage practices such as reduced tillage or no tillage) or installing flood control structures in the most affected catchments (such as permeable earth dams or small flood retention basins). All measures taken are aimed at reducing sediment production and sediment connectivity in the affected landscapes.

6.2.3 Prevention of excessive soil erosion.

This step mainly focusses on cropland plots that suffer annually from high erosion rates (as predicted by the RUSLE). Application of erosion-reducing measures by the farmers is encouraged and partly subsidized by the Flemish government, e.g. growing cover crops, mulching, increasing soil organic matter content, conservation tillage practices, installing grass buffer strips at the border of parcels or grassed waterways in concentrated flow zones in the landscape to reduce the probability of ephemeral gully development as well as check dams or geomembranes to control bank gully development on earth banks (e.g. sunken lane banks). For this to happen, the erosion coordinators discuss all options with local stakeholders and attempt to convince them to take appropriate action. This is facilitated by the fact that subsidies are given for most of the implemented erosion control measures.

6.2.4 Implementation of erosion control measures.

The follow-up of the implementation of all erosion control measures is done by the erosion coordinator in collaboration with all stakeholders (farmers, technical services, inhabitants of the towns regularly affected by muddy floods).

6.2.5 Monitoring and evaluation of erosion control measures.

The erosion coordinator also monitors and evaluates the effectiveness of the implemented erosion control measures and informs stakeholders if adjustments need to be made. At the same time, the Flemish Government monitors the impacts of the erosion control measures taken on the reduction of the sediment load in the rivers draining erosion hotspot areas, using the WATEM-SEDEM model (see, e.g. Verstraeten et al. 2002). Initially, this model was mainly used to map plots (parcels) and hillslope sections that suffer annually from significant soil losses by sheet and rill erosion and that therefore need erosion control via the implementation of soil and water conservation measures. Regular updates of these erosion maps allows assessment of the impacts of the soil conservation measures taken (Swerts et al. 2019, 2020).

More recently, this model has been adapted to predict catchment sediment yield (SY) and predicted SY has been compared with measured SY at 26 catchment outlets, spread over the erosion-sensitive regions of Flanders (Deproost et al. 2019). The recalibrated model is now used to create maps that visualise soil erosion, sediment connectivity, sediment deposition on the land and sediment delivery to rivers. The model outcomes can be used to analyse the impact of land use choices, agricultural practices and erosion control measures. In this way, the effects of policies can be evaluated, priority areas for areaoriented actions can be determined and prognoses can be made of the effectiveness of future actions (Deproost et al. 2019).

Other European examples

In Switzerland it is not common to perform specific planning of erosion control measures. 'Soil has been protected by legislation in Switzerland only since 1983, when the Environment Protection Act (EPA) was passed. The federal government strives to improve soil protection on various levels. However, there has been limited success to date because at the cantonal and communal levels financial and human resources are still very scarce'. Together with the construction, agriculture and forestry sectors, the federal government and cantons have developed a series of instruments and taken precautionary measures. These include, for example, the training of building consultants, who advise construction companies on large-scale projects. The obligation to prevent erosion is delegated to the farmers. By means of appropriate cultivation practices, in particular by means of erosion-resistant cultivation techniques, crop rotations and field design, they ensure that erosion does not endanger soil fertility in the long term. (www.bafu.admin.ch).

In France, erosion management is a stipulation of the French Environment Act (Code de l'environnement). Different public institutions can exert this authority for erosion control on slopes, agricultural lands or even ski resorts. Moreover, works are regulated by the IOTA (Installations, Ouvrages, Travaux et Aménagements) procedure from the French Water Law (Loi sur l'eau). Projects affected by this law, such as artificial construction on riverbanks, must be authorized by the water police. Projects carried out illegally must be rehabilitated. Some activities that may alter the morphology or hydrology of the environment fall under the regulation of ICPE (Installations Classées pour la Protection de l'Environnement), and require national (Ministry of Ecology) or regional authorization, depending on the scale of the project, to be carried out (https://www.eaufrance.fr). As in Switzerland, there is no systematic implementation of planning in the ESC strategies, except when private companies (experts) propose this kind of implementation in public projects, whatever their spatial scale (national, regional, communal, or farm).

7 Prevention measures

Prevention measures aim to maintain the equilibrium of sediment production and transport in an ecosystem. The implementation of erosion prevention strategies ultimately relies on the final land-user and local authorities. Implementation of sustainable soil management practices at farm scale remains a challenge due to lack of awareness and information on the best practices, and the benefits of their use. Participants unanimously recognised a clear need of strong action to raise awareness of the economic, production, and environmental costs of soil erosion in the general public (FAO 2019).

Next to the numerous prevention measures in agriculture, such as those listed in several governmental documents (e.g. BAFU 2010), in alpine countries the management of forests has a centuries long tradition in preventing several erosion processes, in particular related to the mitigation of risk due to natural hazards and forest productivity. As an example, we report below an overview of protection forest management in Switzerland.

7.1 Protection forest management

7.1.1 Description and assessment of effectiveness

The management of protection forest in most of the alpine countries is based on the principle of a sustainable forest utilization that maximizes the protection function as well as the resistance and resilience of forest ecosystems. The protective function is maximized by mixed tree species composition, heterogeneous vertical structure formed by trees of different ages, maximum possible soil cover in time and with sufficient natural regeneration. To create/maintain such conditions human intervention in the form of forest operations and harvest are necessary (see Fig. 5). To fulfil these requirements, the implementation of protection forest management is based on two fundamental tools:

1 identification of spatial distribution of protection forest (in Switzerland called *SilvaProtect-CH*), and

2 definition of guidelines for the planning of silvicultural interventions (in Switzerland called NaiS – Nachhaltigkeit in Schutzwald).

Figure 5. Monoculture-unstable vs mixed-stable forests. The latter increasing resistance and resilience of forest ecosystems. (Photos: M Schwarz)

Financial subvention payments (from a profit company to a loss company) are an important political tool for the application of protection forest management strategies. Communication and public awareness of the values of the forests protection ecosystem services are important for the acceptance of these public subventions. Risk-based analysis of the economic value of protection forest are used to quantify the cost-benefit analysis of investment in protection forest management (Schwarz et al. 2019a).

The guidelines for forest protection management consist of two types of indications, defining:

1 the ecological spectrum of the stand (/station)

2 the stand characteristics to mitigate a specific natural hazard process.

In Switzerland, these guidelines are in continuous development and updating. This work is supported from specific working groups such as GWG (Gebirgswaldpflege Gruppe, directly coordinated by the ministry), the Fachstelle Gebirgswald, and other associations (such as EcorisQ, FAN- Fachleute für Naturgefahren).

Depending on the process and the ecological characteristics of the station, the possibility of mitigating process frequency and magnitude through silvicultural measures may change considerably (Moos et al. 2017). For instance, protection again rockfall with rock dimensions larger than 1 m^3 is considerably lower than for blocks with volumes lower than 1 m^3. In the case of shallow landslides, the selection of species and forest structure may completely change the effect of protection (Schwarz et al. 2019b).

Comments on the possible implementation in NZ

The basic concept of protection forest management could be adapted in NZ in both production forest (e.g. Radiata pine plantation) as well as in new, defined protection forest areas. In production forests, the protective function could be improved by considering two levels of measures: 1. Adapting the tree stems per hectare for afforestation after clearcutting, depending on the hazard probability of erosive processes (see Giadrossich et al. 2020); 2. planning the spatial and temporal location of clear cutting in the risks related to erosive processes (e.g. shallow landslides, large wood entrainment and transport).

Coupled with the protection against natural hazards, is the issue of managing the forest for sustainable soil management, which should be defined as a maximum tolerable soil erosion rate depending on the lithological and morphological characteristics of forest stands. Based on the tolerable limit, forest operations should be planned to minimize the loss of productive soil.

8 Recovery and mitigation techniques

This section considers the different erosion processes.

8.1 Surface ’sheet and rill’ erosion

In New Zealand, surface erosion by sheet and rill flow is controlled with a range of practices grouped in mainly 3 types:

- Runoff control
- Control of sediment generation
- Sediment control.

In many cases, the erosion control combines several approaches, such as mulching or strip cropping.

Internationally recognized effective erosion control techniques that are already applied in New Zealand are: Conservation tillage (no tillage, reduced tillage, wheel track remediation, mulches, rotational and strip cropping, surface roughening, contour drains and soil binders (Phillips et al. 2020).

In Europe and the Mediterranean, various measures to prevent or control sheet and rill erosion have been and are still being applied. These range from changing land use type (e.g. from cropland to pasture) to the application of specific soil and water conservation (SWC) techniques, for example:

1 crop and vegetation management (i.e. cover crops, mulching, grass buffer strips, strip cropping and exclosure),

2 soil management (i.e. no-tillage, reduced tillage, contour tillage, deep tillage, drainage and soil amendment) and

3 mechanical methods (i.e. terraces, contour bunds and geotextiles).

The effectiveness of all these measures has been tested at 103 plot-measuring stations throughout Europe and the Mediterranean. A meta-data analysis of these plot measurements has assessed the effectiveness of these measures on reducing runoff and soil loss by sheet and rill erosion (Maetens et al. 2012a,b).

Figure 6 indicates the effects of various land use types on runoff coefficient (RC) and area-specific soil loss (SL), allowing a first estimate of the impact of a land use change on runoff production and soil loss.

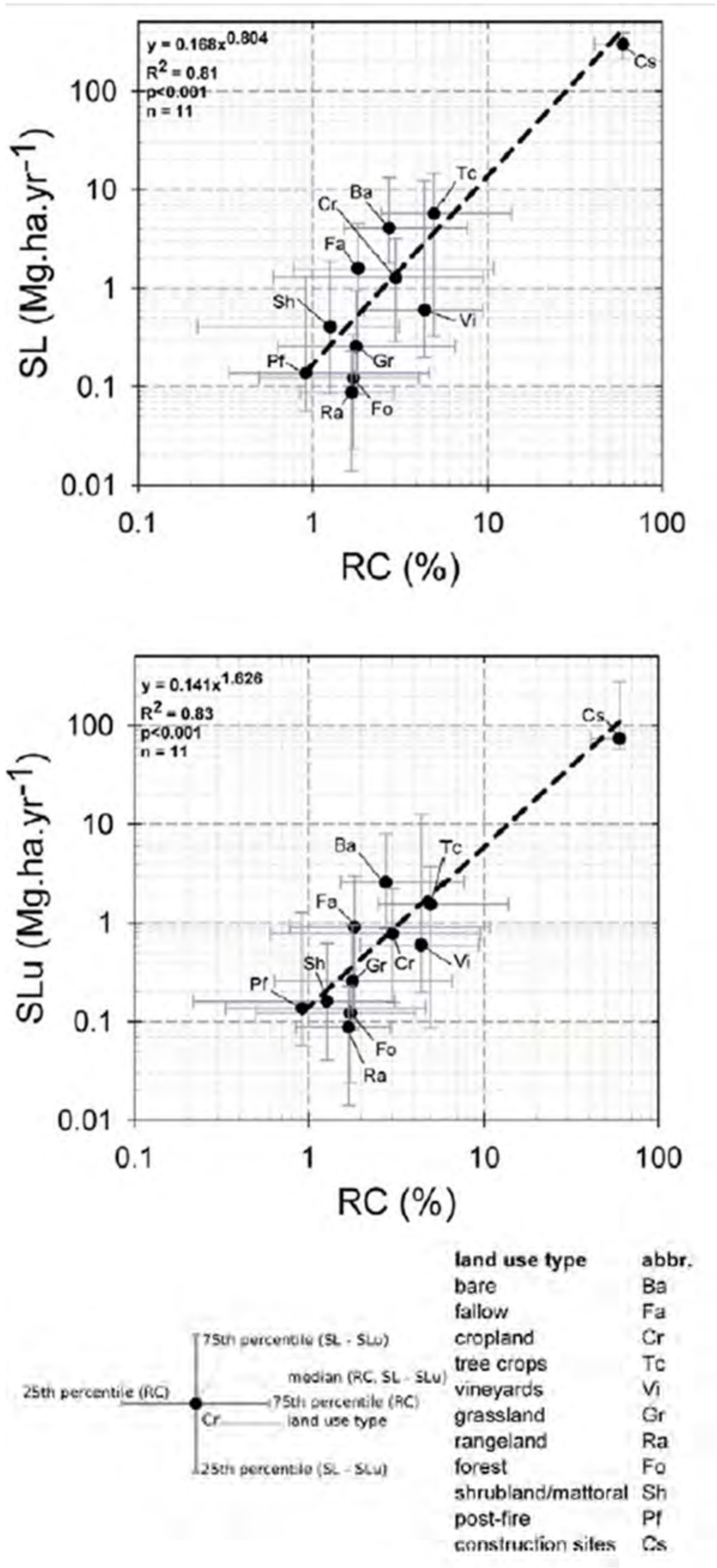


Figure 6. Impact of land use on plot runoff and soil loss by sheet and rill erosion for all runoff and erosion plots in Europe and the Mediterranean. Median annual runoff coefficient (RC), median annual soil loss (SL) and median annual unit plot soil loss (SLu) by land use with indication of the 25th and 75th percentile for RC, SL and SLu (Maetens et al. 2012). Unit plot soil loss (SLu) represents soil loss from a standard runoff plot (length = 22.1 m on a slope of 9%; Maetens et al. 2012a).

Figure 7 presents the effect of the application of specific soil and water conservation techniques (SWCT) on runoff and on area-specific soil loss. Note that most SWCT have a larger effect on reducing plot soil loss than on reducing plot runoff. These data make it possible to select the most effective SWCT.

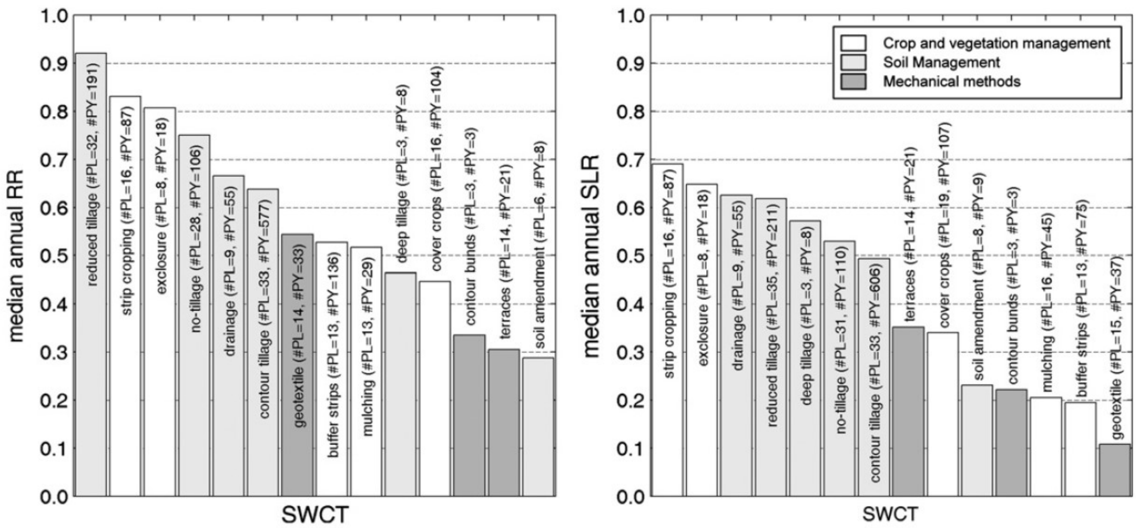


Figure 7. Median annual runoff ratios (RR)and soil loss ratios (SLR) for different soil and water conservation techniques (SWCT) based on the paired plot database for Europe and the Mediterranean. Runoff ratio is the ratio of runoff depth from a plot with SWCT application and runoff depth from a reference plot with the same characteristics but without SWCT application. Soil loss ratio (SLR) is the ratio of SL from a plot with SWCT application and SL from a reference plot with the same characteristics but without SWCT application RR = 1 or SLR = 1 for plots with conventional practices (tillage, cropping) and without any runoff or erosion control practice applied. SWCTs are ranked from left to right in order of increasing effectiveness. #PL: number of plots, #PY: number of plot-years (Maetens et al. 2012b).

The following sections briefly summarize additional globally known management practices that might be useful for New Zealand.

8.1.1 Use of Ectomycorrhiza inoculum

Description and assessment of effectiveness

Natural or industrially produced inoculum of Ectomycorrhiza fungi are added to seeding mixtures to increase the building of water-stable soil aggregates and thus reduce surface erosion. Improvements of soil structure also improve the control of runoff. Figure 8 shows the results of measured percentage of water-stable soil aggregates after the application of Ectomycorrhiza fungi on eroded slopes. Laboratory experiments show that with inoculum soil erosion generation can be reduced by 20% compared with treatments with plants only (Graf 1998).

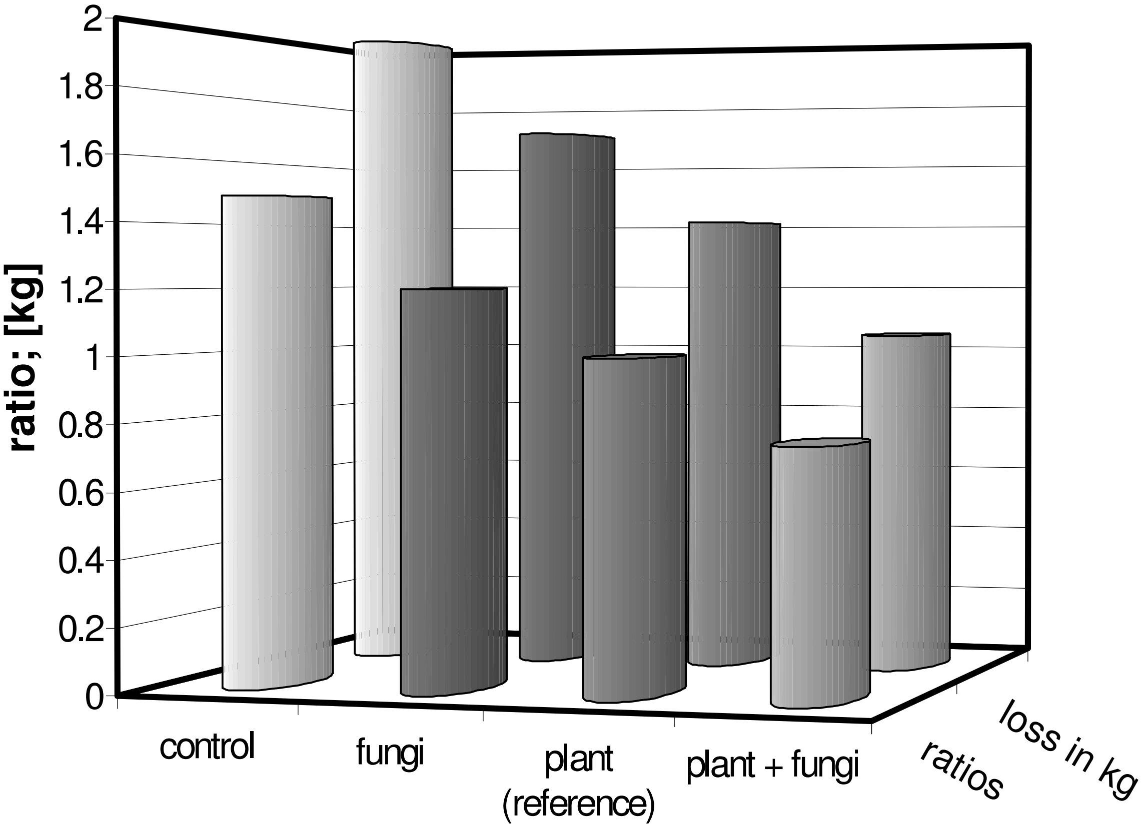


Figure 8. Reduction of erosion rate compared with a reference sample considering combined effects of plants (Salix Sp.) and fungi (Mychorrhiza) (Graf 1998)

The measurement of the percentage of water stable aggregates in a soil sample is the most used widely used approach to assess the effectiveness of the mycorrhiza effect. Field measurement of eroded materials is expensive, although remote sensing techniques can be used.

Comments on the possible implementation in NZ

Mixing natural soil with inoculum during the preparation of new ESC measures is the most economically affordable way to use this technique. In areas particularly exposed to surface erosion, the inoculum of Ectomycorrhiza can considerably reduce surface erosion (in the short term), improve the growth of vegetation, and protect vegetation from pathogens. Adapting inoculum to local conditions and production costs could be limiting factors for the application of this technique in more general practice.

8.1.2 'Rough and Loose' in earthworks

Description and assessment of effectiveness

This less visually appealing technique reduces runoff velocity, runoff amount, and creates ideal conditions for the establishment of vegetation, thus increasing the stability of soil. Figure 9 shows an application of this technique along an artificial dam.

Figure 9. Example of application of the 'rough and loose' technique (source: D. Polster).

Comments on the possible implementation in NZ

The application of this technique is limited to small areas, especially along human-made structures. However, an adapted version of this technique could be tested in eroded areas of New Zealand's hill country landscapes to reduce surface erosion on regressive erosion areas (such as those triggered by shallow landslides or intensive pasture).

8.1.3 Plantation along wheel tracks

Description and assessment of effectiveness

During forest operations, the soil along wheel tracks may undergo strong compaction. The compacted soil has reduced permeability, which leads to an increase in overland flow and erosion. Moreover, the limited diffusion of gases can lead to anaerobic conditions that reduces soil productivity. These effects have a long-term impact on soil properties, and short rotation-intense forest utilization may considerably compromise the productivity of forest stands. Planting of trees/poles along wheel tracks can improve the recovery of soil properties (see Fig. 10). Due to the difficult growing conditions, species such as alder and poplar are more suited for these applications.

Researchers and practitioners disagree on the time span that the subsoil needs to regenerate itself. Estimates range from many years to several decades, depending on local conditions and the depth of compaction. Mayer et al. (2011) show that at depths of 20–40 cm, the pore volume of the soil increased 5–15% with planting of black alder (*Alnus glutinosa*) within 6 years, compared with only about 3.6% without planting. Irrigation experiments showed that the planting also normalized the water conductivity in the wheel tracks. This means less overland flow and a better oxygen supply for the soil, and thus better conditions for a healthy soil flora and fauna.

Figure 10. Plantation of black alder along wheel tracks (Mayer et al. 2011).

Comments on the possible implementation in NZ

This approach could be particularly suitable for repairing damage in plantations for wood production in New Zealand. An additional improvement would be the identification of potential tree species that can maximize the recovery, considering different conditions of soil and susceptibility to erosion.

8.2 Shallow Mass movements

8.2.1 Afforestation

Description and assessment of effectiveness

Afforestation is globally acknowledged as being effective against erosion processes (e.g. see Phillips et al. 2013). For shallow mass movements, it is known that vegetation influences slope stability mainly through 2 effects:

1 Mechanical effects of root reinforcement within the process zone (see definition in chapter 1.1.), and

2 Hydrological effects mainly in the contributing zone.

Although, reliable quantitative data on the effectiveness of afforestation are limited in the literature, qualitative studies and documentation demonstrate their positive long-term effect. Based on experiences in the European Alps, some aspects should be considered and improved on in future afforestation projects. The choice of tree species for afforestation was initially based on ecological and economic criteria, often resulting in mono-species plantations of spruce. The downsides of this decision only appeared decades later, and consists of:

- accelerated acidification of the soil that led to reductions in soil biological activity, that again lead to reduced properties of forest soils (e.g. soil water storage capacity, shear strength) (Schwarz 2017).
- reduced resistance and resilience of forest ecosystems, from two perspectives – ecological (against pathogens and invasive neophytes) and mechanical (against disturbances such as storms and snow).

While the first of these downsides is still being discussed by many experts and generally lacks quantitative data for the evaluation of its' impact on hillslope processes, the reduced resistance and resilience of monocultural plantations is a well-documented phenomenon that leads to adaptation in forest protection management.

After an intense afforestation period (between 1850 and 1950) triggered by extreme hazards events, at the end of the 20th century forest stands became progressively unstable. Guidelines and financial subsidies for the introduction of sustainable protection forest management practices were implemented. As mentioned in Chapter 6.1, forest management practices aimed to mimic natural disturbances such as from storms and fires in order to improve the resistance and resilience of forest ecosystems. Currently, natural hazard hotspots (also considering runoff and erosion processes) are mapped at the national level in Switzerland, and guidelines are mandatory for forest operations in such areas. Figure 11 shows the temporal development of afforestation with spruce in the Swiss pre-Alps. In 2010 damage from bark beetle is evident. This will contribute to an increase of forest structure heterogeneity and will in the long-term contribute to an improved resistance and resilience of the forest ecosystems. Such processes should be anticipated by protection forest management interventions.

Figure 11. Temporal series of the development of a spruce afforestation in the Swiss pre-Alps (modified by M. Schwarz).

Afforestation may be needed to recover forest functions after large disturbances such as extreme forest fires or avalanches. The experiences from the Alps show that investments in afforestation can be optimized considering the ecology of stands, potential of natural renovation and effects of wild damages (browsing). For instance, Flepp et al. (2020) showed that afforestation after fire in mountain zones may accelerate the recovery of forest functions for about 20–30 years, whereas in the subalpine zone there is almost no difference between afforested areas and naturally regenerated areas (Fig. 12).

Figure 12. Forest fire area in Müstair 1986, after the standing trees were felled (left), and in 2018, 32 years later (right) (Flepp et al. 2020).

Comments on the possible implementation in NZ

It is expected that afforestation for ESC will gain importance as both population and awareness of risks associated with erosion processes increase. In this case, the diversification of planted tree species should be considered an important aspect in the planning. The long-term effectiveness of this type of measure will depend on the sustainable management of the forests, anticipating the effects of natural disturbances.

8.2.2 Spaced-planted trees

Description and assessment of effectiveness

The use of spaced planted trees (or soil conservation trees in New Zealand) is a well-known measure in New Zealand where it is widely used on hill country to reduce the incidence of rain-triggered shallow landslides. Improving this technique focuses on the optimization of the spatio-temporal effectiveness of slope stabilization and on grass production.

The spatial distribution of trees and the optimization of the mechanical effects of the tree's root network can be achieved using slope stability models that identify the most probable unstable areas and calculate the needed root reinforcement to reduce the probability of shallow landslides. Models such as SOSlope (Cohen & Schwarz 2017; Schwarz 2019) calculate the distribution of tensile, compression, and shear stresses on a slope and quantify the potential contribution of roots to stabilize that slope. Figure 13 shows the application of SOSlope for the identification of unstable areas (red colours) and the quantification of activated root reinforcement (green areas) along railways in Switzerland. This type of information can be used in the planning of spaced planted trees and for monitoring. The evaluation of the effectiveness of such measures depends then on the temporal development of the stand and the root reinforcement that this can provide in the process area. The impact of the vegetation's hydrological effect should be considered more at the level of a contributing area.

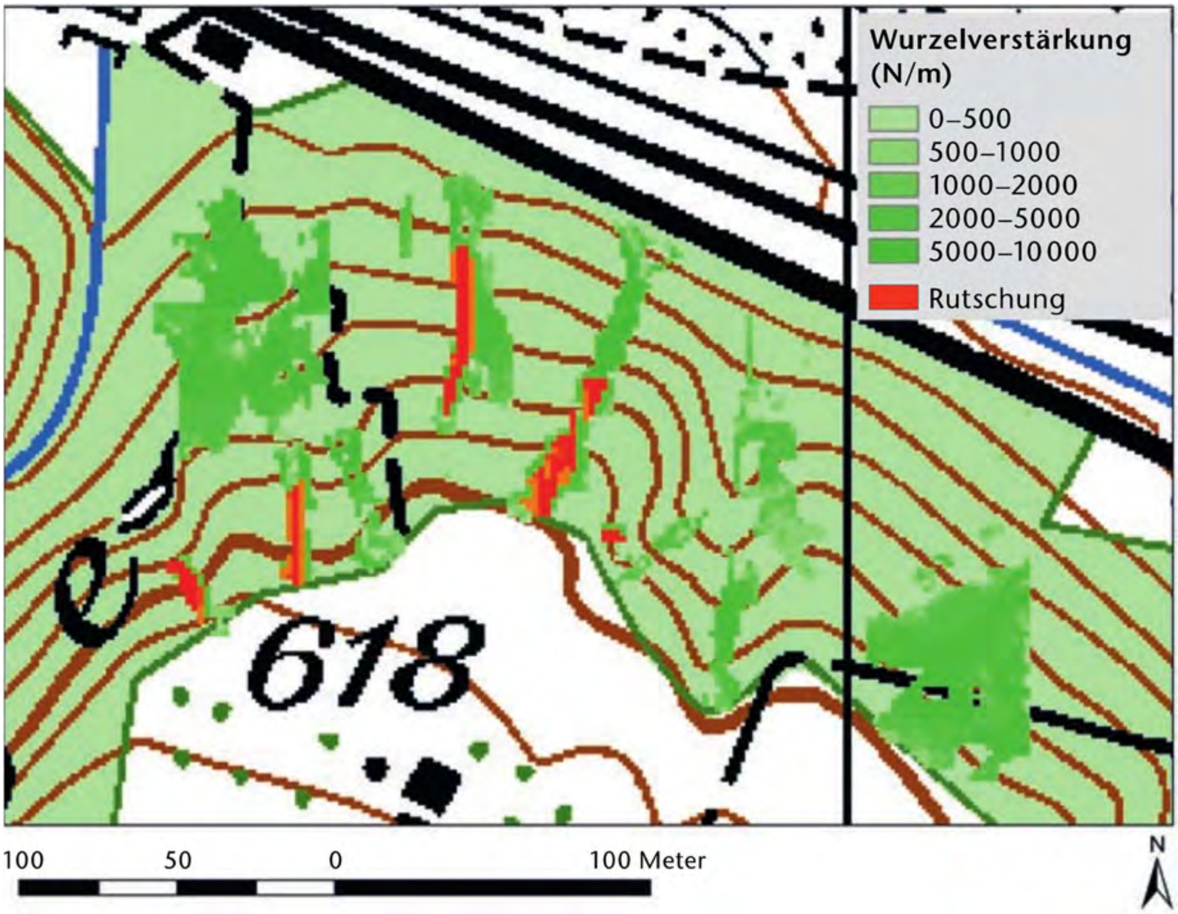


Figure 13. SOSlope calculated landslide areas (red areas) and activated [lateral] root reinforcement (green area) for a 100-year precipitation scenario (Schwarz 2019).

The temporal development of trees in a bioengineering measure such as in a spaced planted tree treatment is important for evaluating its' effectiveness and eventually for planning maintenance interventions such as thinning. Figure 14 shows the temporal variation of root reinforcement depending on the initial spacing of the planted trees (in this example grey alder in the Swiss Alps). Preliminary studies of such approaches for poplar (the most commonly used species in New Zealand space-planted treatments) are presented in Schwarz et al. (2016). Their results show that in order to reach effective values of root reinforcement, a density of between 40 and 100 stems per hectare (respectively corresponding to about 15 and 10 m distance between tree stems) are needed for Veronese poplar with DBH between 0.1 and 0.3 m). How effective the space-planted tree treatment is in the long term depends on the intensity of rainfall triggering events and its return period. If the return period of the triggering rainfall event is much higher than the time needed for the plantation to reach significant development of root reinforcement at the stand scale (estimated in about 20–40 years usually, e.g. Fig. 14), then the effectiveness of the measure is significantly high. On the other hand, investments in measures that can be destroyed due to frequent erosion processes are expected to be less effective.

It is a common experience that where a single tree species is grown, there may be a considerable shift of tree species composition within the first decades after establishment. In some documented cases (e.g. Schwarz 2017; Fig. 15) a mixed plantation of tree species (alder, willows, and maple) developed in a secondary succession (within 25 years) on an almost monospecific plantation (dominated by alder) where renovation is dominated by climax species such as spruce. In pastured areas this species composition is strongly regulated, resulting in a more constant species composition.

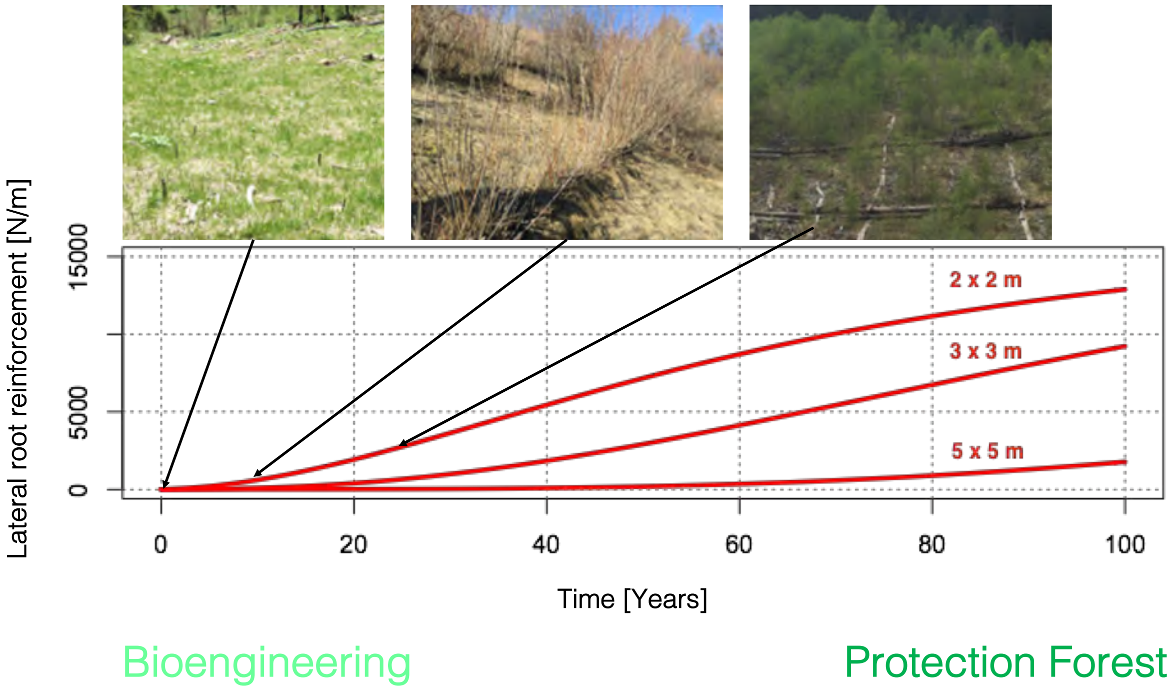


Figure 14. Temporal dynamic of root reinforcement in a bioengineering measure with grey alder (*Alnus incana*) (modified from Schwarz 2017).

Figure 15. Documented development of a bioengineering measure (edge layers, analogous to spaced-planted trees) in the Swiss alps, showing the transition from classical bioengineering setup in 1994 to a protection forest stand (modified from Schwarz 2017).

Comments on the possible implementation in NZ

Quantitative approaches for both planning and evaluating effectiveness of spaced-planted trees (e.g. Cohen & Schwarz 2017; Schwarz et al. 2019a) could improve how investments in such biological measures are optimised in New Zealand. The results of such analyses are the basis for cost-benefit calculations needed for regional-scale prioritization of interventions.

Furthermore, future analyses should be directed on how mature stands of spaced-planted trees should be managed to guarantee long-term stabilisation, analogous to protection forest management.

8.3 Gully erosion

Concerning prevention and control of gully erosion, a distinction needs to be made between:

- measures taken in the catchment draining towards the concentrated flow zone where a gully might develop or where there is already a gully developing, and
- measures taken in the concentrated flow zone (where a gully might develop) or in the gully channel itself.

Measures taken in the catchment draining towards the gully are those that significantly reduce runoff (and sediment) production (e.g. a land use change or the application of particular soil and water conservation techniques, see Figs 5 and 7 for their effectiveness).

For measures applied in the concentrated flow zones, where gullies might develop or where there are already gully channels, a distinction needs to be made between ephemeral gully erosion (on cropland) and permanent gullies (i.e. on land that is not tilled, e.g. grassland, rangeland, bushland, construction sites, etc.)

<u>Ephemeral gullies</u>: techniques that have been tested (to prevent or reduce ephemeral gully erosion) are those that increase the resistance of the (top) soil to hydraulic erosion in the concentrated flow zone (Poesen et al. 2003), i.e.:

- No tillage and reduced tillage (conservation tillage)
- Topsoil compaction
- Double drilling of crops in concentrated flow zones (to increase root cohesion and hydraulic roughness)
- Vegetation barriers (dead vegetation: e.g. straw bales; life vegetation: hedges of grasses and shrubs)
- Grass buffer strips (perpendicular to concentrated flow direction)
- Grassed waterways
- Minimal soil profile disturbance (by e.g. subsoiling) to maintain the erosion resistance of particular soil horizons.

Permanent gullies: measures that are most often taken in such gullies are:

- The installation of check dams: see various types of check dams: e.g. FAO field guide (2020): http://www.fao.org/3/ca8381en/CA8381EN.pdf
- Revegetation of the gully channel and banks with selected grass and shrub species that have optimal above- and below-ground properties (De Baets et al. 2009).

8.3.1 Erosion control

Description and assessment of effectiveness

From a practical point of view, the list of the structures usually used for gully erosion control appears in Table 2.

Table 2. List of the structures usually used for gully erosion control (adapted from Zeh 2007)

Type of structure (living/dead)	Name of structure	Use on the gully	
		in the concentrated flow zones	In the catchment
Dead structures	Flattening and shaping	X	X
	Terracing		X
	Open channel		X
	Rock channel		X
	Wooden sill	X	
Seeding	Seeding		X
	Seeding on geotextile		X
	Topsoil application		X
Planting	Plantation		X
Cutting	Single cuttings	X	X
	Palisade	X	
	Brosses, peignes vivants	X	
	Wattle fences	X	
	Fascines	X	
	Brush mats	X	X
	Brush layers	X	X
Mixed structures	Vegetated crib walls		X
	Slope grid		X
	Stones (vegetated rockfills)	X	X
	Vegetated gabions	X	X
	Vegetated geotextile		X

Information on techniques to prevent and control gullying is scattered and often incomplete, especially regarding failure rates and effectiveness (Frankl et al. under review). Vegetation barriers made of (dead) plant residues have the advantage of being immediately effective in protecting against erosion but have a short life expectancy compared to barriers made of living vegetation. Once incised, the further development of gullies may be controlled by diverting runoff away from headcuts, but this comes at the risk of relocating the problem. Additional measures such as headcut filling, reshaping, and armouring can also be applied. Multiple studies report on the use of check dams and/or vegetation to stabilize gully channels (Fig. 16). For example, Rao et al. (2018) recommend using bamboo-based structures for gully management, especially bamboo live check dam treatments (equivalent to vegetated rockfills), as they are hydrologically best-suited in this situation.

Reasons for failures of these techniques depend on the runoff and sediment characteristics and cross-sectional stability and micro-environment of the gully. In turn, these are controlled by external forcing factors that can be grouped into three main categories (i) geomorphology and topography, (ii) climate and (iii) the bio-physical environment.

Overall, vegetation establishment in gully channels and catchments plays a key role in gully prevention and control. Once stabilized, gullies may turn into rehabilitated sites of lush vegetation or cropland, making the return on investment to prevent and control gullies high (Frankl et al. under review).

Figure 16. Gully channel stabilization with wooden dams mixed with vegetation in New Caledonia (F. Rey 2018).

Comments on the possible implementation in NZ

We propose the following strategy for erosion control for gully systems (Table 3).

Table 3. Strategy for erosion control on gully systems

Type of gully	Situation on the gully	Structures	Inert materials	Vegetation materials	Function
Permanent gullies in the concentrated flow zones	Gully channel	Rock sill	Stones	-	To limit regressive erosion on slopes
		Wooden sill	Wood	-	
	Bottom of slopes	Fascines or wattle fences or palisades	Wooden stakes	Cuttings	To limit erosion in the bottom of slopes
	slopes	Slope grid	Wood	Plants or cuttings	To facilitate vegetation resprout and growth on slopes
		Fascines or wattle fences or palisades	Wooden stakes	cuttings	To avoid sheet and rill erosion by draining water
		Rock channel	Stones	-	
	In the catchment draining towards the gullies	Open channel	-	-	To avoid concentrated flows towards the gully channel
		Draining fascines or wattle fences or palisades	Wooden stakes	Draining fascines	
		Seeding and/or planting	-	Seeds and/ or plants	
Ephemeral gullies in the concentrated flow zones	Gully channel	Rock sill	Stones	-	To avoid concentrated flows towards the gully channel
		Brush layering	wood	cuttings	To trap sediment

8.3.2 Sediment control

Description and assessment of effectiveness

Gully erosion is also a major driver of elevated sediment yields across many areas of the globe, and considerable rehabilitation has occurred to reduce the amount of sediment eroded from gullies. In gully systems, this is a key research topic today (Castillo & Gómez 2016) with investigations examining the role of vegetation in ESC (Gallart et al. 2013). However, compared with other forms of erosion, there has been little systematic review of the effectiveness of gully rehabilitation on reducing sediment yields.

Retaining sediment within the catchments is possible with vegetation and it can be both efficient and sustainable (Phillips et al. 2013). The cover provided by vegetation can allow eroded slopes to recover, and also to act as a barrier to sediment. To install such vegetation obstacles in eroded catchments, bioengineering structures must be used. Although these structures are usually established on all the eroded slopes, they can also be installed only on gully floors, so that they aid in developing vegetation barriers able to trap sediment eroded upstream (Rey et al. 2019).

Bartley et al. (2020) reviewed the global literature to provide an understanding of the potential sediment yield reductions that can occur following the rehabilitation of gullied landscapes. The review focused on studies reporting a measured response on how gully and catchment sediment yield changed since treatment. A total of 37 studies were found that met this criterion. The studies were partitioned into three broad categories, including those focused on: (i) treating the catchment above the gully; (ii) installing treatments in the actual gully channel; and (iii) a combination of approaches, which include treating both the catchment and the gully channel.

All the studies demonstrated a reduction in sediment yield following gully rehabilitation, with reported values ranging between 12 and 94%. The timeframes associated with the reductions in sediment yield varied considerably (2–80 years).

Lira-Caballero et al. (2018) studied the efficiency of live barriers, corresponding to brush layers installed in gully floors, for plant cover development and erosion/sediment control in the Mixteca Region of Sierra Madre del Sur in Mexico. They found that live barriers favour the occupation of soil by native species from the tropical deciduous forest, with specific spatial distribution process of plants in the gullies cross section.

Research carried out in the French Southern Alps, in a mountainous Mediterranean climate, showed that (Rey 2018): (i) in a gully with a surface area less than 1 ha, a partial vegetation cover of 20% can be enough to stop the sediment yield at its exit, if this vegetation is located downstream of the gully; (ii) bioengineering works made of willow cuttings, namely brush layers and brush mats on fascines, can be used to install such vegetation barriers in eroded gully floors, except in southern exposure (Erktan & Rey, 2013); (iii) repeated and sustainable sediment trapping is effective with these barriers, when the slope of the gully floors is less than 40%; (iv) natural vegetation colonization is possible on bare gully floors when sediment is stabilized by bioengineering works and slight vegetation is present on the gully slopes (Burylo et al. 2014) (Fig. 17).

Figure 17. Bioengineering structures aiming at trapping sediment in France (F. Rey 2018).

These studies highlight the importance of the distribution of vegetation within catchments and on slopes for erosion and sedimentation control based on sediment trapping processes (Molina et al. 2009). Applying a variety of rehabilitation measures, which generally includes treating both the hillslope above the gully, and trapping sediment within the gully, appears to result in shorter (median) timescales for sediment yield reduction. Overall, the review by Bartley et al. (2020) indicates that gully rehabilitation strategies that combine both engineering and vegetation measures are often the most successful. Engineering measures such as check dams are important for stabilizing sites in the early phases to support the revegetation of gullies and adjacent hillslopes. However, vegetation is the key to the long-term success of gully rehabilitation (Bartley et al. 2020). This is because many engineering structures eventually fail, or have a limited life span as an active sediment trap (Stokes et al. 2014).

Comments on the possible implementation in NZ

For gullies needing rehabilitation in New Zealand, we suggest the following strategy for fine sediment retention using bioengineering:

- The gully with a surface area less than 1 ha is the maximum size of gullies where soil bioengineered re-vegetation is appropriate; rehabilitation actions should be carried out on gully floors only, to reach a minimum plant cover rate of 20% at the scale of the gully
- The bioengineering works must only be installed in favourable ecological conditions, e.g. not in northern exposure
- These works must be installed on the gully floors when slopes are less than 40% to provide efficient sediment trapping
- The choice of the appropriate bioengineered structure inside gullies is guided by the presence of vegetation on slopes. Therefore, if vegetation is present, brush layers on fascines are recommended: this intervention limits the operation to punctual installation of linear vegetation cover during the period of natural colonization of bare soils from surrounding vegetation. Otherwise, using brush layers and brush mats on fascines is recommended: this intervention, more expensive than the first one, is necessary for directly installing a vegetation mat without waiting for natural colonization by vegetation, especially when the surrounding vegetation is too far away from rehabilitated sites.

8.4 Hydraulic streambank erosion

The effect of vegetation in reducing bank erosion may be distinguished in two main groups of processes: hydraulic bank erosion and geotechnical bank erosion.

Hydraulic bank erosion is driven by the effect of flowing water (with or without sediment transport) at the interface between water and soil along streams. Geotechnical bank erosion is soil mass movement driven by gravity on stream banks. The effects of vegetation on those erosive processes are review in Gasser et al. (2019).

8.4.1 Conserving or restoring riparian vegetation: effect of root networks

Description and assessment of effectiveness

Several studies have measured the effects of root distribution on reducing hydraulic erosion (e.g. Pollen-Bankhead & Simon 2010; Zhu & Zang 2014). Figure 18 shows a densely rooted stream bank, where roots are dense enough to prevent severe bank erosion, even though they have been exposed by water erosion. Once exposed, these roots represent significant hydraulic roughness on the banks that will dissipate flow energy and hence reduce bank erosion. The effectiveness of roots to reduce hydraulic bank erosion may vary considerably depending on the characteristics of the stream and the properties of the stream bank/soils. Gasser et al. (2020) applied a physically based model to quantify conditions by which roots may reduce hydraulic bank erosion. The results show that the variable channel slope and channel width are the most important proxy variables to estimate the effectiveness of roots in reducing hydraulic bank erosion. Figure 19 shows that for small streams (<2 m width) roots mostly have a considerable stabilizing effect, while for larger streams effectiveness depends on the channel slope. For large rivers, the effect of roots is almost negligible. The effects of roots may be limited in situations where water table fluctuations prevent root growth in deep layers of the stream banks (Tron et al. 2015). Further, Gasser et al. (2020) calculated and discussed how the effect of roots on the hydraulic erosion processes depends on the intensity and duration of the flood event, showing that this decreases with increasing return period.

Figure 18. Example of conditions in which roots along a stream bank may contribute to reduce the magnitude of hydraulic erosion processes (source M. Schwarz).

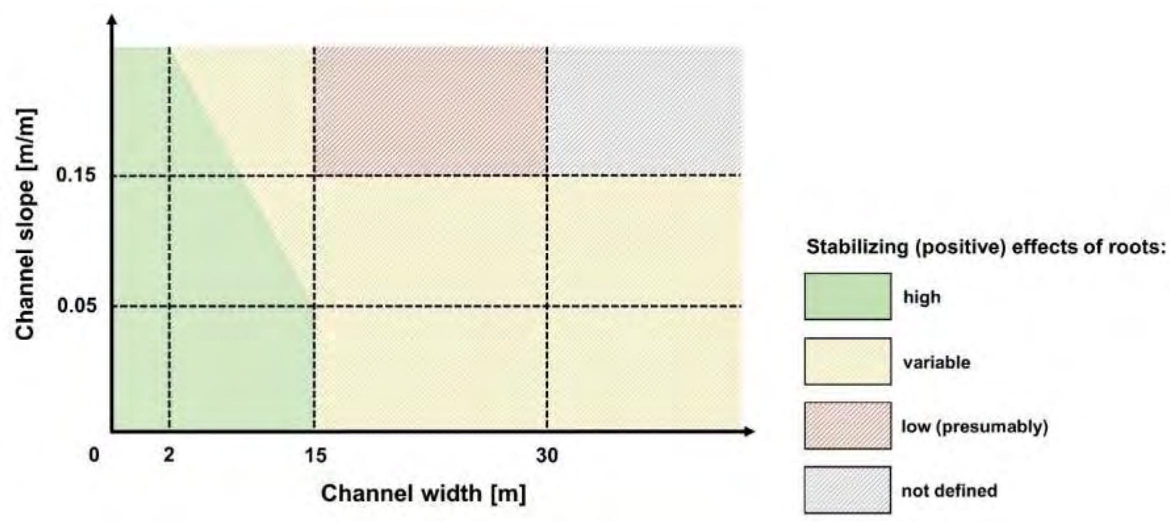


Figure 19. Schematic classification of conditions for the classification of the stabilizing effects of root, based on numerical calculation of Gasser et al. (2020).

Comments on the possible implementation in NZ

The application of event-based modelling of stream bank hydraulic erosion at catchment scale (e.g. Gasser et al. 2018) may be useful in the future to identify localized hotspots of sediment sources due to hydraulic bank erosion. Such models may also help prioritize investments in bioengineering measures to assess the estimated potential mitigation effects of vegetation.

9 Controlling and maintenance

Controlling and maintenance of measures is a relatively new aspect in ESC management. In the following sessions the main topics considered in the last decade in the Alps are briefly described.

9.1.1 Cadaster of measures

The first information needed to guarantee long-term monitoring of measures at regional scale is the establishment of a geo-referenced cadaster. While technical measures (e.g. engineered structures) are usually better documented both now and in the past, bioengineering measures usually have worse documentation and often these get lost within few a decades.

A modern cadaster of measures consists of two parts: the list of measures that have been built and the relevant responsibilities. In addition to the correct geographical location of the measure, the cadaster also contains basic information (e.g. type of structure, year of construction, hazard process, design parameters, costs) and allows spatial links to data on damage potential. In addition, the results of the management of protective structures (e.g. operational and maintenance measures) are linked to the corresponding cadastral objects in a relational (or spatial) and historical manner.

In Switzerland, the need for such a cadaster of measures was launched by single cantons (analogous to Regional Councils in New Zealand). The cantons are responsible for managing the data of the cadaster and organizing the type of information needed, in some cases with the help of specialized consulting companies (see example in Fig. 20). Usually the details of the cadaster are accessible for internal personal only (i.e. not publicly accessible). The perceived value of these cadasters for experts is high and they have become a fundamental tool, a cadaster of protective structures that serves the safety responsible authority in planning and in the execution of periodic inspections and maintenance. Finally, such information supports long-term financial planning.

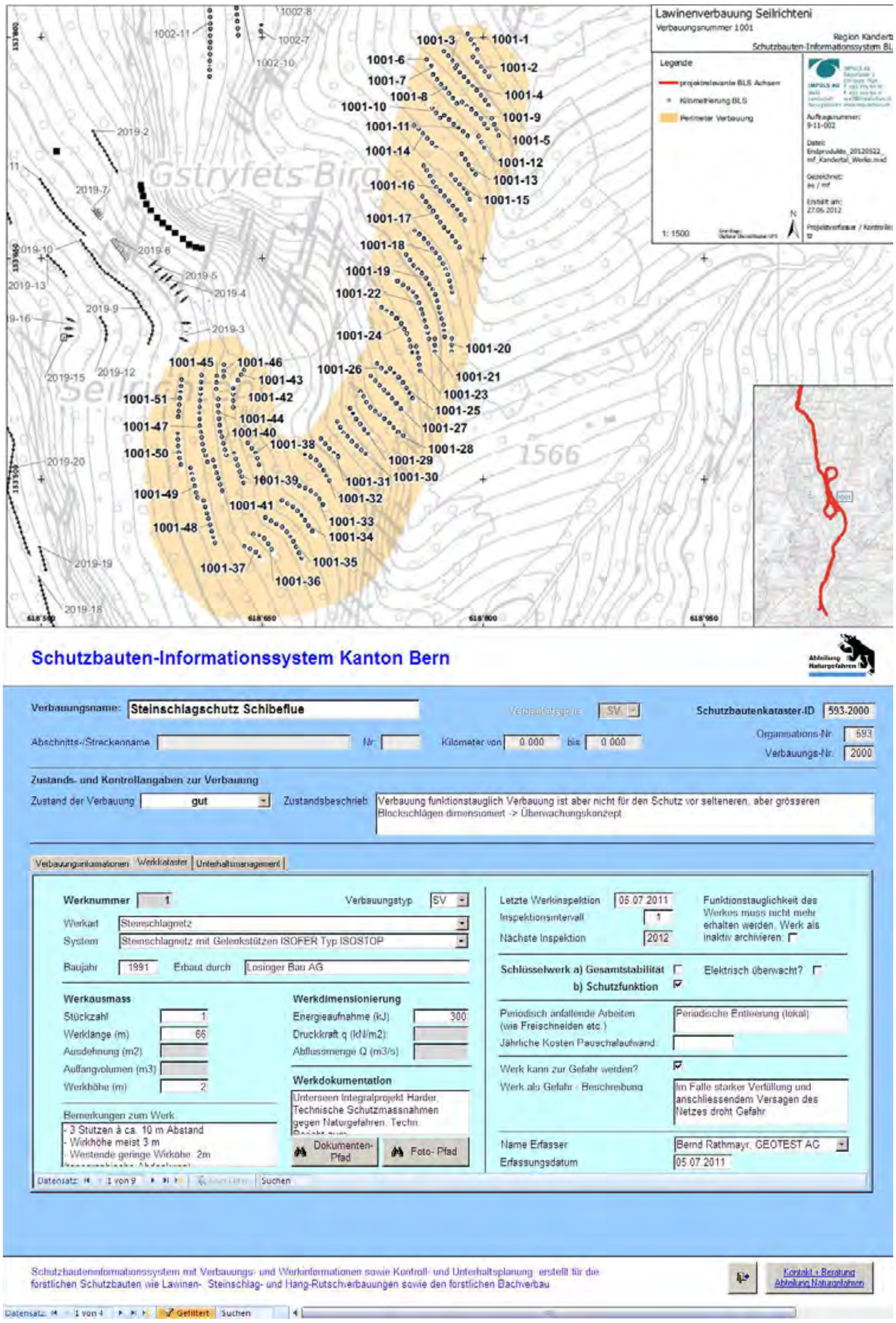
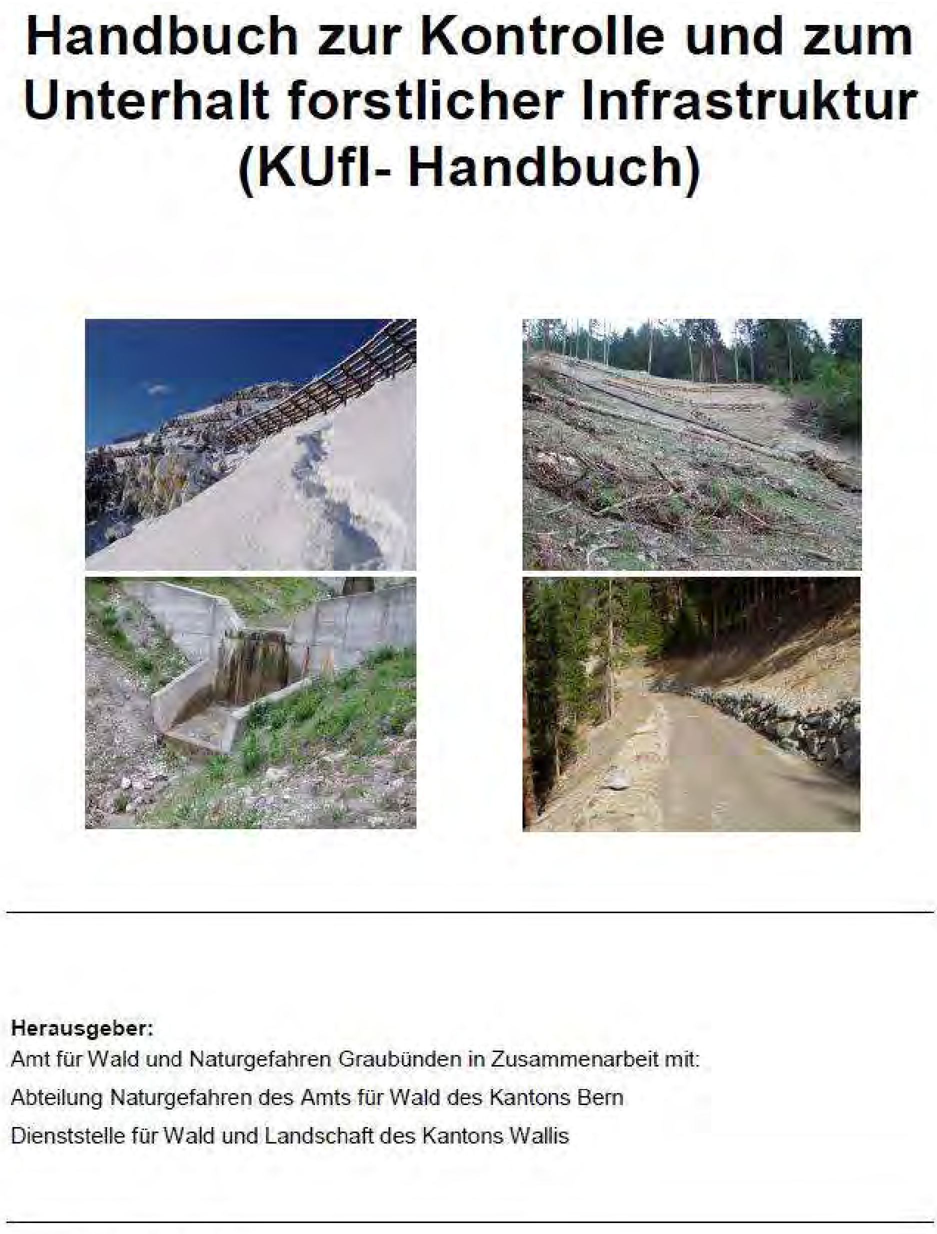


Figure 20. Example of georeferenced protection measures against natural hazards in the canton of Bern (top: geodatabase, bottom: extract of the databank) (source: AWN-Bern).

9.1.2 Standards for measures evaluation

An emerging issue concerning the maintenance of bioengineering measures is the definition of standardized criteria for the evaluation of their effectiveness. Analogous to technical measures (see example of handbook in Fig. 21), it is expected that bioengineering measures fulfil criteria such as load-bearing safety, serviceability, and durability (as described in the Eurocodes 7). For bioengineering measures, it is difficult to define such criteria, but the improvement of quantitative methods in the future may support the formulation of such criteria. For instance, remotely sensed data of vegetation structure coupled with root reinforcement calculations implemented in slope stability models may allow the real time assessment of the safety factor of slopes susceptible to shallow landslides (e.g. Schwarz et al. 2019a).


Handbuch zur Kontrolle und zum Unterhalt forstlicher Infrastruktur (KUfI- Handbuch)

Herausgeber:
Amt für Wald und Naturgefahren Graubünden in Zusammenarbeit mit:
Abteilung Naturgefahren des Amts für Wald des Kantons Bern
Dienststelle für Wald und Landschaft des Kantons Wallis

Figure 21. First document released in 2012 for the control and evaluation of measures against natural hazards (source: AWN-Bern).

10 Discussion

10.1.1 Discussion on activities within an adaptive ESC management concept

This review provided the opportunity to discuss the application of ESC measures from a broad and international point of view. The formulation of a general concept to include all phases of an adaptive ESC management cycle (session 1.2) allows actions to be clarified and responsibility for an optimized and harmonized implementation of ESC measures. This analysis highlighted the importance of clearly defining the role of stakeholders (authorities/experts/privates) at different spatial scales, as well as the standards and methods for the assessment of processes and measure's effectiveness. Some of the points listed in Table 4 are already standard in many countries, but a general overview seems to be missing in the literature.

Depending on the level of action, different standards of affordability need to be defined depending on the available resources (in the form of legislation or guidelines). For instance, at a national level, erosion susceptibility maps (called 'Hinweiskarte' in Switzerland) are sufficient to locate hotspots that, combined with information of potential socio-economic damages, give a general indication of the regions that most need the implementation of ESC measures. At regional (canton/council) level, hazards maps (that consider different scenarios of frequency and magnitude of the processes) may be used to calculate risk maps, which quantitatively help to prioritise the investments in ESC measures (e.g. using cost-benefit analysis in a planning phase), eventually allowing an objective distribution of subsidies. At communal or private level, specific criteria/guidelines and methods (including models) allow for a systematic and effective implementation of ESC measures considering their spatial and temporal evolution. Table 4 provides an example of actions that could be undertaken at different spatial level to implement ESC measures considering different phases of an adaptive ESC management concept and types of activities (political, administrative, technical, and research).

Table 4. Summary of possible activities for the implementation of ESC measures at different spatial scales and management phases (source M. Schwarz)

Levels or Phases	Assessment	Planning	Implementation	Monitoring & Evaluation
National	• Define national targets for sustainable erosion and sediment flow • Elaboration of susceptibility maps • Definition of standards and methods for Assessment (integrated in research activities)	• Coordination of research activities to improve planning • Set budget for research activities on planning methods and data	• Set budget for subsidies • Set budget for research	• Definition of standards for the monitoring and evaluation of ESC measures (e.g. guidelines) • Set budget for the documentation and analysis of extreme events
Regional (Council)	• Define guidelines for assessment • Elaboration of hazards and risks maps • Management of georeferenced data (e.g. soil maps, rainfall/weather data, assessment results) • Coordination of assessment projects.	• Set criteria for the prioritization of ESC measures at regional scale (e.g. cost-benefit analysis). • Adopt quantitative methods for the assessment of measure effectiveness at regional scale. • Coordination of planning projects. • Management of data from planning projects.	• Set budget for subsidies • Supervision of executive ESC projects • Coordinate knowledge and material at regional scale (e.g. willow stakes/poles)	• Management of monitoring data and evaluation protocols (e.g. set a regional georeferenced cadaster of measures) • Coordination of data collection of measures evaluation and events documentation (e.g. cadaster of events) • Set up of monitoring areas
Communal	• Coordination of assessment projects. • Communication with local experts and population	• Coordination of planning projects. • Optimization of local resources (experts, materials, methods)	• Supervision of executive ESC projects • Optimization of local resources (experts, materials, methods)	• Execution/coordination of monitoring and evaluation activities • Documentation and data collection of events (e.g. landslides, gully erosion, floods, debris flow, etc.)
Farm or Private	• Cooperation and delivery of information • Execution of assessment projects (e.g. local consulting companies)	• Participation or Cooperation • Elaboration of Planning projects (e.g. local consulting companies) • Adopt quantitative methods for the assessment of measure effectiveness at local level (e.g. consulting companies)	• Execution of implementing Projects (e.g. farmers or local companies) • Courses for companies involved in the execution of ESC measures	• Participation or Cooperation to monitoring, evaluation of measures and event documentation (e.g. farmers or local consulting companies).

Although, the assessment of some erosion processes is already implemented in New Zealand at national level, the elaboration of hazard and risk maps at regional scale could be improved. A fundamental condition for achieving this would be the standardization and enhancement of regional scale meteorological, land use, and pedological information and data. New research techniques (such as new remote sensing techniques and modelling approaches) could considerably improve the quality and quantity of those type of data and results. In particular, hazard and risk mapping at regional scale should consider probability approaches in event-based models that consider different return periods (e.g. use of SlideforMAP, Gasser et al. 2018).

In the planning phase, improving methods for cost-benefit analysis at the regional scale and for planning of single ESC measures (communal and private level) have the biggest future potential. Simplified approaches that combine risk-based analysis (e.g. Schwarz et al. 2019a) and cost-benefit analysis need to be further developed and tested. Numerical models such as SOSlope (Cohen & Schwarz 2017), BSTEM (Bankhead et al. 2013) or BankforNET (Gasser et al. 2020) can be applied to quantify the effectiveness of bioengineering measures in slope and river bank stabilization measures (depending on the quantity and quality of data available). Process-based analysis for determining effectiveness of measures for controlling surface and gully erosion are still missing and have potential to be improved using existing models (e.g. GLEAMS model). The effort needed to quantify effectiveness needs to also be differentiated based on the size of the project, i.e. large projects with budgets >NZD$100k vs smaller projects.

In the implementation phase, the major challenge is represented by the optimization of local resources to improve the efficiency and the quality of measures. It is common experience that the knowledge collected by local companies and experts is fundamental for a long-term effectiveness of investment on ESC measures. Part of this knowledge can be improved by the organization of specific local training courses. A summary of additional ESC measures that could be implemented/improved in NZ follow in the next section (10.2).

In the monitoring and evaluation phase, the expansion of national or regional cadasters of events (e.g. Swiss StorMe databank), and measures (e.g. the Swiss Schutzbautenkataster) are a fundamental tool. Evaluation and management of measures can be coordinated between different stakeholders and authorities (e.g. local expert conduct monitoring and evaluation protocols, regional authorities manage data of the monitoring and evaluation measures, national authorities set criteria for a standardized monitoring and evaluation at national level). The set-up of well-instrumented monitoring areas treated with ESC measures, delivers important information for the long-term assessment of effectiveness.

The consideration of the sustainability and life cycle assessment of ESC measures is an important aspect that should be considered in the future. In a re-engineering phase of the management concept, the ecological and economic sustainability of measures is important and should be evaluated in the planning phase. This aspect of management has been quantitatively introduced only in the last decades. The limiting factors for the application of this concept in practice are the limited quantitative information needed for the calculations (e.g. estimation of CO_2 emissions for different products or operations).

Well-documented projects and organization of the information in regional cadasters would help to underpin this issue in the future.

10.2 Recommendations based on European experience for improved application of ESC in New Zealand

In this section we summarize possible application or improvement of ESC measures in New Zealand, considering the different erosion processes presented in this review.

10.2.1 Surface sheet and rill erosion

Protection forest management

The basic concept of protection forest management could be adapted in New Zealand in both production forest (e.g. Radiata pine plantation) as well as in newly defined protection forest areas. In production forests, the protective function could be improved considering two levels of measures:

1 Adapting the tree stems per hectare for afforestation after clearcutting depending on the hazard probability of erosion processes,

2 Planning the spatial and temporal location of clear cutting as a function of risks related to erosion processes (e.g. shallow landslides, large wood entrainment and transport).

Alongside the protection against natural hazards, there is also the issue of managing the forest for sustainable soil management. A maximum tolerable soil erosion rate should be defined depending on the lithological and morphological characteristics of forest stands. Based on the tolerable limit, forest operations should be planned to minimize the loss of productive soil.

Use of Ectomycorrhiza inoculum

Mixing natural soil with inoculum during the preparation of new ESC measures is the most economically affordable way to use this technique. In areas particularly exposed to surface erosion, the inoculum of Ectomycorrhiza can considerably reduce surface erosion (in the short term), improve the growth of vegetation, and protect vegetation from pathogens. Adapting inoculum to local conditions and production costs could be the limiting factor for the application of this technique in practice. This could be investigated with research projects.

Rough and Loose in earthworks

The application of this technique is limited to small areas, especially along human-made structures. However, an adapted version of this technique could be tested in an eroded area in the hill country New Zealand landscapes in order to reduce surface erosion on regressive erosion areas (such as those triggered by shallow landslides or intensive pasture).

Plantation along wheel tracks

This approach could be particularly interesting to recover damage in plantation for wood production in New Zealand. An additional improvement would be the identification of potential tree species that can maximize the recovery considering different soil conditions and susceptibility to erosion.

10.2.2 Shallow Mass movements

Afforestation

Considering future population increase and increasing awareness of risks associated with erosion processes, it is expected that afforestation for ESC will gain importance. In this case, the tree species diversification should be considered an important aspect in the planning phase. The long-term effectiveness of this type of measure will depend on the sustainable management of the forests, anticipating the effects of natural disturbances. A quantitative assessment of the effectiveness of such measures is possible using models such as SlideforMAP (Gasser et al. 2018) and SOSlope (Cohen & Schwarz 2017). The limitation for the application of such approaches in New Zealand at present is the availability of data on soil properties and rainfall statistics at different spatial levels.

Spaced-planted trees

Quantitative approaches for planning and effectiveness assessment of spaced-planted trees, as for afforestation, could improve the optimization of investments in such biological measures in New Zealand. The results of such analysis are the basis for cost-benefit calculations needed for the prioritization of interventions at the regional scale. Furthermore, future analysis should be undertaken to investigate how mature stands of spaced-planted trees should be managed to guarantee a long-term stabilizing effect, analogous to protection forest management.

10.2.3 Gully erosion

In addition to the erosion control measures listed in Table 3, the following strategy for fine sediment retention with bioengineering within gullies can be proposed in New Zealand:

- The gully with a surface area less than 1 ha is the maximum size of gullies where soil bioengineered re-vegetation is appropriate; rehabilitation actions should be carried out on gully floors only, to reach a minimum plant cover rate of 20% at the scale of the gully
- The bioengineering works must be installed only in favourable ecological conditions, e.g. not in southern exposure
- These works must be installed on the gully floors when slopes are less than 40% to provide efficient sediment trapping
- The choice of the appropriate bioengineered structure inside gullies is guided by the presence of vegetation on slopes. Therefore, if vegetation is present, brush layers on fascines are recommended: this intervention limits the operation to punctual

installation of linear vegetation cover during the period of natural colonization of bare soils from surrounding vegetation. Alternatively, using brush layers and brush mats on fascines is recommended: this intervention, more expensive than the first one, is necessary for directly installing a vegetation mat without waiting for natural colonization by vegetation, especially when the surrounding vegetation is too far away from rehabilitated sites.

10.2.4 Hydraulic streambank erosion

Conserving or restoring riparian vegetation: effect of root networks

The application of event-based modelling of stream bank hydraulic erosion at catchment scale, such as BankforMAP (Gasser et al. 2018), may be useful in the future to identify localized hotspots of sediment sources due to hydraulic bank erosion. Such models may also help with prioritizing investments in bioengineering measures to assess the estimated potential mitigation effects of vegetation.

10.3 Quantitative assessment of ESC-measures effectiveness

The quantitative assessment of ESC measures is a necessary foundation for improving ESC strategies. The empirical knowledge gained from research studies, monitoring programs and modelling approaches allow the simulation of processes considering the combination of many different factors. Such models are important for the assessment of processes, the planning of measures at different scales (national, regional, single project), and the evaluation of implemented measures. The quality and quantity of data needed for such models depend on the type of application, and these data are often the limiting factor in their application. For instance, for the calculation of susceptibility maps, basic information on soil and topography are sufficient. For the prioritization of investments at regional scales, however, the application of event-based models that consider different return periods are needed. These types of models need detailed information regarding soil geotechnical properties, as well as land use and rainfall data. Finally, depending on the extension of the single project for the implementation of ESC measures, additional field investigations are needed to improve the effectiveness of the measures (e.g. proof of soil properties). A further aspect that can be implemented in modelling approaches is the probabilistic characterization of model parameters to quantify the uncertainty of model results. In the case of technical measures, this aspect is implemented in the norms (e.g. Eurocodes) as calculation of reliability (Bischetti et al. under revision).

In the case of bioengineering measures, the implementation of time-dependent effectiveness of the measures allows for the calculation of the overall effect during a defined period. Figure 22 shows a conceptual example of the quantification of the probability of shallow landslide considering the condition without vegetation, with vegetation, and with the time dependent effect of vegetation. In the case without vegetation, the cumulative triggering probability increases rapidly (for example, corresponding to a rainfall event with a return period of 10 years), whereas in the condition with mature vegetation the cumulative probability is reduced due to the stabilizing effects of vegetation (for example, corresponding to a triggering event with a return period of 100 years). Considering the time-dependent effect of vegetation, it is possible to calculate the long-term cumulative probability of the triggering of a process (in this cases landslides).

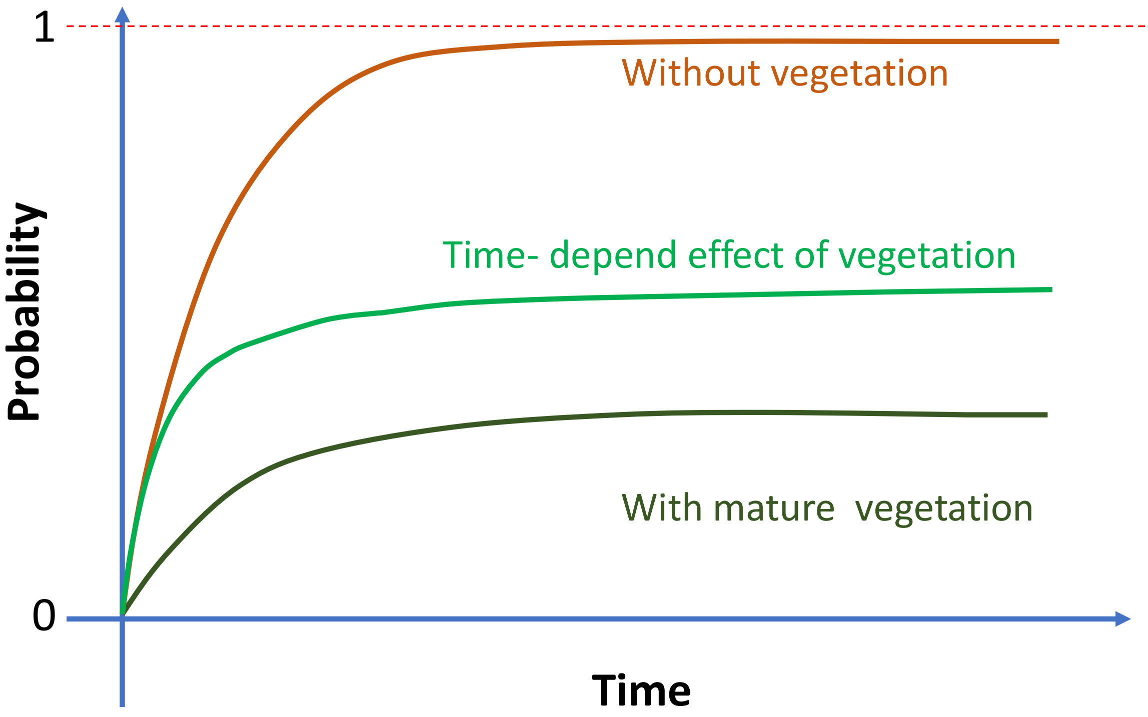


Figure 22. Conceptual illustration of the time dependent effect of vegetation on the cumulative triggering probability of erosion processes (specifically shallow landslide) (Modified from Schwarz, in preparation).

Upscaling of processes and quantifying the connectivity of sediment flows at different spatial and temporal scales is a challenge that currently limits the usefulness of models at regional scales. In addition, improving the understanding and modelling of the interactions of erosion processes is also a challenge for research. In particular, the interaction between hillslope processes such as surface erosion and shallow landslides and the link to sediment transport in channels and streams is still difficult to quantify. Understanding this chain of processes is important for defining the effectiveness of ESC interventions at the catchment scale.

11 Conclusions

In conclusion, we point out the following main topics arising from the present review:

- The formulation and application of an 'adaptive ESC management concept' is a useful tool for the effective and efficient implementation of ESC measures at different administrative levels (national, regional, and local).
- Improvements in remote sensing techniques are important for the assessment of processes and ESC measure effectiveness.
- Different types of models and datasets can be used for the prediction of process frequency and magnitude at different temporal and spatial scales. Their application at

meaningful scales can improve the effectiveness of ESC measures when used during several management phases such as assessment, planning, and evaluation.

- At national scale, empirical and semi-quantitative models can be used to define hotspots of processes with high intensity (susceptibility maps). At regional scales event-based (probabilistic) physically based models can be used to quantify the intensity of processes considering different scenarios, based on the probability of occurrence. This type of approach is needed for cost-benefit analysis of ESC measures (Schwarz et al. 2019a). Detailed models (e.g. that explicitly consider the spatial and temporal effect of single trees – Schwarz 2019) can be used to improve the effectiveness of ESC measures at the local scale.
- Criteria should be set to differentiate the requirements for planning effort depending on the dimension, risks, and complexity of ESC projects.
- Research activities on the quantification and improvement of new ESC measures (e.g. Mycorrhiza inoculum) should be implemented in a general concept of ESC management.
- The effectiveness of bioengineering ESC measures changes drastically (0 to almost 100%) depending on the type of process and set of local conditions:
    - surface erosion: the reduction of runoff (in the contributing zone), the reduction of runoff velocity, and increase of soil critical shear strength (in the process zone) are the effects achieved with bioengineering measures. The most challenging aspect for the implementation of such ESC measures is to assure the establishment of a vegetation cover in degraded areas.
    - gully erosion: the effect of live sediment traps is limited to catchments with limited runoff (depending on the dimensions of the contributing area, channel inclination, dimension of sediments, runoff coefficient, soil properties, and rainfall characteristics).
    - shallow landslides: the hydrological effect of vegetation in the contributing area reduces the probability of building sufficient pore water pressure for triggering instability, whereas root reinforcement, generally up to ca 2 m depth, contributes to increased soil strength (under shearing, tension and compression).
    - The contribution of vegetation to improve streambank stability (hydraulic and geotechnical) is limited by the threshold of hydraulic drag forces (too high in large rivers) and the geometry of streambanks (e.g. when roots do not reach potential shear/tension zones).
- Communication, training, and the passing on of knowledge about ESC measures at the local scale are important to optimise resources needed in the planning and implementation phases.
- To guarantee the resistance and resilience of such ecosystems to climate changes and disturbances, future management of established ESC measures (e.g. spaced-planted trees or protection forests) could be a challenge.
- Building of georeferenced cadasters for event documentation and measures can improve the efficiency in the management and effectiveness of ESC measures.
- Monitoring programmes are fundamental activities for the evaluation of implemented ESC measures, as well as for the calibration/validation of models.

12 Acknowledgements

We thank our colleagues, institutes, and networks for providing local and country-specific information that has aided this review. Raphael Spiekermann kindly reviewed this report and Anne Austin edited it.

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