Prioritisation of neighbourhood catchments in the Fitzroy Basin

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Executive Summary

The Fitzroy Basin Association covers an area of 156,000 km^2. It encompasses the tributaries of the Mackenzie, Isaac and Connors, Dawson, Comet and Nogoa rivers and occupies one tenth of Queensland's land mass. Prioritisation processes conducted under Reef Plan 2013 have resulted in the Fitzroy Basin being ranked as "Very High" for sediment load reduction, and "High" for pesticide load reduction (Reef Plan 2013). The 2009 baseline load report estimated 2.9 million tonnes of sediment, attributed to human activity as annual emissions to the Great Barrier Reef. The increased pressure for efficient sediment outcomes has resulted in the development of this prioritisation approach to further improve the allocation of resources to achieve sediment reductions from the grazing and grains industries.

The proposed process for the Water Quality Improvement Plan highlights the findings from policy and scientific analysis that underpin and inform decisions. The approach utilized a framework approach and was completed on a neighbourhood catchment scale. The approach integrated the sediment load delivered to the reef, residual ground cover, management practice data and cost to develop an understanding of where in the catchment sediment was coming from, what was the capacity to achieve change and the cost to do so. This then allowed neighbourhood catchments to be ranked and priorities for grains and grazing to be identified.

A number of the selected neighbourhood catchments have large proportions of highly erosive soils, which must be considered before any major works are completed. Given the state of current El Niño, ground cover needs to be taken into consideration with landholders to develop strategies that maintain ground cover on a whole of landscape approach. Similarly, the results highlighted what erosion processes are required to be considered when implementing projects.

The results highlight cropping areas which have the potential to achieve sediment reductions with low cost and high adoption rates of supporting management practices. The dominant cropping soils also have very high fractions of particle size below 4 µm, which are increasingly understood to be extremely important in terms of the damage done to reefs. In a number of the neighbourhood catchments selected there is the opportunity to work with growers to achieve sediment reductions and achieve corresponding cumulative benefits through herbicide reductions and the applied dissolved inorganic nitrogen reductions.

Similarly, although mining only occupies 1% of the catchment, mining companies have grazing lease agreements in place for 4% of the catchment. Given that cattle enterprises are not their primary business there is the potential scope for engagement of mining companies to achieve mutually beneficial outcomes. Given the large areas involved, there is potential for low risk engagement with mining companies to facilitate low cost, large impact sediment reductions.

The cumulative cost curve indicated the complexity of achieving the targeted reductions. Further data on spatial and biophysical characteristics would allow the methods to be improved and the process has been developed to be updated as improved scientific information is developed.

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1. Introduction

The National Water Quality Management Strategy (NWQMS), a Federal initiative, is collaborating with Fitzroy Basin Association Inc. (FBA) to develop a Water Quality Improvement Plan (WQIP). The NWQMS aims to reduce pollution released into aquatic ecosystems with high ecological, social and/or recreational values. The key objective of the NWQMS is "to achieve sustainable use of the nation's water resources by protecting and enhancing their quality while maintaining economic and social development". This objective is linked to the pollutant reduction targets that have already been developed for the Fitzroy Basin under the Reef Water Quality Protection Plan (Reef Plan) (2013).

The Reef Plan (2013) is a Federal and State initiative that focuses on halting the decline in the health of the Great Barrier Reef (GBR). The plan states a number of targets for sediment, nutrient and pesticide run-off reduction in the grazing, grains and sugar industries. The targets include:

- pollution reductions of 20% in sediments, 50% in nutrients and 40% in pesticides
- 90% of land managers using best management practices
- a minimum 70% late dry season ground cover.

Funding arrangements from Federal and State programs such as the Australian Government's Reef Programme and industry Best Management Practices (BMP) programs via natural resource management groups has been directed to progress towards these targets.

Prioritisation processes conducted under Reef Plan 2013 have resulted in the Fitzroy Basin being ranked as "Very High" for sediment load reduction, and "High" for pesticide load reduction (Reef Plan 2013). The 2009 baseline load report estimated 2.9 million tonnes of sediment, 3,900 tonnes of phosphourus, and 1,300 tonnes of total nitrogen can be attributed to human activity as annual emissions to the Great Barrier Reef. Run-off reduction work will focus on the two dominant industries of grazing and grains to achieve the targets. An annual Reef Report Card assesses progress towards the targets, and highlights the slow progress as a result of a number of complexities such as climate, existing degree of landholder adoption, and geographical variation. Given these results, there is increased pressure to improved current outcomes.

The proposed process for the WQIP highlights the findings from policy and scientific analysis that underpin and inform decisions. The Fitzroy Basin has been a key part a number of scientific, modelling and monitoring studies and the development of a key document that helped form the basis for Reef Plan (2013): the Scientific Consensus Statement (SCO) (Brodie et al. 2013). The Central Queensland Sustainability Strategy 2030 (CQSS:2030), FBA's overarching Natural Resource Management (NRM) plan considered these studies and clearly articulated the importance of protecting soils, coastal and marine ecosystems. A key deficiency identified in the CQSS:2030, which the WQIP intends to address, is the lack of biophysical and economic data integration across the catchment.

To achieve the Reef Plan targets and the overarching CQSS:2030 NRM plan of reducing sediment loads generated in the Fitzroy Basin, a range of changes to land management practices are required. These may include decreasing the stocking rate on grazing land, re-vegetating and remediating erosion features, and implementing infrastructure such as fencing and earth works. These changes in land management practices may be costly for both landholders and the community. Therefore, it is important to identify the areas within Fitzroy Basin where changes to current land management practices could be implemented cost-effectively.

The objective of the study was to prioritise neighborhood catchments within the Fitzroy Basin based on a number of criteria including biophysical, management practice effectiveness, and cost. This report provides background information about the Fitzroy Basin, its two dominant industries and current understanding of the sediments and nutrient loads entering into the GBR. The methods, variables and data used for the prioritisation of neighborhood catchments in the Fitzroy Basin will then be described and the results will be discussed.

2. The Fitzroy Basin

The Fitzroy Basin Association area covers an area of 156,000 km^2. It encompasses the tributaries of the Mackenzie, Isaac and Connors, Dawson, Comet and Nogoa rivers and occupies one tenth of Queensland's land mass. All the tributaries enter into the Fitzroy River, which drains into the World Heritage–listed GBR. The adjacent catchments of the Boyne and Calliope rivers (which drain directly to the GBR) are commonly considered in conjunction with the Fitzroy Basin (Figure 2.1).

Land use in the Basin is dominated by grazing (80%) and broadacre grain cropping and irrigated cotton (8%). The climate in the Fitzroy Basin is sub-tropical and semi-arid, with highly variable summer rainfall, and drought being a recurring feature. The Basin has experienced extensive land use modifications, with the clearing of Brigalow (*Acacia harpophylla*) dominated woodland for grazing and cropping. By 1996, approximately 60% of all remnant vegetation had been cleared or substantially altered, impacting significantly on the amount of soil run-off (approximately doubling it) exported from native vegetation (Packett et al. 2009). These characteristics, combined with the impacts of the coal, cropping and grazing industries, have raised concerns about water quality and the present and future health of the GBR (Webster 2008).

Recent estimates of modelled post-development, long-term annual suspended sediment export from the Fitzroy Basin to the GBR lagoon range from three to four-and-a-half million tonnes per year (Packett et al. 2009; Waterhouse et al. 2011). The key source of sediment pollutant entering the GBR is an increase in bare ground from grazing lands in the catchments. Karfs et al. (2009) also recognised that increased ground cover, particularly at the end of the dry season, and improved land condition can prevent excessive amounts of sediments entering streams and rivers. With such heterogeneity between land types regarding soil characteristics, land productivity and slope, the sediment loads exported vary significantly throughout the catchment and its land types (Silburn 2011; Silburn et al. 2011b).

Figure 1. Fitzroy Basin

2.1. Neighbourhood catchments

Currently FBA has three sub-regional groups (Dawson Catchment Coordinating Authority, Capricornia Catchments, and Central Highlands Regional Resource Use Planning), which operate with field staff to engage and work with landholders. The field staff have in the past worked in smaller geographical parcels defined as neighbourhood catchments. From these neighbourhood catchments (NC) field staff have alternated neighbourhood catchments, basing their activities for extension, field days and engagement for a period of time solely on the landholders in these NC. The boundaries of the NC are based on the smaller scale catchments and comprise a varying number of landholders. The Basin has a total of 192 neighbourhood catchments and was used as the scale for this prioritisation (Figure 2). The number of NC varies in each of the sub-catchments, with a maximum of 66 in the Dawson and a minimum of 28 in the Boyne.

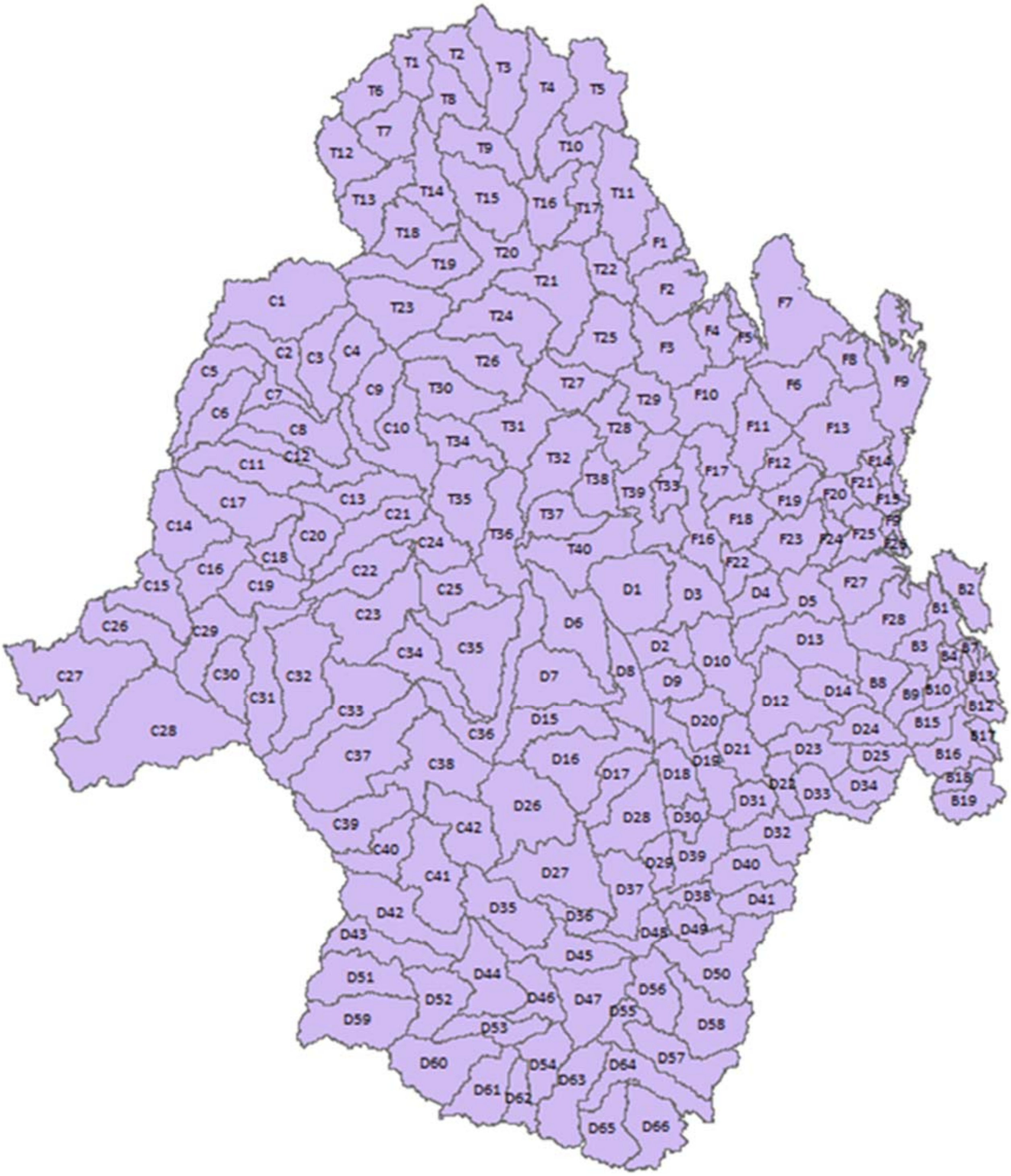

Figure 2: Neighbourhood catchments within the Fitzroy Basin Association area

2.2 Background information

In 2002, regional NRM bodies were required to develop a 'strategy and investment plan' to improve management of natural resources. This involved identifying assets; ranking and prioritising assets after accounting for risk; establishing and prioritising goals, objectives and targets for realistic achievement through the investment planning process; and consulting the public (Farrelly & Conacher 2007).

These tasks are complex and require expertise in gathering and using science and information, local and practical knowledge, and an understanding of public values. These skills and knowledge are reported to be lacking (Seymour et al. 2008), but are critically needed for prioritisation decisions. The spatial and temporal impact of a decision can vary dramatically from an individual field to a whole region and from a year to a whole century, based on the complexity and geography of the NRM issue.

Changing land use management practices may be very costly, thus there is a need to explore how water quality improvement targets can be achieved, the level of potential improvements, and the cost involved (Bouman et al. 1998; Michaud et al. 2007; Cools et al. 2011). Internationally, several approaches have been taken to model environmental and production processes and to evaluate programs and conservation policies to further inform policy design (Wu & Boggess 1999; Wu & Skelton-Groth 2002; Langpap & Wu 2004; Wätzold & Schwerdtner 2005). These previous studies have included land use models encompassing hydrological, biophysical and soil models (Cools et al. 2011). However, many studies have excluded or paid little attention to spatial or economic aspects (Massoud et al. 2006). Few studies in Australia have integrated biophysical, economic and spatial models at a catchment scale to explore the options for cost effective water quality improvements through program design (Johst et al. 2002; Ferraro 2004; Thurow et al. 2004; Lant et al. 2005).

Water Quality Improvement Plans aim to provide direction and allocation of future resources to achieve water quality outcomes. In the past, NRM investment programs have experienced deficiencies in delivering targeted investment efficiently and were lacking the ability to demonstrate measured outcomes (Pannell, 2009b). Criticisms of past policies and programs have resulted in changes to natural resource management in Australia and increased pressure to demonstrate outcomes that are based on biophysical and economic information. Pannell (2009a) noted that environmental problems are often technically complex and uncertain. Robust decisions about natural resource management need to be based on knowledge about the degree of threat or damage to environmental assets at risk, and the extent to which this threat or damage can be reduced by particular changes in management. In many cases, generic knowledge is not sufficient, hence, local specific knowledge is required (Pannell, 2009a).

The Reef Plan targets were developed based on the Scientific Consensus Statement (SCS). This statement provided an understanding of the science to form and shape improvements in Reef Plan 2013-2018. These findings and synthesis of scientific findings provides a framework for understanding the complexity of the water pollution issue and broader information of how the

WQIP prioritisation process can better account for these complexities. Findings and implications from the SCS relevant to this project are provided in Table 1.

Table 1. Findings and implications from the Scientific Consensus Statement 2013

Finding	Learning incorporated in to the WQIP
Shifting all landholders to B grazing management practices (excluding management of gullies and stream bank) will not achieve the Reef Plan targets.	Gullies and stream bank management interventions will be required. General statements of shifting all landholders to a higher management level are not particularly useful when time lags and biophysical considerations have not been considered.
Hotspot areas of hill-slope erosion will also be priorities for efficiently reducing sediment loads where they are well connected to river outlets.	Spatial consideration is critical, not only for where the pollutant is coming from but the transport function to the GBR lagoon.
No potential low cost solutions (as shifting everyone to B will not achieve the target) to achieve the targets as there are no net private benefits to graziers from achieving higher level targets.	For gully and stream bank remediation a mix of extension and engineering works will be required and further contributions from public funds will be required.
Regional-scale gradients in sediment contribution rate result from variation in soil, rainfall and topography across grazing and cropping lands that are independent of management practices.	Consideration of land type and productivity is critical in effectively spatially targeting.
Heterogeneity exists in the costs involved at a farm level and the pollutant reduction achieved.	Spatial targeting is critical, and utilising existing pollutant modelling is critical.
Forage utilisation of less than 25-30% of annual biomass is required to sustain productivity and land condition.	Ground cover and the relationship between cover and long-term drought is critical. Utilising ground cover products provides insights into these relationships.
As the scale of properties increase there are increased opportunities for more cost effective outcomes.	Property size is an important consideration in achieving cost effective outcomes.
Economic trade-offs vary across different land types and the costs of achieving reductions vary by two orders of magnitude.	Costs vary depending on biophysical characteristics and this must be taken into consideration when estimating costs for neighbourhood catchments.

The findings and implications from the SCS highlight that the prioritisation process of neighbourhood catchments for water quality improvement investments need to be driven by an interdisciplinary approach, using spatial, biophysical, social and economics expertise.

3. Current mechanisms

As an extension of Reef Plan and in line with the national priority areas of Caring for Our Country, Reef Rescue was formed. Reef Rescue has the objective "to improve the water quality of the Great Barrier Reef lagoon by increasing the adoption of land management practices that reduce the run-off of nutrients, pesticides and sediments from agricultural land" (Queensland Department of the Premier and Cabinet 2009).

Over $2 billion has been allocated to fund this objective, through the following five main components:

- Water Quality Grants ($146 million over five years)
- Reef Partnerships ($12 million over five years)
- Land and Sea Country Indigenous Partnerships ($10 million over five years)
- Reef Water Quality Research and Development ($10 million over five years)
- Water Quality Monitoring and Reporting, including the publication of an annual Great Barrier Reef Water Quality Report Card ($22 million over five years).

(Source: Queensland Department of the Premier and Cabinet 2009)

Recently re-named as Reef Programme, the Water Quality Grants and Reef Partnerships components have been key for funding on-ground practice change. The program has been based as an incentives package where a contribution was required from landholders. The payment for infrastructure was to encourage land management changes across the whole property. The projects funded through Reef Programme have been focused based on a prioritisation tool developed by FBA and include: riparian fencing projects for streambank and gully remediation and fencing to land type for hill-slope remediation.

Operating parallel to Reef Programme has been the initiatives of Grazing Best Management Practices (Grazing BMP) and Grains Best Management Practices (Grains BMP). The two BMP programs were developed as a partnership, which is a strategic self-assessment review of all aspects of the grazing business where graziers complete a voluntary self-assessment of management practices against industry standards. Focused as an extension program and as a pathway to access incentives the two policies have worked together to have an overall shift in management practice.

Table 2. Programs and mechanisms implemented to achieve sediment reductions

	Reef Programme	Grazing and Grains BMP	Reef Water Quality Research and Development
Mechanism	Incentives	Extension	Research and development

3.1. Private costs benefits and adoption

Depending on the complexity of the NRM issue, an astute policy response will include a suite of policy responses, where many instruments can complement each other. This approach is therefore more likely to achieve outcomes and provide more flexibility in responding to changed conditions. Some instruments are more likely to function more efficiently when used in conjunction with others. However, in practice, the selection of mechanisms is often not conducted through a rigorous process, so the policy response tends to rely on a small number of policy mechanisms. This highlights the importance of understanding the public and private benefits in selecting an appropriate suite of mechanisms (Pannell 2009a).

Key considerations include the understanding of the public and private costs and benefits to evaluate which policy mechanism is most effective at achieving environmental outcomes (Pannell 2009a). Similarly, information regarding the importance of the environmental asset to the community, the project risks, adoption of new practices, time lags and costs are all required to fully understand how to prioritise investments and the subsequent policy recommendations.

'Public net benefits' are defined as benefits minus costs accruing to society other than to the person whose land management is to be altered. 'Private net benefits' on the other hand are defined as the benefits minus the costs accruing to the private land manager as a result of the proposed changes in land management excluding transaction costs that are a part of the policy intervention (Pannell 2009b). Landholders will adopt land management practices with positive private net benefits, provided that they are able to learn about those practices. Positive incentives refer to land use change being encouraged through the use of regulation or financial instruments. Negative incentives are regulatory or financial incentives that are used to inhibit change.

Pannell (2009b) articulates the following rules for selecting policy mechanisms:

1. Do not use positive incentives for land-use change unless the net benefits of change are positive.
2. Do not use positive incentives if landholders would adopt land-use changes without those incentives.

3. Do not use positive incentives if private net costs outweigh public net benefits.

4. If private net benefits outweigh public net costs, the land-use changes should be accepted if they occur, implying no action. Alternatively, if it is not known whether private net benefits are sufficient to outweigh public net costs, a relatively flexible negative incentive instrument may be used to communicate the public net costs to landholders (e.g. pollution tax) leaving the decision to landholders. Inflexible negative incentives, such as regulations, should not be used.

5. If public net costs outweigh private net benefits from a set of land-use changes, use negative incentives to discourage uptake of land used in this case.

6. If public net benefits and private net benefits from a set of land-use change are both negative and landholders accurately perceive this, then no action is required. Adverse practices are unlikely to be adopted. If there is concern that landholders have misperceptions about relevant land uses, adoption of environmentally adverse practices could be discouraged by extension, or more strongly by negative incentives. Pannell (2009b) illustrates this concept further in Figure 1.

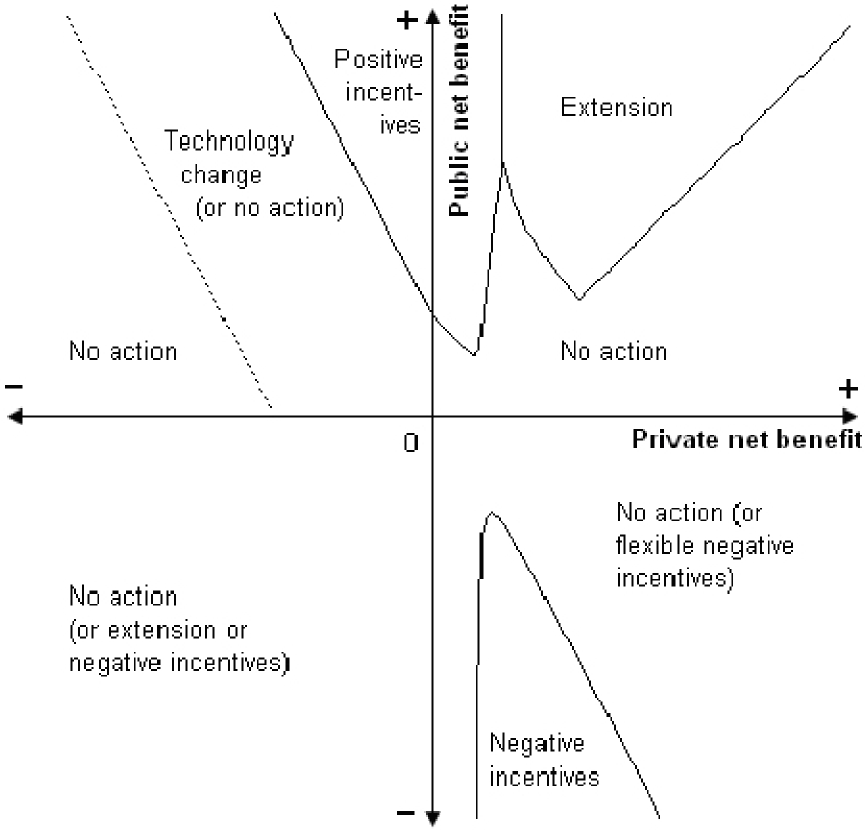

Figure 3. Selecting policy mechanisms based on public and private trade-offs

It is clear from the adoption literature that the approach required to achieve water quality improvements, via adoption of specific management practices, should be a diverse suite of instruments to accommodate the heterogeneity of attitudes, circumstances and conditions faced by graziers. The management practices promoted through the instruments must take the goals of landholders into account, including a financial advantage over their existing counterparts and have the ability to be trialled by graziers. In addition, conservation programs need to take advantage of farmers' stewardship ethic for maximum effectiveness and efficiency, and minimise the risk of crowding out intrinsic motivation and altruistic behaviours of the landholders (Greiner & Gregg 2011).

3.2. Cropping systems — sediment, nutrient and PSII herbicides

The use of nutrients and the reductions of Dissolved Inorganic Nitrogen (DIN) and Photosynthesis II-Inhibiting herbicides (PSII herbicides) have been targeted to the cropping industry due to the applied use for growth and management of crops. The Fitzroy Basin has two main areas of cropping: the Central Highlands and the Callide Valley. The development in the Fitzroy Basin involved clearing of native vegetation on both hillslopes and floodplain areas. In the Fitzroy Basin approximately 84% of the cropped soils are self-mulching, black, cracking clay vertisol soils (Murphy et al. 2013).

A study comparing natural brigalow forest (*Acacia harpophylla*) to brigalow land cleared for cropping led to an increase in annual rainfall run-off from 5% to 11%, while also increasing the frequency of run-off events, the mean peak rate of storm run-off and time to run-off commencement; all of which contribute to increasing sediment loads (Cowie, Thornton & Radford 2007). The use of mechanical cultivation on cropping soils has led to issues of compaction, reduced infiltration and soil loss. Silburn, Robinson & Freebairn (2007) note that soil physical and chemical degradation associated with cropping occurs slowly, but insidiously, with the effects potentially hidden by variability in climatic and economic cycles. Mathers, Nash & Gangaiya (2007) discuss how soil surface crusting or sealing can increase with cultivation on most soils, which then restricts water infiltration. In addition, many poorer soils have intrinsically low infiltration rates and lose a high proportion of rainfall as run-off (Silburn, Robinson & Freebairn 2007).

There is an established relationship between the application and intensity (mass per area) of nitrogen-based inputs and the exported average into river systems. Although the fertiliser rates are lower in cropping systems in the Fitzroy Basin (<35 kg km^2 yr^{-1}) compared to other cropping systems such as sugar cane (>160 kg km^2 yr^{-1}) nitrogen (N) fertiliser applications increase concentrations of inorganic N in soils, so DIN exports increase with increasing N fertiliser use. DIN exports are somewhat better related to N Surplus, the difference between N applied to crops and N in crop off-take, than N fertiliser. Given the size and importance, both ecologically and economically, of cropping in the Fitzroy, there have been surprisingly few measurements of run-off N losses from cropping systems, especially measurements made under different management regimes (Thorburn et al., 2013).

DIN exports in run-off from fields range from 0.4% to 7% of N fertiliser applied, except for one study in grains where exports were 20% (Murphy 2013). Given the substantial area of grains cropping in the Fitzroy region, it is important to know the generality of this result. There can be considerable run-down of soil organic matter and associated mineralisation of N (e.g. 80 kg ha^{-1} yr^{-1}) following clearing of native vegetation (Radford et al. 2007) that may contribute to N exports. However, organic matter run-down becomes negligible after approximately two decades (Huth et al. 2010), and Thorburn & Wilkinson (2013) reasoned that net mineralisation of N from soil organic matter made negligible inputs to recent N balances of GBR grains lands. Their conclusion is supported by DIN exports from the Fitzroy region being similar to those from other regions relative to N fertiliser applications. The sites studies by Murphy et al. (2013) had been cropped for many decades, so soil organic matter run-down following clearing of native vegetation seems an unlikely explanation for their results. While a much better understanding of the N export process from grains cropping areas in GBR catchments is required, contemporary understanding at this point is that applied inorganic nitrogen from fertiliser application is making a significant contribution to observed loads of DIN in receiving waters.

PSII herbicides are soil residual herbicides including atrazine, ametryn, diuron, hexazinone, metribuzin and simazine, which have moderate half-lives (30–100 days; Shawet al. 2011) and are typically weakly sorbed to soil (i.e. soil organic carbon sorption coefficient less than 5; Hornsby et al. 1995) and tebuthiuron, which has a longer half-life. Loss or transport in run-off refers to total loss, in water and sediment, unless otherwise specified. The most common PSII herbicides used in the Fitzroy are atrazine and tebuthiuron. Losses of both are highly dependent on the timing of the rainfall events following application, and the amount of ground cover retained on the paddock as residues from previous crops or residual pasture (Shaw & Silburn 2013). As conservation tillage has increased and as improved management practices take place (shifting from high risk to low risk management in relation to sediments) there is an increased reliance on all herbicides for weed control. This results in a trade-off between tillage, which greatly increases run-off and soil loss, and the increased use of herbicides, which results in increased potential for loss into receiving waters (Shaw et al., 2013; Thorburn et al., 2013).

Contour banks have been used in dryland farming for a long time, and are designed to withstand run-off from specific return periods for rainfall events. Contour banks are the most common practice implemented to reduce erosion since erosion was recognised as a serious issue across all Queensland cropping regions in the 1930s (Murphy et al. 2013). While contour banks are widely used, under high intensity storms, failure of poorly designed contour banks can occur, particularly in blocks with low soil surface cover, which results in greater deposited sediments blocking channel flow (Freebairn & Wockner 1986).

Murphy et al. (2013) report on a nine-year Central Queensland (Capella) study of sediment movement in run-off from grains dryland cropping with differing distances (slope length) between contour banks. All contour bays were farmed under a zero tilled/controlled traffic farming system

(Murphy et al. 2013). In addition, the study measured the nutrient and herbicide movement in run-off from a sorghum (*Sorghum bicolour*) crop for a single wet season (Murphy et al. 2013). This study found that the standard use of contour banks (spaced 180m apart) produced 40% less soil loss than triple-spaced contour banks (540m apart) over the nine-year trial. This provides justification that standard spaced contour banks are still a valuable management tool even in zero-till/controlled traffic farming systems for reducing soil loss compared to contour bank placement with longer slope lengths (Murphy et al. 2013).

3.3. Grazing lands — suspended sediments

Due to the large size of the Fitzroy Basin there are vast amounts of heterogeneity in land types, soil types, elevation, slope, rainfall, industry uses and management practices (Karfs et al., 2009; Silburn et al., 2011; Whish, 2011). These factors impact significantly on soil erosion process and suspended sediments entering into the GBR. Soil erosion is both a natural and land use management accelerated process (Shellberg and Brooks, 2013). Management practices that contribute to soil erosion include excessive stocking rates, grazing on streams and riparian area and inappropriate placement of roads and fence lines (Bartley et al., 2010a; McKergow et al., 2005; Shellberg and Brooks, 2013; Stavi et al., 2010; Wilkinson and Bartley, 2010).

There are three primary mechanisms through which sediment loss can occur: hill-slope, gully and streambank erosion (Thorburn & Wilkinson 2012; McKergow et al. 2005). Early spatial modelling identified hill-slope erosion as the dominant sediment source within the GBR catchments (McKergow et al. 2005). However, recent evidence suggests that a much greater proportion of sediment losses can be attributed to the sub-soil erosion process (Burton et al. 2013; Bartley et al. 2010a; Wilkinson et al. 2013; Thorburn & Wilkinson 2012) and that the majority of this likely to be from gully sources (Hughes et al. 2009). However, consideration of the solvability must also be factored into attempts to ameliorate the erosion processes.

3.3.1. Gully erosion

A gully is typically defined as a deep hillside channel that is usually too large to plough across, which has generally been cut out by running water and often does not contain a perennial flow (Kirkby & Bracken 2009). Gully erosion is the loss of soil from the head, walls or floor of a permanent erosion feature driven primarily by the overland flow of water. Evidence from international studies indicates that gully erosion is often the main source of total exported sediment (Wasson et al. 2002; Sylvain et al. 2005; de Vente et al. 2005). Land use change leading to reductions in ground cover have been identified as the primary catalyst of gully formation (Valentin et al. 2005; Desta & Adugna 2012). However, there exists only limited understanding and quantitative information regarding the location, rates and drivers of gully erosion within the GBR catchment, including within the Fitzroy catchment (Thorburn & Wilkinson 2012).

This point is highlighted by the lack of conclusive evidence as to the primary source of erosion within gullies themselves. The current consensus amongst the literature suggests that the majority of gully erosion occurs at headcuts rather than elsewhere in the gully (Wilkinson et al. 2013). However, the vast majority (90 to 98%) of gully erosion was previously thought to be sourced from gully walls (Krause et al. 2003). The uncertainty surrounding the primary sources of gully erosion therefore makes it difficult to effectively manage the loss of sediment. Moreover, many gullies initially grow very rapidly, expanding at the head and breadth to large dimensions, making effective control technically difficult or prohibitively expensive (Valentin et al. 2005; Desta & Adugna 2012).

Areas of high gully density tend to occur on sloping land, where variable climate results in seasonally depleted ground cover and with soils typically formed on granitic or sandstone parent material (Hughes et al. 2001). The removal of ground cover and topsoil on highly dispersive sodic soils has been found to be one of the major causes of gully expansion in Queensland's Burdekin Catchment (Bartley 2011). Similar findings have been reported in other parts of Australia, importantly these studies emphasise the significant role that ground cover and soil type play in episodes of gully erosion (Brooks et al. 2009; Ford et al. 1993; Olive & Walker 1982).

The effect of grazing on the gully erosion has been widely documented (Thorburn 2013; Desta & Adugna 2012; Trimble & Mendel 1995) and two primary mechanisms have been identified: the removal of ground cover and compacting the soil through trampling (Thorburn & Wilkinson 2012). Through these mechanisms grazing pressure upslope from gullies reduces impediments to the overland flow of water, restricting the time allowed for infiltration (McIvor et al. 1995). Grazing pressure also reduces the infiltration capacity of the soil in the long term (Thorburn & Wilkinson 2012) and the reduction of ground cover on gully walls has the potential to increase sheetwash and rill erosion from the walls (Thorburn & Wilkinson 2012). Lastly, grazing has the capacity to enhance the sediment transporting ability of gully channels by increasing the slope gradient of the gully and by reducing impediments to flow within the gully. This decreases the rate of sediment deposition on gully floors and increases net export of sediment from gullies (Thorburn & Wilkinson 2012).

The uncertainty surrounding the primary sources of gully erosion and their ability to initially grow very rapidly implies that preventing gully erosion should be the primary focus in ameliorating gully erosion (Kirkby & Bracken 2009; Desta & Adugna 2012), particularly as once gullies are established effective control can be technically difficult or prohibitively expensive (Bartley 2011). Similarly, repair work carried out in the early stages of gully formation is preferable to the far more costly and difficult repair work required when gully formation has gone unchecked. However, if the gully is relatively new it is likely that revegetation and stock exclusion may not be sufficiently effective so controls and engineering works may be required. If a gully has already formed then the first priority should be to correctly establish the cause of gullying and a case-specific approach to ameliorating the gully erosion should be undertaken.

The primary method for preventing the formation of gullies is establishing adequate ground cover to minimise run-off in vulnerable areas with highly erodible soils (Prosser & Slade 1994; Prosser & Dietrich 1995; Bartley 2011). In addition to increasing ground cover, engineering projects can also be effective in preventing gully formation by minimising the velocity of overland flows and run-off.

Once a gully is formed there are three primary processes which contribute to gully erosion (Thorburn & Wilkinson 2012):

1. run-off from upslope of gullies
2. cover on gully walls
3. the sediment transport capacity of gully channels.

All three processes are significantly affected by ground cover and as such rehabilitating or establishing adequate cover is often seen as the most effective method for treating erosion from established gullies (Thorburn & Wilkinson 2012). Stock exclusion through the fencing of vulnerable gully areas has been widely shown to improve ground cover (Desta & Adugna 2012; Valentin et al. 2005; Thorburn & Wilkinson 2012). However, limited quantitative evidence of this relationship exists and there is an obvious need for further studies, particularly within the GBR catchment (Thorburn & Wilkinson 2012).

In smaller and more stable gullies, shaping and filling can be effective measures, while in the event of severe gullying, earthworks may be required. Engineering works to control gullying include diversion of run-off from a gully head; construction of erosion-resistant rock chutes, which lower the slope of gully heads; and drop structures to dissipate the velocity of the water flow (Desta & Adugna 2012; Whitford et al. 2010). Stabilisation of the gully floor is also important, and may be achieved by establishing good ground cover to inhibit overland flow by reducing its velocity allowing more time for infiltration (McIvor et al. 1995).

In the Burdekin catchment, experiments showed that by combining check dams with grazing management in adjacent paddocks a large reduction in exported sediment from gullies occurred in subsequent years (Wilkinson et al. 2013). This result is consistent with several studies elsewhere including in the United States of America's south-west, where check dams, combined with good land management, resulted in greater than 90% reduction in sediment moving downstream (Thorburn & Wilkinson 2012; Heede 1979).

3.3.2. Hillslope erosion

Rangelands consist of relatively low-level soil fertility and poor soil structure, therefore when extreme weather patterns occur (drought or intense wet periods) Australia's rangelands are vulnerable to rapid deterioration (McIvor 2012). During the dry periods or when stocking rates are too high the pasture species deteriorate and there is increased bare ground. Rangelands are vulnerable to soil movement when heavy rain does occur; this soil movement eventually enters into waterways and is exported to the GBR lagoon in the case of the Fitzroy and Burdekin regions (Karfs et al. 2009).

Hill-slope erosion priorities should be focused towards improving the relative condition of ground cover in these vulnerable areas. This includes reducing grazing pressure, which is quantified by reductions in pasture utilisation rates or stocking rates (Thorburn & Wilkinson 2012; Karfs et al. 2009; McIvor et al. 1995). Wet season spelling, defined as resting an area for an eight-week period over the wet season also has been recommended as it allows pasture to grow in the peak period of growth time. The optimal utilisation rate for a given property is case-specific; however, there is significant evidence that reducing rates to a long -term equilibrium level can improve both pasture productivity and land condition (Ash et al. 2011; Orr et al. 2010; O'Reagain et al. 2009). As grazing pressure increases and land condition declines, the level of bare ground increases. This then makes the surface vulnerable to further degradation when summer-dominant rainfall occurs and the soil is suspended as sediment into waterways (Karfs et al. 2007). Land condition changes have often been explained as ecological responses to changes in pasture composition and animal production (Ash et al. 1995). Extreme pressure on rangeland resources through over-grazing has the potential to have severe consequences for these resources and their future productivity, both economically and ecologically (MacLeod & McIvor 2008). Inappropriate grazing strategies, particularly in response to climatic variability, has resulted in the depletion of native grasses and decline in land condition (MacLeod & McIvor 2007).

Land condition has been defined by the Grazing Land Management framework (Chilcott et al. 2005) as the capacity of land to respond to rain and produce useful forage and is a measure of how well the grazing ecosystem is functioning. The ABCD Land Condition Framework classifies land based on 3P grasses (perennial, palatable and productive), bare ground, weeds, soil condition and woodland thickening. A is classified as “best” through to the D “worst” condition. Land that has declined to D condition is described as requiring more than simple changes in grazing management and requires a large input of external energy to improve condition (Chilcott et al., 2005). The initial treatment necessary involves earthworks, re-seeding and de-stocking for extended periods of time (MacLeod and McIvor, 2008; Orr et al., 2006).

Recent studies have contributed to further understanding the key components in land degradation and management required to either regenerate land or mitigate degradation (Table 3). Although not all studies have been completed in the Fitzroy region, the studies in other catchments have similar rangeland characteristics.

Table 3. References for components in land degradation and management

Paper reference	Research design	Variables included	Research conclusions
Campbell et al. (2006)	Rangelands grazing strategy Bio-economic modelling	Environmental variability and predictability Degradation and land type resilience Property rights, discount rates and market stability and prices	A conservative stocking strategy is optimal to reduce degradation and environmental variation. Conservative stocking rates are optimal when there is high risk in rainfall and weather events. If there is prolonged drought (1 year or longer), stock fetch low prices due to the contributing factors of poor condition, market prices and high supply. Discounts rates and market stability both impacted on stocking strategy and the variation in economic return that can occur.
Orr et al. (2006)	Grazing trial Central Queensland	Stocking rate, burning, rainfall, black spear grass	Exclusion of stock for short periods of time (of up to 12 months), especially during winter and in years when rainfall is average or below, will not ensure pasture condition with perennial native species improves. Rainfall was a significant variable in pasture recovery.
Macleod & McIvor (2008)	Case study, Northern Australia, in monsoonal grasslands and subtropical woodlands	Riparian fencing, tree clearing and stocking rate	Riparian fencing for the monsoonal grassland case study had overall more public benefits (environmental benefits) than costs, although it was an expensive task for the landholder to undertake alone. Tree clearing resulted in large economic returns but there were also large negative environmental impacts.
O'Reagain (2009)	Grazing trial in Charters Towers	Stocking rates	Live weight gain in the heavy stocking rate enclosures was lower per head, and there were increased costs of drought feeding and management costs in years of low rainfall. Lighter stocking rate had good individual production performance and did not require drought feeding.
Orr et al. (2010)	Grazing trial, Central Queensland Black spear grass	Stocking rates, burning	30% pasture utilisation or 4 and 5 ha per steer was the sustainable pasture utilisation rate. Light spring burning also encouraged seed recruitment.
Scanlon et al. (2013)	Bio-economic modelling based on grazing trial in Charters Towers	Stocking rate, climate, profitability	Moderate stocking rate proved to be the most profitable over the 30-year time frame explored.

3.3.3. Streambank erosion

The main processes of streambank erosion are bank scouring and the mass failure of banks. The relative significance of each process varies within catchments and is affected by local factors such as soil type and land use (Abernethy & Rutherfurd 1998). Streambank erosion commonly results in channel widening and/or deepening, as well as the formation of flood chutes (shortcuts formed by rivers in the event of flooding). This highlights the relative significance of streambank erosion within Australia. The National Land and Water Resources Audit in 2001 reported that more than 120,000km of riparian vegetation along eastern Australia's streams and rivers has been classed as degraded and requiring rehabilitation (National Land and Water Resources Audit 2001). Current evidence also indicates that many Australian rivers have doubled in width since European settlement (Rutherford 2000).

Evidence suggests that streambank erosion is most pronounced in high velocity rivers (Wilkinson et al. 2005; Hateley et al. 2007; Marston et al. 2001) however, extreme rainfall events causing flooding can also result in extensive damage to streambanks and the riparian zone (Ryan 2013). Flood events have been attributed to the removal of ground cover and bank slumping, which typically occurs when saturated streambanks collapse under their own weight (Ryan 2013), as well as the extensive scouring of streambanks and adjacent floodplains (Croke et al. 2012). Further impacts of streambank incision also include increased flow velocity, reduced flow to adjacent floodplains and increased size and velocity of peak discharges in downstream areas (Olley & Wasson 2003).

The relationship between riparian vegetation and streambank erosion has been widely reported (Trimble & Mendel 1995; Thorburn & Wilkinson 2012), with recent evidence indicating that that average streambank erosion rates with established riparian vegetation can be 85% lower than streambanks without riparian vegetation (Bartley et al. 2008). Consequently, grazing can have a pronounced effect on streambank erosion (Trimble & Mendel 1995). As with gully erosion, grazing pressure in vulnerable areas increases the potential for erosion by reducing ground cover and exposing more vulnerable substrate. Trampling from livestock also affects streambank stability and directly causes streambank erosion (Trimble & Mendel 1995; Thorburn & Wilkinson 2012).

Similar to gully erosion, limiting stock access to streambanks and improving riparian ground cover are the primary factors that can be managed to reduce streambank erosion in grazing lands (Thorburn & Wilkinson 2012). The simplest means of slowing the rate of streambank erosion is to maintain and increase ground cover of trees, shrubs and grasses in the riparian zone. Preventing stock access to waterways by fencing off rivers and streams is an effective means of achieving this (Thorburn & Wilkinson 2012; Trimble & Mendel 1995). The nature of the riparian restoration site (including width, length and placement in the landscape) should be targeted to consider the specific causes and types of streambank erosion (Abernethy & Rutherfurd 1998). Similarly the nature of the surrounding landscape, including land use, as well as the available nutrient and their potential for re-establishment must be considered (Burger et al. 2010).

Reduction of stream flow velocity, particularly during flood events, is also an important aspect of streambank erosion control and can be achieved by improving the extent of riparian vegetation, as well as by retaining in-stream woody debris (Hubble et al. 2010). In particular, the reinforcement of streambank soils by tree roots significantly reduces the likelihood of erosion through bank failure (Abernethy & Rutherfurd 2000; Hubble et al. 2010).

4. Are there private benefits of adopting grazing management practices?

4.1. Stocking rates, ground cover monitoring and land condition

Adequate pasture management includes, for example, adequate stocking rate according to the site-specific land condition (reduced grazing pressure) and wet season spelling. It is important that pastures are maintained in a healthy condition, particularly during seasonal change from wet to dry seasons. This is vital to ensure that during dry periods, when pastures naturally deteriorate, bare ground condition is prevented as this leads to soil movement and hence sediment transportation when the rain period sets in (Karfs et al., 2009).

Given the complexity of rangeland grazing systems, there are a number of contributing factors, along with grazing pressure, that may affect the cost of sediment reductions. To estimate the costs of changing production systems for environmental benefits, a bio-economic model integrates biophysical and economic components. This economic link makes available the connection between the production system and its environmental impact (Cacho 1997). Bio-economic modelling was devised to explain and predict cause-and-effect relationships in ecosystems and then determine associated economic effects (Bennett 2005a). The challenge of linking the cost of changing production systems with environmental changes, which are encompassed in different biological processes and ecological systems is complex. Broadly, these can be grouped into the interrelated characteristics of land type, location and starting condition (Figure 2).

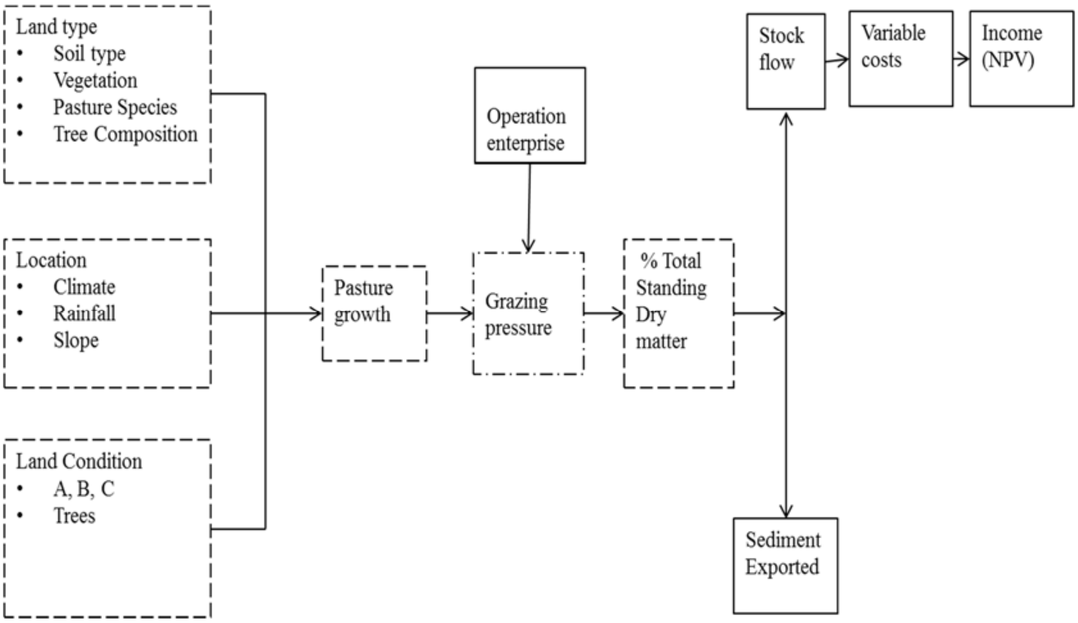

Figure 4. Components, both biophysical and economic, that have gone into the bio-economic model.

The net private benefits of various pasture utilisation rates and in A, B or C land condition for each land type was modelled (Table 2). The bio-economic modelling approach allowed a better understanding of the impacts that changes in land management practices would have on business profitability, land condition and sediment exported to the GBR. For each land type, the cost of reducing sediment loss was calculated, which allows for identification of the lowest cost options for reducing sediment loss from the modelled land types. In addition, for some of the land types, additional work has been undertaken to develop strategies to restore degraded land condition (Star & Donaghy 2010; Star et al. 2011; Edwards & Star 2013).

Table 4.Production changes for shifting from C to B and B to A at the economically optimal point

	Pasture Utilisation (%Total Standing Dry Matter)											
Actual AE's for 5,000ha	15	20	25	30	35	40	45	50	55	60	65	70
A Condition	706	914	1,110	1,294	1,468	1,639	1,791	1,915	1,895	1,791	1,772	1,805
B Condition	700	907	1,099	1,276	1,404	1,513	1,639	1,677	1,552	1,539	1,551	1,591
C condition	664	846	1,000	1,048	976	1,047	1,126	1,173	1,217	1,286	1,354	1,425

The reports have demonstrated that more productive land types such as Coolibah Floodplains and Brigalow Blackbutt produce higher levels of income and relatively low sediment exported, which makes further reductions per tonne of sediment exported expensive. On the other hand, less productive land types such as Narrow-leaved Ironbark Woodlands and Narrow-leaved Ironbark Ranges generate low income and relatively high sediment exported, which makes reductions per tonne of sediment exported relatively cheap.

The starting land condition also impacts on the cost of reducing sediment exported. More degraded land presents a relatively cheap way to reduce sediment exported compared to land currently in A or B condition. This is because the profitability of cattle production is lower at all pasture utilisation rates for poorer condition country and hence this results in a lower cost to reduce a tonne of sediment (Figure 3).

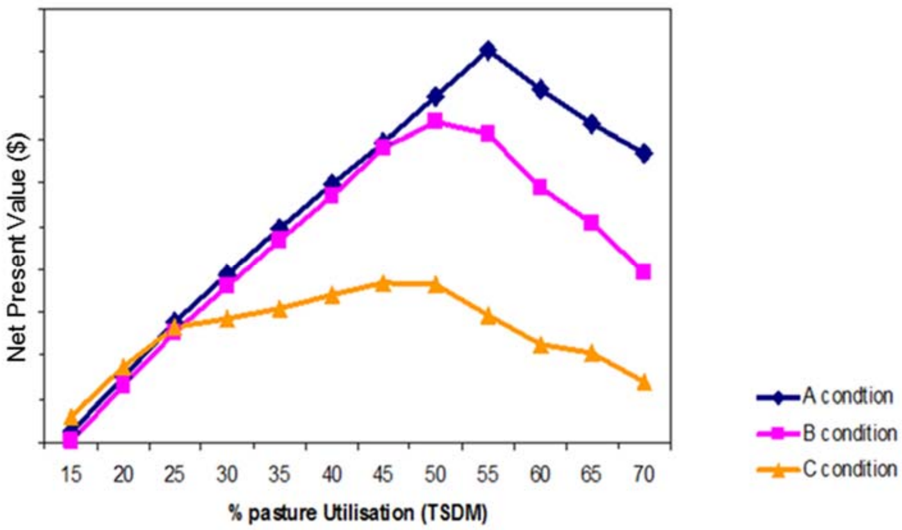

Figure 5. Trade-offs for different start condition for a productive land type, Brigalow Blackbutt

In pastures or land types with trees, the productivity of grazing enterprises is lower as the trees compete with pasture species for nutrients and water. So, trees also impact on the cost of reducing sediment exported, with more treed areas providing cheaper reductions in sediment exported.

Overall, the most cost-effective methods of reducing sediment export need to take land type, land condition, and tree basal area into consideration, as all are important determinants of the cost of reducing sediment reaching the GBR. The range varies considerably making this a critical factor when assessing the overall costs of sediment reductions.

These same three factors also impact on the economic viability of regenerating land. It is generally more profitable to regenerate land in C condition than land in D condition, as the effort required and cost of regeneration is significantly higher when land is more degraded. For more productive land types, the accumulated private benefit of land regeneration can be sufficient to cover the cost of the regeneration, and can sometimes offer substantial returns over a relatively short timeframe. For these landholders, targeted extension will achieve improvements in land condition, and associated reduction in sediment exported. However, for country that is inherently less productive (eg. Narrow-leaved Ironbark), there are insufficient private benefits for these landholders to undertake land regeneration. Incentive payments should be considered for landholders that are operating in less productive land types, as regeneration of these land types is critical to reducing sediment exports. Significant reductions in sediment movement could be achieved through incentives to landholders not to graze these land types.

In addition, for any landholders who are operating at levels higher than the optimal pasture utilisation rate, targeted extension is recommended as an inexpensive method for encouraging graziers to reduce their utilisation rate to a level that is more financially beneficial to them and results in a decrease in the amount of sediment exported.

The productivity of the land type is a key parameter in the cost of sediment reduction, as it influences the types of enterprise that can be operated on the particular land type, as well as relating soil type and slope, key factors driving sediment movement. The combination of enterprise, soil and slope result in variations in costs per tonne of sediment reduced. Land types with a lower inherent productivity only have the capacity to operate lower value enterprises, are situated on poorer soils that are more susceptible to soil run-off, and often have a greater degree of slope. Conversely, land types with higher inherent productivity tend to have more profitable enterprises and lower levels of sediment moment.

4.2. Economic Implications

4.2.1. Private benefit and social cost

Sediment and nutrient run-off that result from poor land management practices create a negative externality for the GBR (off-site costs) over time. A negative externality affects someone or something who or that is not directly involved in the production or consumption of a good or services. In the context of this study, sediment- and nutrient-rich run-off is produced by management practices on private land, which has a negative impact on the health of the GRB and thus produces a significant social cost. Private landholders do not bear the costs of their land management practices nor are there potentially any private benefits; however, they impact on the health of the reef and market mechanisms to provide an incentive for reduction in sediment and nutrient rich run-off do not exist. Therefore, there is a role for the government to intervene and to encourage a change in the behaviour of the private land management practices.

There are three aspects to costs to consider: the initial capital cost of implementing change (e.g. fencing and earthworks), the opportunity cost for the landholder to not graze or allow access to stock to particular areas, and the cost to maintain the infrastructure and ensure that over time an outcome is achieved. Documented trial sites in the Fitzroy Basin are limited (e.g., Bartley et al., 2010b; Shellberg, 2011; Wilkinson et al., 2015). Hence, there is only limited information available about best long-term management practices for different spatial scales and locations. A major reason for the limited experience with gully rehabilitation practices in Australia may be the costs involved in soil erosion management.

Previous work in land regeneration under the Paddock to Reef and Reef Rescue programs highlighted the heterogeneity of costs that exist in not only the capital cost suitable for regeneration but also the time period and maintenance to ensure that the land regeneration is achieved. This is based by the underpinning land type and its inherent productivity. Critical aspects for cost considerations included opportunity costs were the cheaper costs relative to infrastructure, with variance obviously existing regarding the land type.

There are a number of previous studies that assessed on-farm and off-farm cost of soil erosion in other regions of the world (Pimentel et al., 1995; Telles et al., 2011; Yitbarek et al., 2012). However, full costs of soil remediation have not yet been assessed in the literature. Consequently, there is a need to identify cost components and to develop a functional form that could be universally applied to different soil erosion settings. Furthermore, cost values for the respective cost components need to be collected in order to value soil management activities over time.

The potentially high soil management costs are the major reason why a prioritisation of areas within the Fitzroy Basin needs to be undertaken. Previous studies (McCosker 2009) have shown that the production margin from cattle grazing in the Fitzroy Basin is only 2%, hence, high capital investment required for changes in land management practices may limit landholders' financial engagement in soil erosion management. Given that private and public funds to undertake soil management to stabilise sediment rates that enter the GBR are limited, the available funds need to be directed towards the areas that are most cost effective in the reduction of sediment loads.

4.2.2. Private costs

Changes in land management practices may come at significant costs. While on-ground benefits to landholders (here mostly graziers) from management changes to improve water quality may only be minor, e.g. improvements in pasture yield (short term) and less soil erosion (long term), their (short term) opportunity costs, e.g., lower stocking rates or stock exclusion on buffer areas of affected sites, coupled with high capital and maintenance costs, may likely outweigh the benefits. These are some reasons why soil conservation adoption rates by landholders are generally low in the reef catchments and worldwide (DeGraff, 1980; Kuhlman et al., 2010; Rolfe and Gregg, 2015; Valentin et al., 2005). Pannell et al. (2006) provides a list of factors that affect the adoption of conservation practices by landholders, which include, for example, awareness of the problem, perception of risk, demographics, costs and impacts of profits and links between landholders.

This highlights that financial incentives and extension work (e.g., awareness raising, to some extent changing perception, ongoing scientific advice on land management) may be required to encourage landholders to participate in soil management (Valentin et al., 2005). This can be dealt with by either designing policies or programs that provide landholders with incentives to change their land use practices or public investment on private land may be considered to achieve the sediment reduction target outlined in the Reef Plan. Yet, expectations regarding extension and financial incentives should be kept at a realistic level as proposed changes to land management need to be in line with the land user's goals (Pannell et al., 2006). Furthermore, an issue for extension is that it does not have automatic legitimacy and credibility — these have to be earned (Pannell et al., 2006). This highlights that policies to improve soil management have social components that need to be dealt with appropriately and cost effectively.

4.3. Scalds, streambank and gully management

There are three aspects to remediation costs for gullies and streambank to be considered. This includes the initial capital cost of implementing change (e.g., fencing and earthworks), the opportunity cost for the landholder to not graze or allow access to stock to particular areas and the cost to maintain the infrastructure and ensure that over time an outcome is achieved. Documented trial sites for gully and streambank erosion management in the Fitzroy are limited (e.g. Lewis et al. 2013; Shellberg 2011; Wilkinson et al. 2015). Hence, there is only limited information available about best long-term management practices for different spatial scales and locations.

Previous work in land regeneration under the Paddock to Reef and Reef Rescue programs highlighted the heterogeneity of costs that exist in not only the capital cost suitable for regeneration but also the time period and maintenance to ensure that the land regeneration is achieved (Table 5). This is based by the underpinning land type and its inherent productivity. The high capital costs of completing gully and streambank projects is an impediment to landholders. This is due to the limited private benefits to gain relative to the capital costs associated with the project. It is these types of projects that will require more than incentives to landholders in order to achieve outcomes.

Table 5. Capital costs for remediation

Treatment	Total ($)	Price ($)	Units/ha
Fencing	5000	5000	1
Troughs	2000	2000	1
Tank	5000	5000	1
Poly Pipe	5000	5000	1
Contour bank/woa boy	800	4	200
Diversion bank	800	4	200
Seeding	75	74.85	1
Deep ripping	150	150	1
Chisel ploughing	100	100	1
Crocodile seeding	40	40	1

The potentially high soil erosion management costs are the major reason why prioritising areas within the Fitzroy catchment need to be undertaken. Previous studies (McCosker 2009) have shown that the production margin from cattle grazing in the Fitzroy Basin is only 2%, hence, high capital investment required for changes in land management practices may limit landholders financial engagement in soil erosion management. Given that private and public funds to undertake soil erosion management to stabilise sediment rates that enter the GBR are limited, the available funds need to be directed towards the areas that are most cost effective in the reduction of sediment loads.

4.4. Risk and uncertainty

The experience with rural landholders is that there is no one approach to fostering on-ground practice change to improve water quality, rather it needs to be a tailored, multi-faceted approach (Pannell et al. 2006). It is also known that setting correct long-term stocking rates, wet season spelling, forage budgeting, and protecting vulnerable areas are critical to achieving and maintaining sound land management outcomes (Rolfe & Gregg 2013).

Management practices and projects to improve water quality have complex and uncertain economic and environmental outcomes, as it involves reductions in grazing pressure but offsetting improvements in pasture quality and land condition over time (Rolfe & Gregg 2013). Predicting the consequences of management changes at the enterprise level is difficult, and typically requires detailed knowledge of both enterprise and biophysical characteristics (Pannell and Roberts, 2010).

Economic analysis of grazing operations has shown that there are long-term private benefits generated from shifting to B level management practices (Ash et al., 1995); McIvor & Monypenny 1995; O'Reagain et al. 2011; Star et al. 2013a). Particularly, over the long term as major land degradation events tend to occur during drought periods there are economic benefits of maintaining lower stocking rates or reductions in utilisation rates (Landsberg et al. 1998; O'Reagain et al. 2011). Given that over-grazing leads to private losses in the longer term, an important research question is to identify why many landholders do not voluntarily reduce long-term grazing pressure and what is the most effective policy to achieve sustainable grazing systems.

Although the grazing management practice framework has been developed and targets were set for practice change, achieving the pollutant reduction targets remains difficult when attempting to encourage practice changes by private land managers. A key aspect of achieving increased adoption is improving an understanding of the relative profitability over the long term regarding the specified practices. Past research completed over a number of land types has explored the trade-offs between grazing pressure, profit and sediment, highlighting the heterogeneity between land types, land condition and impact of trees on profit and subsequent sediment exported (Star, Donaghy et al. 2010; Star, et al. 2012). However, key challenges in the targeting of resources for improved rangelands grazing management are to understand how the private benefits associated with changing grazing management practices may be sensitive to climate patterns over time. Understanding how private net returns may interact with issues of risk and uncertainty may provide insights into efficient policy delivery and targeting of resources.

The difficulty in applying the current natural resource management frameworks when there is uncertainty and dynamic variation in the private benefits of changing landholder management practices. It also provides insights into why offering a bundle of practices to adopt may reduce the uncertainty and variability in private benefits and costs and therefore allow for further flexibility and ability to make dynamic changes (Figure 4).

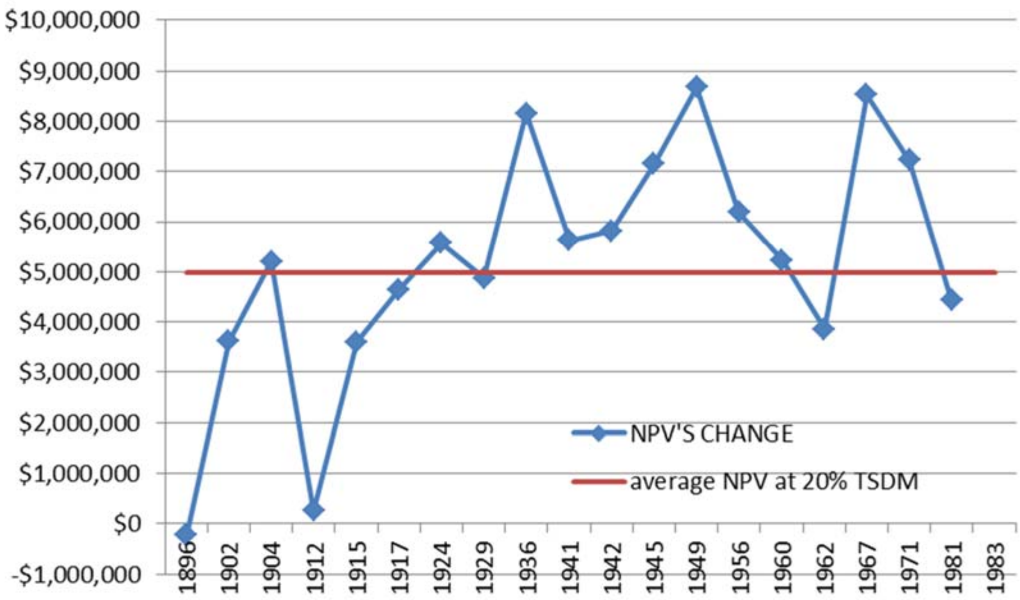

Figure 6. The trade-off between profits and sediment for Brigalow Blackbutt land type at Blackwater

The more optimistic landholders are in regards to future weather patterns, the more likely they are to perceive that practice change will generate net private returns. This helps to explain the link between attitudes and increased rates of adoption identified by researchers such as Greiner et al. (2009) and Greiner & Gregg (2011). The current approach of Grazing BMP through allowing people to consider where they are in relation to the rest of the industry creates a flexible opportunity for the various policy mechanisms to be considered. It would also indicate that landholders who are more optimistic about future weather patterns are more likely to adopt than those who are not.

Improved long-term information regarding the future climate sequence and the production implications for the particular spatial location of interest will allow better predictions of the private benefits available from practice change as currently different management practices can be varied across the NRM framework based off seasonal variation alone (Figure 5). The ability to provide quality extension and development is critical in supporting the adoption of a group of practices to mitigate the risk and uncertainty.

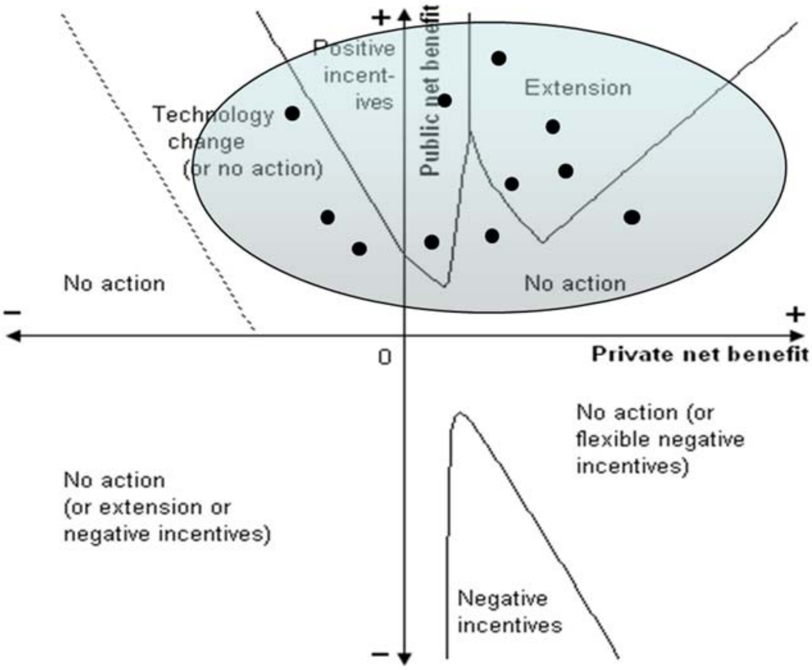

Figure 7. Range of private benefits and costs for any one landholder at different points in time on the natural resource management framework.

The key limitations of the natural resource management framework is it assumes that the public and private trade-offs are understood, and are homogenous across different enterprises, locations and management practices (Figure 5). It also does not account for time required to shift to a new overall environmental position. It provides a static-state analysis for policymakers; however, it does not fully consider the landholder perspective, which is key in selecting the correct mechanism improving adoption.

5. Are there private benefits of adopting grains soil management practices?

The area used by the grain cropping industry of Queensland has increased significantly since the 1950s, with a four-fold increase in area between 1950 and 2000 (Carey, Leach & Venz 2004). This expansion in area involved clearing of native vegetation on both hillslopes and flatter floodplain areas. In the Fitzroy Basin approximately 84% of the cropped soils are self-mulching, black, cracking clay vertisol soils (Murphy et al. 2013). A study comparing brigalow forest (*Acacia harpophylla*) to brigalow land cleared for cropping led to an increase in annual rainfall run-off from 5% to 11%, while also increasing the frequency of run-off events, the mean peak rate of storm run-off and time to run-off commencement (Cowie, Thornton & Radford 2007). The use of mechanical cultivation on cropping soils has led to issues of compaction, reduced infiltration, and soil loss. Silburn, Robinson & Freebairn (2007) note that soil physical and chemical degradation associated with cropping occurs slowly, but insidiously, with the effects potentially hidden by variability in climatic and economic cycles. Mathers, Nash & Gangaiya (2007) discuss how soil surface crusting or sealing can occur with cultivation on most soils, which then restricts water infiltration. In addition, many poorer soils have intrinsically low infiltration rates and lose a high proportion of rainfall as run-off (Silburn, Robinson & Freebairn 2007).

The grain cropping industry of Queensland has created a set of best management practices (BMPs) designed to minimise the off-site environmental impacts of cropping. In addition, the range of management practices has been categorised into an ABCD framework, with D class representing outdated practices (deemed unacceptable in terms of the water quality outcomes), C class representing common practice, B class representing best management practices, and A class representing aspirational practices. Landholders will implement a collection of practices suited (and unique) to the needs and constraints of their property that may fall across a few different management practice classes; however overall, the ABCD framework identifies major differences in management systems that have an impact on water quality leaving a paddock (Shaw et al. 2013). The grain ABCD management practice framework is shown below in Table 6.

Table 6. A,B,C,D management framework for grains and the various parameters for each classification.

	Till	Traffic	Erosion control	Crop rotation	Pesticides application	Pesticides management	Nutrients	Overlap% - nutrients/ pesticides
D	Cultivation	Random wheel traffic	No contour banks/sediment dams	Sorghum Wheat Chickpea	Inability to control weeds in inter-row without cultivation	Broadacre spray for weeds	None	26
C	Minimum till	Partially matched wheel traffic	Some contour banks/sediment trapping	Sorghum Wheat Chickpea	Hooded sprayers for weed control	Broadacre spray for weeds	Pre-plant	11
B	Zero till	Partially matched wheel traffic	Some contour banks/sediment trapping	Sorghum Wheat Chickpea Mungbean Sunflower	Hooded sprayers for weed control	Broadacre spray for weeds	Split	7
A	Zero till	Full controlled traffic	Adequate contour banks constructed	Sorghum Wheat Chickpea Mungbean Sunflower Maize	Hooded sprayers for weed control	Broadacre spray for weeds	Split	2

Some of the practices in this ABCD framework have had significant research undertaken to validate them, while for others there remains little trial data to conclusively determine their effectiveness at reducing sediment, nutrient and herbicide/pesticide run-off at the paddock scale. There has been limited economic data collected in the Central Queensland grain growing region.

Shaw et al. (2013) used agricultural systems models to predict changes resulting from improved management systems (based on the ABCD management practice framework) on pollutants exported at the paddock scale, then used this information in a catchment-scale modelling project. They found that there are considerable differences in the magnitude of sediment loss between management classes, but also differences for one management class spatially across different soils within the Fitzroy Basin (Shaw et al. 2013). They concluded that linking detailed paddock models with a catchment-scale model provides an effective approach for assessing impacts of the adoption of improved land management practices. Freebairn, Cutajar & Thornton (2014) used HowLeaky? to model differences in run-off, deep drainage, soil loss, and nutrient and pesticide losses. Their modelling showed that if a farm moves from all D class practices to all C class practices, there is a slight reduction in water run-off, but sediment and phosphorous losses are reduced more than three-fold. They also model further improvements in water quality indicators with adoption of B and A class management practices.

5.1. Contour banks/sediment trapping

Contour banks have been used in dryland farming for a long time, and are designed to withstand run-off from specific return periods for rainfall events. Contour banks are the most common practice implemented to reduce erosion since erosion was recognised as a serious issue across all Queensland cropping regions in the 1930s (Murphy et al. 2013). Murphy et al. (2013) reports on a nine- year Central Queensland (Capella) study of sediment movement in run-off from grains dryland cropping with differing distances (slope length) between contour banks. All contour bays were farmed under a zero tilled–controlled traffic farming system (Murphy et al. 2013). In addition the study measured the nutrient and herbicide movement in run-off from a sorghum (*Sorghum bicolour*) crop for a single wet season (Murphy et al. 2013). This study found that the standard use of contour banks (spaced 180m apart) produced 40% less soil loss than triple-spaced contour banks (540m apart) over the nine-year trial. This provides justification that standard spaced contour banks are still a valuable management tool in dryland cropping zero-till controlled traffic farming systems for reducing soil loss compared to contour bank placement with longer slope lengths (Murphy et al. 2013).

In one wet season with conditions conducive to run-off, double- and triple-spaced slope lengths produced 67% and 57% more unit soil loss per hectare respectively, than the standard single-spaced slope length (Murphy et al. 2013). From the single year’s data on nutrient and herbicide movement in the run-off, Murphy et al. (2013) discovered that nitrogen run-off from cropping land with double-spaced contour banks (360m apart) was approximately 20% of the total nitrogen applied at planting, without taking into account any nitrogen losses through other means. This finding was much higher than other studies that quantified fertiliser run-off in the Burdekin Basin, the Burnett-Mary catchment and in Texas, United States of America (Murphy et al. 2013). Murphy et al. (2013) concludes that while the current grain BMPs are effective at reducing soil loss, high concentrations of nutrient and herbicides can still be moved off-farm in run-off, and further research is required to develop new BMPs that reduce this nutrient and herbicide movement. Run-off of nutrients and herbicides that are more sediment-bound (such as diuron) will be more reduced through minimisation of sediment run-off than for nutrients and herbicides transported more in a dissolved form.

Silburn & Glanville (2002) note that in addition to improved management within the field through increasing cover and using controlled traffic, sediment in run-off can be managed through the use of tail-drains, vegetative filters and silt traps to reduce the velocity of run-off, allowing more time for sediment to deposit before entering waterways. Cogle et al. (2011) also advocate for the use of structural mechanisms such as contour banks, as well as minimising the length of time with low soil cover to maintain sustainable production systems.

Contour banks are relatively low cost in achieving sediment outcomes. Although there are marginal private benefits, there are significant public benefits through achieving significant sediment reductions. Hill-slope erosion in cropping can be as much as four times higher than in the grazing situations and therefore provides an opportunity to offer incentives for grain growers to implement contour banks.

5.2. Tillage

Conventional tillage is usually to a depth of around 20-30cm (Mathers, Nash & Gangaiya 2007) and usually consists of bare fallow periods with frequent tillage (Tullberg, Ziebarth & Li 2001). Conservation tillage is associated with a variety of systems that provide greater soil protection, including minimum tillage (using a mixture of herbicide and mechanical weed control) and zero tillage, where soil disturbance only occurs at planting (Tullberg, Ziebarth & Li 2001). A survey of grain growers in 2008 indicated that 72% of growers in southern Queensland used no-tillage, although only on approximately 75% of their cropping area (Llewellyn, D'Emden & Kuehne 2012). These growers indicated that soil moisture management was their primary reason for adopting no-tillage, with reducing fuel and labour costs and soil conservation ranking as lower reasons (Llewellyn, D'Emden & Kuehne 2012). Central Queensland was not included in this survey.

Tullberg, Ziebarth & Li (2001) undertook a trial on a self-mulching alluvial black earth near Gatton in southern Queensland to investigate traffic and tillage effects on run-off and crop performance over a period of four years. Their results demonstrate that the mean difference in run-off between zero tillage and conventional tillage (over all years and traffic treatments) is 38 mm/year. The mean difference in run-off associated with traffic is discussed below, but the authors note that traffic and tillage effects on run-off are additive (Tullberg, Ziebarth & Li 2001).

Li et al. (2008) suggest there is still a lack of understanding of the long-term effect of the combination of controlled traffic and zero tillage practices. The Li et al. (2008) modelling suggests that zero tillage results in less run-off and reduced soil loss than when tillage was used for weed control, regardless of whether controlled or conventional traffic was practised (Li et al. 2008). When controlled traffic and zero tillage practices were combined, the results showed even lower levels of annual run-off and soil loss (Li et al. 2008).

Zero tillage requires shifting to further pesticide use to control weeds through the use of hooded sprayers.

5.3. Traffic

Soil compaction from farm machinery lowers soil hydraulic conductivity and encourages run-off across the soil surface (Mathers, Nash & Gangaiya 2007). Mechanically induced compaction reduces the time to ponding, the infiltration rate, and total infiltration compared to non-wheeled soil, with or without crop residue cover (Li et al 2008). Li et al. (2008) used PERFECT to model run-off under different combinations of tillage and traffic. Their results showed substantially reduced run-off and soil loss under controlled traffic than under conventional traffic, and also increased median crop yield by between 12% and 28% (Li et al. 2008). The reduced run-off and soil loss results were consistent for a continuous wheat cropping cycle, a continuous sorghum cropping cycle, or an opportunity cropping system where a second crop is planted in the year if there is sufficient water stored in the soil (Li et al. 2008). Controlled traffic actually enables opportunity cropping, through improved rainfall infiltration and increased water storage in the soil profile, which allows greater crop intensity compared to conventional wheel traffic (Li et al. 2008).

The Tullberg, Ziebarth & Li (2001) trial described in the tillage section investigated both traffic and tillage effects on run-off. They demonstrate the substantial impact of both traffic and tillage, and note that wheeled soil had significant increases in run-off, compared with controlled traffic soil. They demonstrate a mean difference in run-off between wheeled traffic blocks and controlled traffic blocks (over all years and tillage treatments) of 63 mm/year. The difference between conventional tillage and zero tillage was discussed previously. Overall, the mean difference in run-off between conventional practice (wheeled stubble mulch tillage) and optimal practice (controlled traffic–zero tillage) is greater than 100 mm/year, suggesting that traffic and tillage effects on run-off are additive, and the traffic effect is large enough to have a substantial influence on peak run-off and soil erosion (Tullberg, Ziebarth & Li 2001).

Silburn & Glanville (2002) used a simulated rainfall trial to measure run-off, soil loss and sediment concentration from a well-aggregated black vertisol under cotton in Central Queensland. They found that run-off, soil loss, and sediment concentration all decreased with increasing groundcover. Blocks with controlled wheel traffic but no cover reduced run-off by only 4.5 mm than fully trafficked blocks, as surface sealing on bare blocks restricts infiltration. However, when controlled traffic is combined with retained 50% groundcover, 44mm of rain was required before run-off from compacted wheel tracks and 65mm rain before run-off from the beds. This can be compared to conventionally trafficked bare blocks where run-off occurred after only 26mm of rain. The same cotton trial site was also used to measure herbicide and pesticide transport in run-off (Silburn, Simpson & Hargreaves 2002). Herbicide (trifluralin) concentration in run-off was on average 48% lower from controlled traffic blocks compared to conventionally trafficked blocks. The study found that retention of crop residues to provide groundcover gave considerably lower concentrations and total losses of pesticides during run-off events, and this benefit was further enhanced with controlled traffic, although the pesticides measured are relevant to cotton and not for grain crops.

6. State of spatial and bio-physical knowledge

A number of paddock-scale experiments have been conducted in the Fitzroy Basin to quantify and manage the impact of agriculture on run-off and erosion (Douglas et al., 2006a, b; 2008; Smith and Dragovich, 2008). Larger catchment-scale monitoring and modelling has also been undertaken to estimate sediment loads and sources, many of which have focused on the Fitzroy and its sub-catchments (Dougall et al., 2008; Hughes et al., 2009; Joo et al., 2005; Packett et al., 2009).

Recent work by Dougall et al. (2008) and Hughes et al. (2009) has indicated that the majority of the suspended sediment is likely to be generated from less than 30% of the Fitzroy catchment. Dougall et al. (2008) employed SedNet/Annex catchment modelling, while Hughes et al. (2009) utilised geochemical and radionuclide tracing of sediment in Theresa Creek. Importantly, these two differing methodologies found significant agreement that the dominant spatial source of suspended sediment was likely to be the Comet sub-catchment.

Supporting these results Joo et al. (2005) used measured total suspended solids concentrations from the six sub-basins in the Fitzroy to develop sediment rating curves. These rating curves combined with stream-flow data were used to estimate long-term mean annual sediment load of the Fitzroy and its main tributaries for a common 30-year period (1974-2003). Joo et al. (2005) estimated that the majority of the sediment load in the Fitzroy is derived from the Nogoa and Comet sub-catchments, and for a given level of run-off average sediment concentration was highest for the Nogoa and Comet sub-catchments, and the lowest for the Isaac. Packett et al. (2009) used 11 years of floodwater samples to determine representative concentration and total pollutant loads across the Fitzroy sub-catchments. These authors found that during flood events both the northern Nogoa and the Comet sub-catchments contribute high event mean concentrations (EMCs) of sediments. Packett et al. (2009) also found evidence that the Connors River system consistently produced the lowest concentrations of pollutants despite receiving the largest volume of water over their study period. In contrast, flood events from the neighbouring Isaac catchment were found to be comparably short-lived but had the potential to contribute relatively high EMCs. The large Dawson sub-catchment produced few moderate flood events during this study., Of these, the 2003 event contributed both high discharge volumes and high EMC values; and the minor event in 2006 also produced high EMC values relative to other years (Packett et al., 2009).

The results of these four studies are summarised below in Figure 6 These studies highlight that the major sources of sediment to the GBR from the Fitzroy catchment are likely to be from the Nogoa and Comet sub-catchments. The Dawson sub-catchment also appears to be a significant contributor to the total exported sediment loads reaching the GBR; however, the priority areas for FBA should primarily be located within the Nogoa and Comet sub-catchments. The above studies also indicate that the Isaac sub-catchment in the northern region of the Fitzroy catchment contributes the least amount of sediment exported to the Great Barrier Reef and as such reducing sediment losses from within the Isaac sub-catchment should be a relatively lower priority. Importantly however, the potential for sediment to originate from a sub-catchment is primarily driven by the prevalent soils types within that region; this is discussed further in the following section.

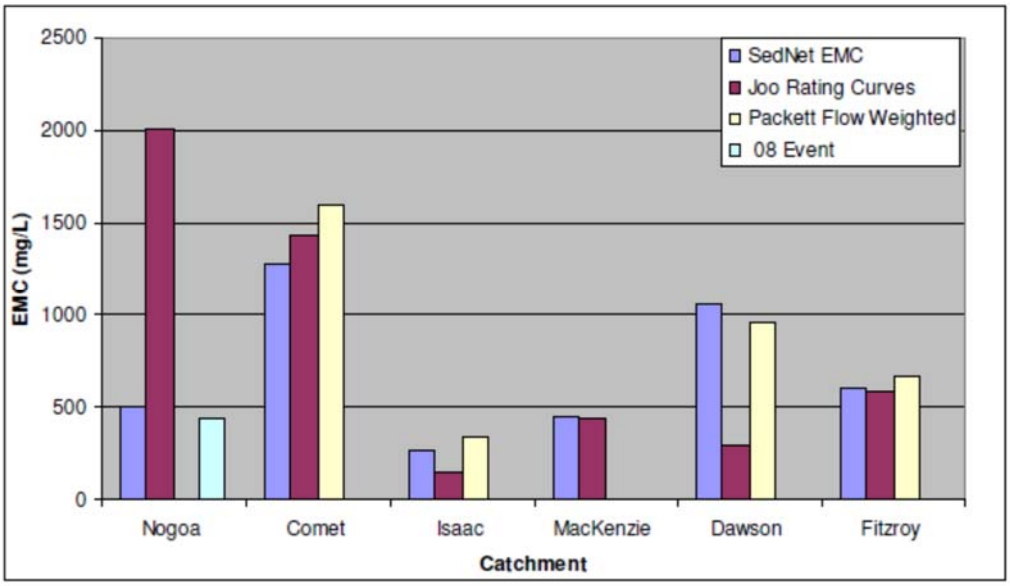

Figure 8. Fitzroy sub-catchment event mean concentrations Source: Dougall et al. (2008)

While there is significant evidence indicating significant differences in the potential to contribute to sediment losses between the Fitzroy's sub-catchments, these differences are driven primarily by the region's prevailing soil types, which relates to the major geological basins that lie within the Fitzroy and its sub-catchments.

In a multi-disciplinary geochemical study Douglas et al. (2006a) identified the relative contribution of soils to the Fitzroy catchment using the properties of sediments collected from dams, weir pools and flood deposits. The results from this study indicated that a substantial proportion of the sediment deposited in the Fitzroy region's impoundments are derived from non-basaltic sources typical of the Thomson Fold Belt. These soils are typically found in the western region of the Fitzroy, and are delivered primarily by the Nogoa River (Figure 6).

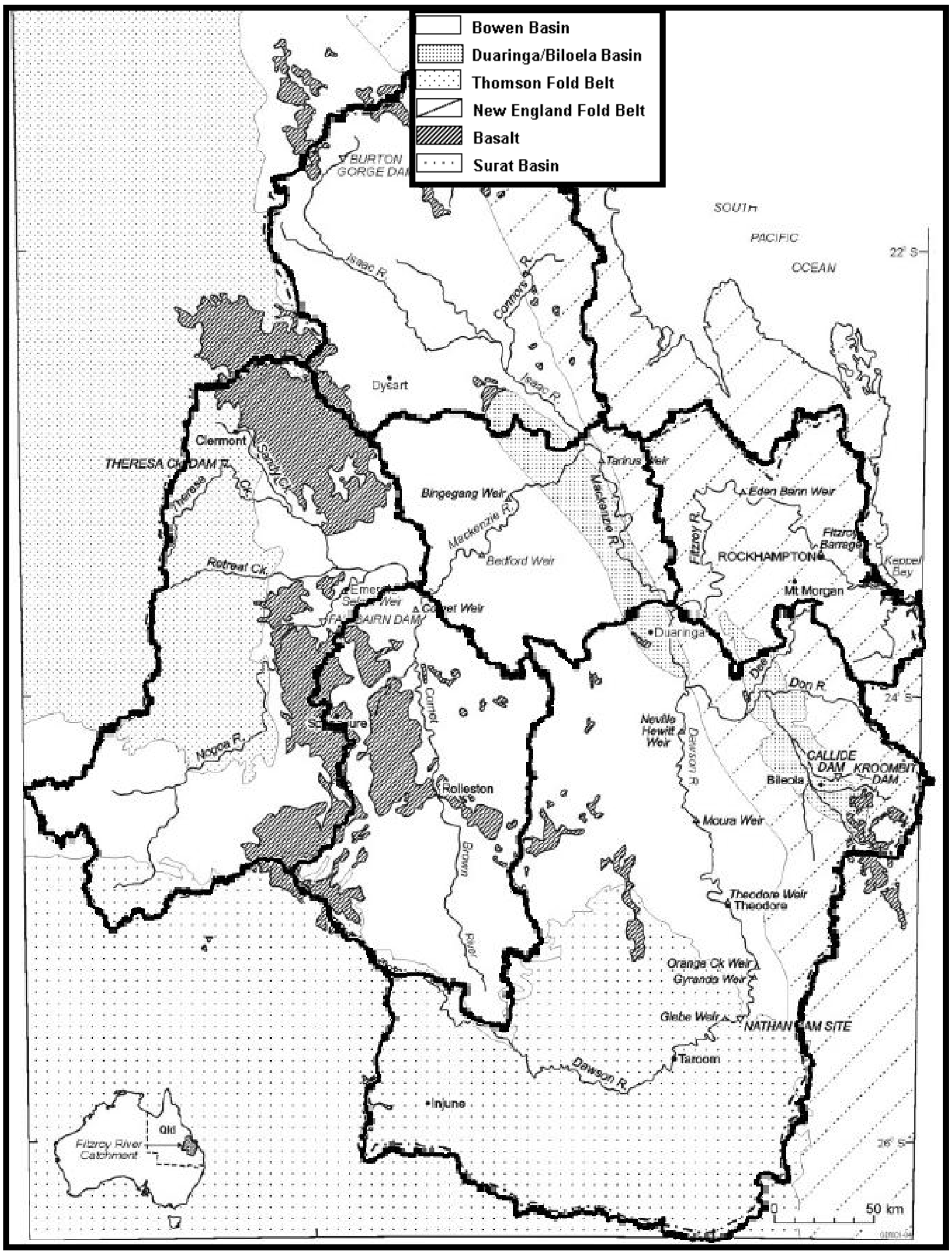

Figure 9. Soil types of the Fitzroy Basin

In contrast, flood events within the Fitzroy Basin have been shown to be dominated by Basaltic material (Douglas et al., 2008) and the majority of the fine sediment (less than 10 µm) exported in these events has been sourced to Tertiary Basaltic soils. These soil types constituted 39% of the fine sediment, but at certain periods in the flood constituted up to an estimated 50% of the suspended solids. Tertiary Basaltic soils are typically derived from the north-western and western regions of the Fitzroy Basin, lying within the Nogoa and Comet catchments and delivered to the GBR lagoon via their respective tributaries (Figure 6) (Douglas et al., 2006a; 2008). Recent studies have highlighted the importance of particle size <4 µm, which form organic-rich flocks (Bainbridge et al. 2013). These particle sizes are found in basalt soils found in cropping with massive sub-soils and predominately cracking clays.

Water storages such as dams and reservoirs have the potential to significantly impede the flow of water and trap large amounts of sediment. Within the Fitzroy region there are four significant water storages:

- Fairbairn Dam on the Nogoa River — 1,400 giga litre (GL) capacity
- Callide Dam on the Dawson River — 58 GL capacity
- Neville Hewitt Weir on the Dawson River — 11 GL capacity
- Theresa Dam on the Nogoa River — 9 GL capacity

7. Potential mix of mechanisms

For some improved land management practices, which have a public benefit (sediment reductions), there is substantial risk and uncertainty for landholders regarding its adoption. A key aspect is that only capital that is focused on achieving a positive public outcome should be invested to avoid creating perverse outcomes such as inflating the price of the capital and crowding out other grain growers and graziers.

For different management practices there will be different perceived risks and subsequent costs and benefits depending on how the practice fits within the production system, time taken to see the benefits, and the underpinning science (Figure 7. This therefore creates a challenge to effectively target funds to where the opportunity for public and private benefits to be achieved within the supply the chain. For example, if there is a management practice that had a small marginal private benefit but is in an area of the production system that can be easily modified or contracted out, the net private benefit will be realised much faster.

The level of risk and uncertainty will vary between practices depending on the production system, prior knowledge, and trialability. This presents a problem for determining which type of mechanism to use to encourage adoption. An adoption framework is required to allow the practice to be trialled by the landholder to determine the private benefits and costs, and also giving more time for the public benefits to be measured, this has a shorter timeframe in grains due to the shorter production time frame for a crop. Figure 7 presents this framework.

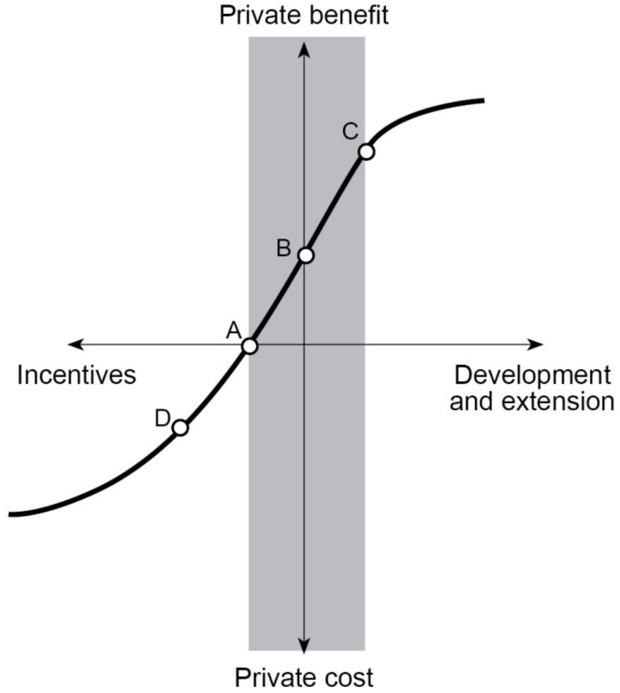

Figure 10. Framework for adoption of management practices

The horizontal axis provides the scale of policy mechanisms to implement and the vertical axis represents the private costs and benefits of the management practice. This example will be applied to a grazier; however, both graziers and growers are faced with the same challenges.

- Due to the unknown private benefits and costs, FBA may initially provide a financial incentive to the grazier. This is point A, where positive incentives are required for the landholders to cover their level of risk and uncertainty. At point A there are still key aspects of the practice that must be understood, such as the impact on efficiency and productivity of the business, the impact of scale, production system, and the long-term sustainability of the practice.
- As time passes, the grazier receives extension support to fully implement the management practice and understand the management and production trade-offs. If private benefits are realised then the practice shifts to point B where other early adopters trial the practice and similarly realise the private benefits.
- If the private benefits are negative, the situation shifts to point D where graziers dis-adopt this practice. At point B, low or no incentives are required as early adopters are willing to take the risk of investing in the practice understanding a private benefit may be achieved although still not definite. If the early adopters continue to realise further benefits, extension and development may still be required to further adapt the practice to the production system. Once this has occurred, the practice shifts to point C where private net benefits are expected for most graziers.

- The development and extension may include specific approaches suited to biophysical characteristics, modifications or further education in the production management of the particular practice.

This is a result of scale, at which the small benefit accumulates much faster for larger properties (Figure 8. Management practice 2). If, however, there is a large perceived private benefit then potentially only one or two graziers will have to demonstrate the larger benefits to achieve much faster and widespread adoption (Figure 8. Management practice 1).

The current rate of adoption of soil management practices in the grains industry indicates there is a faster level of adoption and shift to management practice 2.

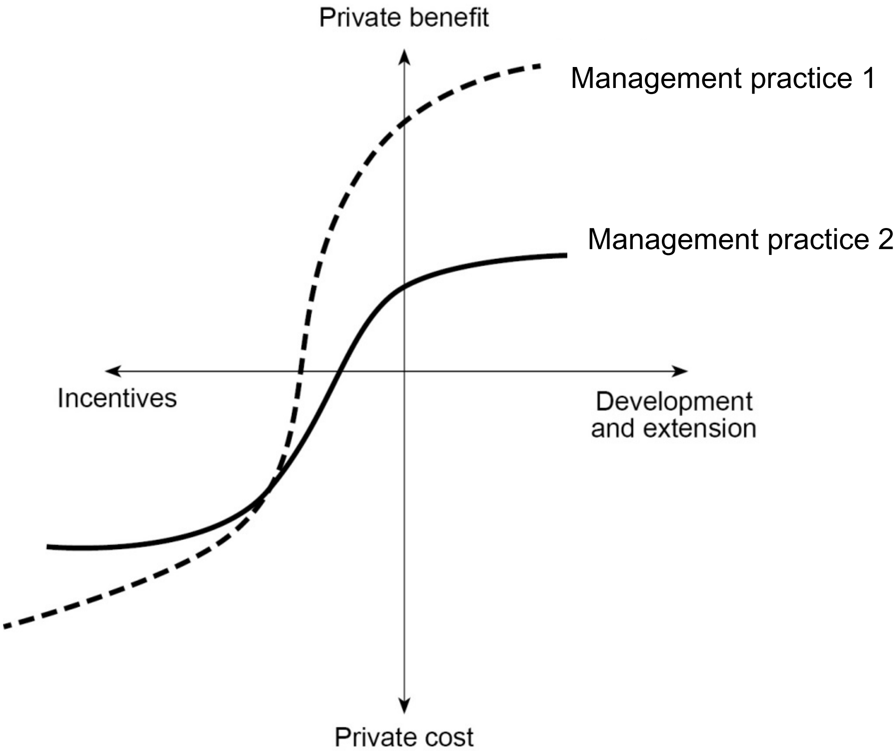

Figure 11. Variance in associated risks and benefits and costs for different management practices

Table 7. Potential mix of mechanisms for achieve more efficient sediment reductions

	Incentives	Extension	Ecosystem service payments	Reverse auctions	Confidence
Grazing	Hill-slope erosion Land Regeneration from D to C.	All projects	Gullies and streambank		High risk of project failure, particularly in medium to low productivity land types.
Grains	Contour banks, gully remediation	All projects	Streambank	Shifting to minimum tillage and controlled traffic	High confidence in achieving outcomes

8. Methods

The approach presented in this study was designed to allow FBA to allocate investments spatially, understand the cost-effectiveness of future investments, to plan and monitor progress towards targets, and to understand the process and the data across all levels of staff. This approach involves modelling climate, biophysical and economic data to predict where estimated reductions can be made at the lowest cost. The five data layers that were implemented in the process were:

1. The Source Modelling data
2. Residual cover data
3. Management Practice survey data is collected currently in the grains BMP, or through the Queensland Department of Agriculture and Forestry Paddock to Reef monitoring and evaluation program
4. Cost data.

The data utilised for the prioritisation process sought to address two different scenarios of prioritising, of which the approach and a further description of the data can be found below. This section will be broken into two main sections. First, the data layers implemented in the process are described and how they are applied in the prioritisation approach is explained. Second, the prioritisation approach will be explained, of which there are two separate components.

8.1. Sediment loads

The Source Catchment Model is currently used to assess all pollutant reductions from the Fitzroy Basin and to analyse progress towards the Reef Plan targets. The Source Catchments Model identifies where the current levels of the sediments and nutrients are coming from, the erosion process and industry. The limited empirical data across the catchment results in the model is the best available spatial data to date.

Although Source Catchments runs at a daily time-step, allowing the user to explore the interactions of climate and management at a range of time-steps, only the average annual catchment loads were required for reporting purposes over a 20-year period. Key land uses of interest were grazing, and cropping, although horticulture and forestry are also accounted for in the model. Models were validated against the six years of loads monitoring data collected at a total of 31 individual sites (12 end-of-systems and 19 sub-catchment sites) (Turner et al. 2013) and any additional data sets available to validate modelled load estimates (Fentie et al. 2013; Dougall & Carroll 2013).

There are a number of levels at which Source Modelling can be chosen as decision variables for the purpose of prioritising neighbourhood catchments. This has been the unit selected as the most relevant management unit for field staff and the relevant sub-regional organisations. The Source Catchments model accounts for a number of biophysical parameters across the catchment, such as slope, soil type, soil erosivity, vegetation, pasture species and bare ground.

The Source Catchment modelling allows the process to identify the sediment loads (in unit of tonnes) from the different erosion process of hillslope, streambank and gully. The model accounts for sediments and nutrients across the different land uses; however, the prioritisation process in this study will only focus on grazing and cropping land uses.

At the end of the prioritisation process, the Source Catchment Model will again be used to model the changes in the prioritised neighbourhood catchments. This will allow an understanding of the actual change that would be modelled in subsequent report cards and to understand the cost effectiveness of the soil management investment ($/tonne).

For Scenario 1, the total sediment loads in each neighbourhood catchment were derived by adding up the available sediment load estimates for gully, hillslope and streambank for grazing area and sediment loads from gully and hillslope erosion on dryland and irrigated cropping area.

For Scenario 2, sediment loads from gully, hillslope and streambank erosion on grazing area were divided by the total grazing area in each neighbourhood catchment. The same was done for sediment loads caused by the three erosion types on cropping land. This provided an estimate for the tonnes of sediments per hectare for the combined erosion processes for each land management type in each neighbourhood catchment.

For Scenario 3, ecologically relevant targets attempt to define the pollutant load reductions that would be required to meet the GBR Water Quality Guidelines, which are set to a standard considered to be suitable to maintain ecosystem health. Thus ERTs are required to be met to achieve the overall long-term Reef Plan goal "To ensure that by 2020 the quality of water entering the reef from broad scale land use has no detrimental effect on the reef's health and resilience" (Brodie et al. 2015).

8.2. Residual ground cover

Ground cover is the non-woody vegetation (forbs, grasses and herbs), litter, cryptogrammic crusts and rock in contact with the soil surface (Muir et al. 2011). The quantity of ground cover present can have significant influence on pasture productivity, infiltration and run-off, and ground cover maintenance is an effective action for minimising the impacts of wind and water erosion (Beutel et al. 2014; Tindal et al. 2014) and increasing productivity in grazing systems (Karfs et al. 2009; McIvor 2001; Star et al. 2013). In the GBR catchments, ground cover targets have been implemented by Regional NRM groups and as part of the Reef Water Quality Protection Plan (Department of the Premier and Cabinet 2013) in an effort to maintain ground cover, particularly in dry periods, to minimise erosion and increase grazing land productivity.

Remotely sensed ground cover measurements have been an integral part of the Reef Plan and associated programs since 2009. This capacity to leverage ground cover data sets is built on approximately 15 years of research that, in its current iteration, produces seasonal (four/year) estimates of ground cover in 30m pixel resolution for about 95% of Queensland (Tindal et al. 2014). In this study a derivative of available ground cover data set was used. Four main alternatives were considered; ΔGC, D condition probability, mean cover and cover residual. These are discussed below.

- ΔGC (Bastin et al. 2012) is the best validated of the ground cover derivatives considered here. ΔGC measures ground cover deficit at times of extreme drought by comparing cover at any point with higher percentiles of cover within a moving window placed around each pixel. It is useful for separating grazing and rainfall effects on cover. In the context of the study, it had two main draw backs; the last available image dates to the 2004 drought and this image is based on an older cover algorithm that is masked over approximately 40% of the Fitzroy where woody cover is too high to permit its use. Additionally, the image is computationally expensive to build, certainly beyond the resources of this work to build an updated image.

- Land condition probability mapping was developed by Beutel et al. (2013) in the Burdekin and Fitzroy NRM regions. These data include four layers, one each for the probability that any point is in A, B, C or D grazing land condition (Beutel et al. 2013). The underlying model included mean ground cover (2009–2011) imagery, ΔGC2004 imagery and long-term average rainfall, and was trained on about 1600 roadside land condition observations taken in 2010 and 2011. The D condition layer was considered in this work. The main drawbacks of this product were that it included the same extensive woody mask as the ΔGC, and the fact that the current version is unvalidated beyond the modelled sites.

- Mean cover images have been available in various iterations for a long time. These images simply average pixel values at any point across a series of dates. The choice of dates is flexible (we chose spring imagery 2008–2014 inclusive), and the imagery is simple to create, so could incorporate the newer "cover under trees" imagery with minimal woody cover masking. The main drawback of this imagery is that it only reflects average rainfall to some extent and hence it is more likely to confound management and climatic impacts on cover.

- Residual cover imagery was developed for this project (Appendix A). The residual cover image was derived from the mean cover image, and had the same minimal woody cover mask. The residual calculated in any pixel indicates the difference between measured and expected cover, but is standardised across the cover gradient. Expected values are based on a sampling envelope around any pixel, similar to the ΔGC that should facilitate discrimination of management and rainfall impacts on cover, but in this study the product was based on more recent imagery (2008–2014) than the current ΔGC. The product has not been field validated, and is used here in the absence of a suitably updated ΔGC product.

Residual cover was summarised at neighbourhood catchment-scale by estimation of the 10th percentile of residual cover in each neighbourhood catchment. We did this to discriminate catchments by their lower cover values since these are most relevant to sediment loss. These resulting neighbourhood catchment rankings provided the next iteration of the optimisation with low residual cover catchments in priority Source Catchments considered highest priority, and those with low residual cover identified as of limited interest given marginal scope to improve cover levels.

8.3. Management practice effectiveness

Ensuring that on-ground investments are effectively spent requires a range of management practices to support the relevant infrastructure in achieving an outcome. To understand the level of management that currently exists to support improvement across the erosion processes and industries the Paddock to Reef (P2R) Water Quality Risk frameworks have been utilised.

For each industry (grazing and cropping) there is a suite of specific management systems defined under the water quality risk framework relevant to hillslope management, gully management or streambank management in grazing systems and soil, nutrient and herbicide management in cropping systems (Shaw et al. 2013) (Appendix B). The framework was used to describe and categorise management practices according to recognised water quality improvements at a paddock scale. P2R Water Quality Risk frameworks seek to align management practice to a range of likely risk states (Tables 8 and 9). For ease of referral these are referred to as A, B, C or D in this document (Tables 10 and 11).

Table 8. P2R classification of management practices in the grazing industry.

Water Quality Risk	Low	Moderate	Moderate-High	High
Resource condition objective	Practices highly likely to maintain land in good (A) condition and/or improve land in lesser condition	Practices are likely to maintain land in good or fair condition (A/B) and/or improve land in lesser condition	Practices are likely to degrade some land to poor (C) condition or very poor (D) condition	Practices are highly likely to degrade land to poor (C) or very poor (D) condition
Previous 'ABCD' nomenclature	A	B	C	D

Table 9. P2R classification of management practices in the grains industry.

Water Quality Risk	Low	Moderate	Moderate-High	High
Previous 'ABCD' nomenclature	A	B	C/D	

A representative sample of grazing properties were surveyed on a one-on-one basis and the managers were asked a series of questions aligned to the practices articulated in the P2R Water Quality Risk framework for grazing in rangelands. The practices are weighted according to their estimated influence on off-site water quality. Responses to questions were used in developing water quality risk scores for each enterprise, and ultimately assigning water quality risk ratings from high risk to low risk outcomes and practices that support erosion processes are included, these are then categorised accordingly. The same outputs for grain growers are derived from assessments conducted through the Grains BMP program. Aggregation of the water quality risk ratings for enterprises at the river basin (e.g. Dawson) level provides estimated distributions of property management, or adoption benchmarks (e.g. Table 10 contains benchmarks for grazing management at the Fitzroy Basin scale).

The justification to focus on landholders that already implement B level management practices is that effective use of financial grants (incentives) and extension should ideally occur in a setting conducive to adoption. Similarly, relatively high management effectiveness in response to previous extension is taken as an indicator that new extension work (possibly with a renewed emphasis on practices more explicitly targeted for sediment reductions) may have a higher probability of adoption by these landholders compared to landholders that have previously not engaged with support staff.

Table 10. Percentage of grazier classification of management practice across the different erosion process in the Fitzroy

Erosion process	Management categories			
	A	B	C	D
Hillslope	**4%**	**14%**	**59%**	**23%**
Streambank	**20%**	**16%**	**15%**	**48%**
Gully	**6%**	**15%**	**55%**	**24%**

Table 11. Percentage of grains management practices effectiveness on cropping land.

	Management categories			
Water Quality Parameter	A	B	C	D
Run-off & Soil loss	**14%**	**27%**	**58%**	**1%**
Herbicide Management	**3%**	**65%**	**29%**	**3%**
Nutrient Management	**1%**	**53%**	**39%**	**7%**

For each scenario, the average management practice effectiveness for grazing on B condition land for the three soil erosion processes is 15% (see Table 10). This ratio was multiplied by the grazing area in each neighbourhood catchment to obtain average management practice effectiveness for grazing. For cropping, the same was done using average management practice effectiveness ratio for run-off and soil loss of 27% (see Table 11). The total average management practice effectiveness for grazing and cropping was then obtained by adding up the effectiveness value for each land use type for each neighbourhood catchment.

8.4. Costs to reduce sediment exported

The costs to reduce sediment exported focus on achieving a 20% reduction of sediment reduction by 2025. The costs were estimated in three key components.

1. Shifting land condition classes through incentives from C to B and D to C land condition.
2. Extension support for incentives
3. Remediation costs for streambank, gullies and d condition land.

The costs were derived from land condition as opposed to the area managed with particular practices, and focused on both incentives and extension approaches. The discount rate of 7% to allow for future costs to be bought back into today's dollar values. There are a number of trade-offs that arise from costing approaches such as:

- There are different trade-offs and costs at a paddock scale and often more cost effective approaches than what is able to be captured at a catchment scale. This must be a key consideration when interpreting the data.

- The grazing management practice framework are practices to avoid land condition decline. The disparity between the current land condition and grazing management practice adoption highlights the time lags and resilience of particular land types in the catchment. This means costing either land condition or management practice have different capacity for change across the catchment in terms of hectares to change and the approach required.
- Regeneration periods are uncertain and have risk of failure making the costs varied and uncertain. Although different interventions have been trialled there is little understanding across the catchment of the effectiveness and the variance regarding the costs and the effectiveness of different approaches. This results in a trade-offs of spending more and reducing the risk or failure to achieve the reductions in the required time.
- Costs in this approach have been based off past work and mechanisms (incentives and extension). The changes in mechanisms and approaches may mean that the costs change over time to reflect these new approaches. Extension has been costed in based off the effectiveness of DAF extension staff, this is obviously varied and currently not well understood.

The base data that has been set as the starting point is the Source modelling data (as described in Section 8.1) and the land condition mapping data. These two primary data sources have then allowed an integration of the incentives and extension costs to achieving the required sediment reductions. The land condition mapping will first be explained followed by how each of the separate components have been costed.

8.4.1. Productivity, land type and condition.

The first step in the opportunity cost curve estimation process is to obtain an understanding of the proportion of land currently in A, B, C and D condition. Accounting for the variation in land condition provides information on the proportions of land that are able to be improved or the scope of change required, and also allows estimation of the stocking rates currently being used by landholders. Although there are no specific targets for land condition, there are targets that represent groundcover and adoption of practices by landholders. The premise of the management practice framework is that the low risk management practices will maintain or improve land condition. Therefore understanding the areas in the catchments with the greatest capacity for improvement, and the associated cost per tonne of sediment reduction is important to consider.

Remotely sensed ground cover measurements have been an integral part of the Reef Plan and associated programs since 2009. This capacity to leverage ground cover data sets is built on approximately 15 years of research that, in its current iteration, produces seasonal (four/year) estimates of ground cover in 30m pixel resolution for about 95% of Queensland (Tindal et al. 2014)

Productivity was measured in this work as AE/Ha. This is the hypothetical number of 400kg cattle that can be sustainably supported per hectare according to the GRASP model (McKeon et al 2000). GRASP takes into account rainfall, land type, tree cover and land condition to determine this long term carrying capacity. To estimate productivity in any sub-catchment we combined four products (Table 12).

Table 12: Parent layers of sub-catchment productivity data.

Dataset	Description
Spatialized GRASP A raster	This raster estimates AE/Ha across the landscape assuming A condition and taking into account local tree cover, GLM land type and long term average rainfall.
Sub-catchment boundaries	Boundaries of the sub-catchments used in this study.
ABCD rasters	Four raster layers modelling the probability of A, B, C and D condition in the Burdekin and Fitzroy (Beutel et al. 2014). The mapping includes a large proportion of unassessed pixels due to an FPC mask in the ground cover data used by Beutel et al. (2014) to create the layers. Where condition is assessed the four rasters sum in any pixel to 1. Note that this product should be considered experimental, but there are no alternative products that estimate actual land condition class.
GLM land type boundaries	GLM land type mapping for the study area. Polygons were assigned to the dominant land type where multiple land types were mapped in a polygon.

In theory, estimating AE/Ha at pixel scale from the spatialized GRASP A raster and ABCD rasters is relatively simple. B, C and D condition land has 75%, 45% and 25% respectively of the AE/Ha of land in A condition. So AE/Ha adjusted for likely land condition equates to

$$(P(A) + .75 \times P(B) + .45 \times P(C) + .25 \times P(D)) \times AE/Ha.$$

However our ABCD raster included significant pixel numbers unassessed by the ABCD modelling due to the FPC mask. To patch these data at pixel scale we used the process below.

1. Sub-catchment and land type boundaries were intersected to create a combined sub-catchment x land type vector layer.
2. The ABCD rasters were converted to a single draft aggregate ABCD raster, null where ABCD land condition was unassessed, and where present, equal to

$$(P(A) + .75 \times P(B) + .45 \times P(C) + .25 \times P(D))$$

3. The mean value of pixels in the draft aggregate ABCD raster were calculated for each catchment, and for each combination of sub-catchment x land type.

4. Where a pixel was unassessed for land condition but there were some assessed pixels within that land type x sub-catchment area, the pixel was assigned the mean aggregate pixel value for the land type x sub-catchment combination. Alternatively the pixel was assigned the mean aggregate pixel value for the sub-catchment. This produced the final aggregate ABCD raster.
5. The final aggregate ABCD raster was multiplied by the Spatialized GRASP A raster to provide pixel-by-pixel estimates of AE/Ha, and these were averaged per sub-catchment to provide estimates of sub-catchment productivity.

8.4.1. Incentives costs

The incentives cost curve the value of the opportunity cost of landholders reducing stocking rate to improve land condition, over a ten year period. To estimate this across the catchment allows an understanding of the reduction in stocking rate required and an estimate of the ceiling for future. The method to estimate this involved a number of different datasets integrated for each of the neighbourhood catchments to allow for spatial heterogeneity to be considered. Each of these components has various complexities.

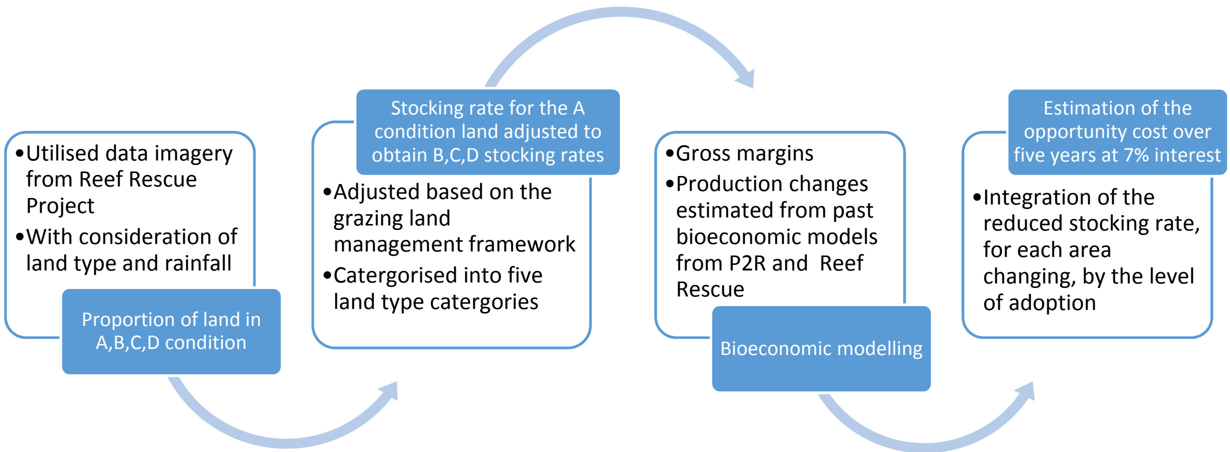

Figure 2. Process and data implimented for the opportunity cost curve.

Bioeconomic modelling

The most dominant land types present in each of the neighbourhood catchments were also critical. Land types reflect the inherit productivity of the land and therefore the possible grazing enterprises able to be undertaken on properties. There are 42 land types described in the grazing land management descriptions, for the purposes of modelling these 42 have been condensed into five broad category groupings.

It is from these broad groupings that the gross margin based on the enterprise has been estimated, with the herd structure, animal production and animal input costs determined by the Beef CRC templates (2009) and the prices received updated for 2015 prices. The gross margins per AE ranged from $312.55 down to $182.32 reflecting that productivity grouping one was turning off heavier Jap Ox and the lowest productivity grouping turning off light store cattle.

Table 13: Gross margins per AE of productivity groupings

Productivity Grouping	Beef CRC template	2015 GM$/ AE
1	R322 Central Qld Brigalow	$312.55
2	R313E Basalt (Dalrymple, Flinders) & Downs (Flinders, Richmond, McKinlay)	$241.98
3	R313C Goldfields (eastern half of Dalrymple Shire)	$199.30
4	R332B Lower Burdekin & Bowen	$197.43
5	R331 Coastal speargrass	$182.32

A critical aspect for each of the land type productivity groupings was to estimate the reduction in stocking rate required to improve the land condition. To do this requires consideration of the optimal level of production for the current land condition. Data from past grazing trials and previous bioeconomic modelling was reviewed, which included a number of land types and ranges of productivity. The difference in stocking rates between the economic optimal from the bioeconomic modelling results was then calculated and averaged for each of the five land type productivity categorisation.

Table 14: Productivity of different land types

Land type	Area (ha)	Catchment predominantly found	Productivity
Brigalow blackbutt	1,024,460	Fitzroy	High
Coolibah floodplains	320,239	Fitzroy	High
Loamy alluvials	625,050	Fitzroy	High
Narrow-leaved ironbark on shallower soils	624,558	Burdekin	Low
Narrow-leaved ironbark woodland	1,056,490	Fitzroy	Medium
Open downs	284,987	Fitzroy	High
Silver-leaved ironbark	2,611	Burdekin	Medium
Silver-leaved ironbark on duplex	626,859	Burdekin	Low

The reductions in productivity are essentially a proportion of the whole neighbourhood catchment and it is assumed that collectively the change occurs across the area. A reduction of 0.26 across the NC represents the percentage reduction in stocking rate that would be required to occur for ten years to produce an improvement or shift in land condition to C condition.

The marginal changes in stocking rate for each of the neighbourhood catchments was then multiplied by the current gross margin, for the duration of five years and at a seven percent discount rate to bring everything back into today's dollars.

8.4.2. Extension costs

The extension cost curve estimates the costs of achieving reductions in sediment based on landholder improvements in management practices instigated through government provided extension services. The method to estimate the extension cost curve involved a number of different datasets integrated for each of the neighbourhood catchments to allow for spatial heterogeneity to be considered (Figure 15). Each of these components has various complexities that are described.

Figure 15 below shows an overview of the method used to calculate the extension costs.

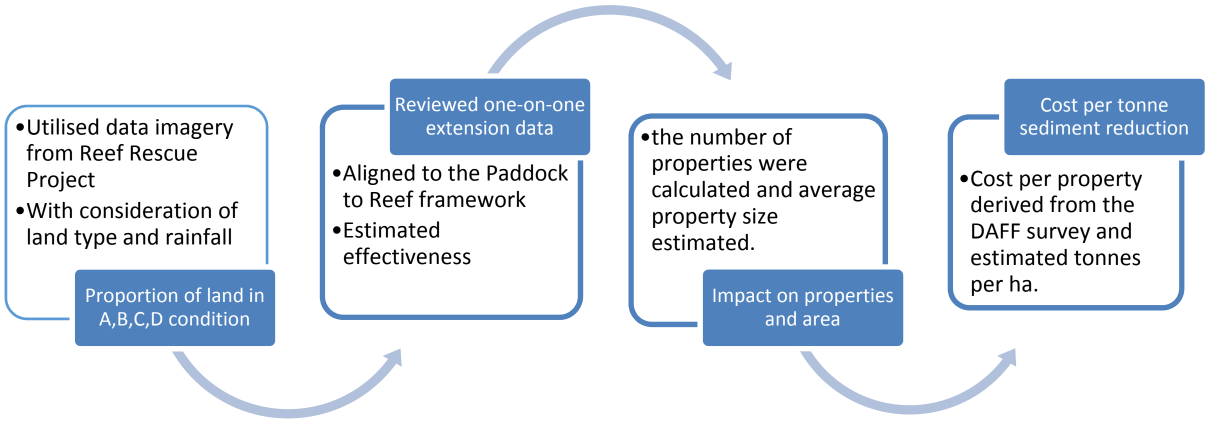

Figure 15. Overview of method used to calculate extension costs.

Productivity, land type and condition.

The first step in the extension costs estimation process is to obtain an understanding of the proportion of land currently in A, B, C and D condition. This step is exactly the same as described in the incentives cost estimation, and will not be repeated here for brevity.

Estimating effectiveness

Estimating the level of extension effectiveness is difficult as there may be significant time lags in both landholder adoption and achievement of outcomes. In addition, it is likely that there are diminishing returns to extension expenditure, as extension services tend to engage with the more willing landholders first and over time the extension services are working with less willing landholders and therefore more costly to engage with. A significant barrier facing this project when trying to understand the effectiveness of past extension programmes is the poor alignment of the Grazing BMP program to the Paddock to Reef management framework. Therefore only the DAF one-on-one extension program which included a landholder survey that was able to be aligned to the Paddock to Reef management framework was able to be evaluated in this extension cost curve estimation.

The DAF management practice survey when aligned to the Paddock to Reef framework showed that 11% of landholders had shifted from a C to B level of management. It is likely that there were many other landholders who may have taken smaller steps towards improved management practices, however these small changes are impossible to quantify. Therefore for estimation of the extension cost curve, 11% of landholders was used to provide an indication of the potential outcomes that may be expected from future expenditure on extension, based on the past DAF extension investment.

Impact on properties and area

The number of properties per sub-catchment was derived from property mapping for the study area. Properties were included in the counts where they covered >200Ha of grazing land. Each property was only counted in one sub-catchment to avoid double counting properties that straddle multiple sub-catchments. In these cases, the property was assigned to the sub-catchment in which it had the largest proportion of its area.

For each neighbourhood catchment 11% of properties were used, combined with the average property size for that neighbourhood catchment, to understand the hectares of change likely to occur. The estimated DAF extension cost per property was then extrapolated out across the catchment, with the average tonnes per hectare then used to understand to dollars per tonne per hectare.

8.4.1. Remediation costs

The cost to remediate gullies, streambanks and scalds were costs from past literature collected within the catchment. The costs vary significantly based on the biophysical parameters and were based on a number of site specific actions; these actions included but were not exclusive to:

- Stick raked log lines
- diversion banks
- Battering of three gully heads (to a moderate angle)
- Fenced for stock exclusion (solar powered electric fence)
- A number of whoa boys
- One battered rock chute with short diversion banks on either side (temporary solution to generate grass cover) Rust and Star (2016).

The range of cost per tonne were $66.93 to $516.23 demonstrates the heterogeneity and site specific characteristics for each gully and the subsequent range in actions (Rust and Star 2016).

For scalds and D condition land the costs were generated from Star et al (2011) and Hall et all (2012) and were based around mechanical intervention re-seeding and stock exclusion for significant periods of time. The costs ranged from $7,800 per hectare through to $200 per hectare with the time frame to achieve the land condition improvement varying based on land type characteristics and climate. For this approach $1,200 per hectare was used which represent mechanical intervention, re-seeding, stock exclusion and on-going maintenance.

Finally, the streambank costs were estimated from the Bartley et al (2015) and were for fencing each side of the stream and inserting off-stream watering points. The total costs per kilometre of streambank were estimated to be $10,000 km for each side of the stream and then a cost of $8,700 for an off stream watering point (inclusive of tank, trough and polypie) every 4km.

These costs have extremely large ranges and the approach which is required is site specific and impacts the risk of failure and the time period to remediate.

8.4.1. Costs to achieve change based on mechanisms

To date there has been a total of $34.7 million and achieved on average a level of 15% adoption in the grazing industry. The complexity of engagement and policy mechanisms demonstrates that continuing to implement the same strategy will not yield the level of adoption required.

To make progress towards the Reef Plan targets the federal and state governments have employed the different policy mechanisms of incentives, extension, market based instruments, regulation and land retirement. A grants scheme termed Reef Rescue followed by Reef Programme was initially implemented where farmers were incentivized to change management through changing capital machinery, or developing infrastructure (Queensland Science Taskforce 2016). From 2009-2013 the federal government allocated $366.8 million across the reef catchments to be allocated to on-ground change (Queensland Science Taskforce 2016). With landholders co-investing in the capital changes, Natural Resource Management (NRM) groups were the administrators of the programs. Each NRM group had a different approach to engagement and prioritising in the catchment with what changes were required.

To support the capital infrastructure changes the State government supported extension mechanisms aimed at building capacity and knowledge of landholders in supporting the capital developments with the required management to achieve the environmental outcomes.

Rolfe and Gregg (2015) identified five groups of landholders in the grazing industry focusing on the motivation of each of the groups in regards to their management focus. These groups were:

1. Satisficing landholders: Traditional landholders content to maintain their current operation.17% of landholder identified most strongly to this group.

2. Nature and leisure: These landholders placed emphasis on having good natural resources and leisure time. 4% of landholders identified with this group.

3. Maintain resource base: These landholders are focused on managing stocking rates to maintain cover at the end of the dry season.21% of landholders identified with this group.

4. Profit and Production: These landholders are very focused on maximising profits and production. 46% of landholders identified most strongly with this group.

5. Minimising costs and losses: Focused on reducing climate, market risks, 21% of landholders identified most strongly with this group.

Given the motivations of landholders the required levels of adoption may not be achievable with singular mechanisms resulting in the consideration of the levels of policy mix required (Rolfe and Gregg 2015). Majority of the costing work to date has focused on the costs to shift landholder using incentives, extension or regulation (Alluvium 2016, Whitten 2015, Star 2015) with emphasis of mix relative to areas required to achieve the pollutant reduction however little attention has been paid to estimating the most effective mix of policy mechanisms or the changes in overall costing that will be required to shift particular groups of landholders.

The interaction and level of adoption for different groups of landholders varied between the different policy mechanisms, similarly the costs vary as the policy mix changes. The use of incentives and extension to date has most likely led to the engagement of those landholders who are motivated by nature and leisure and those motivated by maintaining resource base (Table 2). Those motivated by profits and minimising costs and losses may have been engaged in projects that has larger private benefits however are less likely to have generated the environmental benefit, and those that are satisficing may have had some exposure to extension however are unlikely to change their practices.

Market based instruments have not been implemented in the grazing industry however have been implemented in the sugarcane industry. The participation rates of these tenders is relatively low compared to the grants and extension. The design of the tenders which entails a payment each year for the reduction in inputs is more likely to engage with landholders who are seeking to minimise cost and losses and their general exposure to risk.

Regulation is a mechanisms that captures all groups of landholders but is driven to capture the 46% of landholders that are motivated by profit and production. It would be these landholders who are unlikely to engage in the other mechanisms that are the focus for achieving the 90% Reef Plan target. The minimum standard would achieve the desired level of adoption, however in implementing a regulation policy this would then result in the other groups of landholders not willing to engage in the incentives, extension or market basket instruments mechanisms.

The cost approach to engage these different groups of landholders will not only require different mechanisms but the costs associated with the change (Figure 2). The overall supply curve of costs will vary based on both the mechanism implemented and the types of landholders engaged. Market based instruments have shown that they can generate the largest range of costs associated with pollutant reductions from very cheap through to extremely expensive, however have lower participation rates and attract the smallest group of landholders. The incentives and extension categories engage with approximately 25% of landholders and with these costs too ranging significantly based on ability for landholder to be engaged through different extension processes and where diminishing returns are present finally regulation which captures the last remaining group of landholders however is expensive to implement.

Table 15. Links to motivations and mechansims

	Types of motivations of landholders

<table>
<tr><th></th><th>Satisficing (17% landholders)</th><th>Nature and leisure motivations (4% of landholders)</th><th>Maintaining resource base (21% of landholders)</th><th>Profit and Production (46% of landholders)</th><th>Minimising costs and losses (12% of landholders)</th></tr>
<tr><td>Incentives (Reef Rescue, Reef Programme, Reef Trust 3)</td><td></td><td colspan="2">These landholders are likely to be the landholders who have been engaged with the NRM groups in projects already.</td><td colspan="2">These landholders will participate for significant private benefit which is unlikely to have environmental outcomes.</td></tr>
<tr><td>Extension (BMP programs, DAF one-on-one, RCS)</td><td colspan="3">The traditional landholders to a lesser degree however may make small production changes but the nature and leisure motivated and the maintain resource are those that are likely to be engaged with extension through the BMP.</td><td></td><td></td></tr>
<tr><td>Market Based Instruments (Reef Tenders)</td><td></td><td></td><td></td><td>Some of these landholders are likely to participate if they think there is scope to game the outcome.</td><td>These landholders are mostly likely to have a good handle on their costs and margins to be able to put in a bid.</td></tr>
<tr><td>Regulation</td><td colspan="5">This mechanism will capture all landholders. It will most likely ruin the trust of the Nature and Leisure motivated, and those Maintaining resource base - making extension and grants harder to roll out, but will capture the remaining three groups, which form the largest portion of the industry.</td></tr>
</table>

8.4.2. Costs to achieve the targets

There are a number of other key consideration used in the prioritisation that must be considered for project selection. Based on costs alone of shifting land condition through incentives, extension and remediation to achieve the 20% target required by 2025 an estimated $558 million approximately will be required.

8.5. Prioritisation approach

Given the large area in the Fitzroy Basin that is affected by either gully, hillslope or streambank erosion, a prioritisation of neighbourhood catchments within the Basin needs to be undertaken to determine the relative importance of areas based on different decision variables. Two different prioritisation scenarios were considered in this study (Table 13). Each of the approaches uses the data differently. Given that sediment is the key pollutant for reductions, the focus has been predominately on sediment with particulate nutrient highly correlated. It was assumed that where sediment reductions occurred inherently particulate nutrient reductions also occurred. The first scenario explored achieving the Reef Plan targets (20% reduction in sediment) through a cost effective approach, from the exported pollutant across the neighbourhood catchment. The second scenario assessed under which prioritisation decisions the ecologically relevant targets (ERTs) of a 20% reduction of sediments in coastal catchments and 50% reduction in fine fraction (<4 µm) suspended sediments expressed as a 30% reduction in bulk total suspended sediment could be achieved (Table 13).

Table 13. Prioritisation scenarios

1) Cost effective outcomes	Contribution
The neighbourhood catchments were ranked based on: • tonnes of sediments per hectare for combined erosion processes on grazing and cropping land, respectively • residual cover • management practice effectiveness for each of the processes • costs for combined processes on grazing and cropping land, respectively Prioritised to achieve the Reef Plan targets of a 20% reduction in sediment.	To understand in a functional form what catchments have the potential to be the most cost effective.
2) Ecologically relevant targets	**Contribution**
The neighbourhood catchments were separated into coastal catchments and the Fitzroy and were ranked based on: • total sediment loads (grazing and cropping combined) • residual cover • total average management practice effectiveness (grazing and cropping combined) • costs (grazing and cropping combined); and • sediment export ratio Prioritised to achieve the ERTs of a 20% reduction of sediments in coastal catchments and 50% reduction in fine fraction <4 µm) suspended sediments expressed as a 30% reduction in bulk total suspended sediment.	The ranking of Scenario 3 follows the same process as Scenario 1; however, it is separated into the Fitzroy and the coastal catchments.

The first scenario aims to prioritise the data using a cost effectiveness approach, which also considers ability to change. There are three parts in achieving this: first understand the loads data, second identifying the required adjustments in the landscape that can be made; and finally identifying the cost to achieve this. Given that the data is in different units, to allow a function to be developed the data was normalised. The data was then given a cost effectiveness score based on the function:

$$CEgr, crp = \frac{loads\ (t/ha)\ (N.Cover \times N.Mgt)}{N.Costs}$$

Where the loads refer to the tonnes per hectare for the NC, *N. Cover* refers to the residual ground cover data that was normalised (Section 3.2) and then multiplied by *N.Mgt,* which is the level of adoption for B management practice for grains and grazing (Section 3.3). This was then divided by *N.Costs*.

9. Results

The results presented in this section only focus on the prioritisation of neighbourhood catchments. The first scenario ranked the neighbourhood catchments based on the cost effectiveness of each industry. When data is normalised it allows each NC unit and value to be modified and to fall within 0 and 1, this allows the units to be compared in the function. Essentially the function results in catchments that have large loads on a per hectare basis to be multiplied by the scope for change and then divided by the normalised cost. It can be noted that NC with high loads per hectare and large scope for change along with a lower cost are ranked higher.

Table 14. Parameters and ranking based cost effectiveness approach for grazing

Neighbourhood catchment	Sediment Load T/ha	Normalised. cover	Normalised management	Normalised revised Cost	Function score
T33	475.656	0.45	0.61	0.04	1303.15
F15	375.385	0.81	0.09	0.04	615.15
B2	199.271	1.00	0.11	0.05	452.74
F5	242.391	0.69	0.21	0.08	413.25
B13	334.978	0.76	0.07	0.08	211.83
B6	241.705	0.57	0.04	0.03	187.16
B11	274.322	0.63	0.03	0.03	161.11
T31	114.602	0.60	0.20	0.33	15.19
F25	3278.217	0.69	0.02	0.33	129.76
B9	269.795	0.50	0.16	0.16	120.14
T29	374.873	0.56	0.33	0.11	236.24
B1	328.972	0.76	0.05	0.11	102.02
F20	854.582	0.57	0.06	0.21	100.83
F1	435.536	0.70	0.07	0.21	100.40
T39	417.476	0.63	0.09	0.23	43.94
F4	313.324	0.58	0.10	0.23	74.07
F17	918.652	0.64	0.10	0.42	64.25
B4	445.771	0.43	0.03	0.11	60.01

10. Discussion

The aim of this report was to the prioritise neighborhood catchments to achieve the Reef Plan reductions on loads per hectare and the ecologically relevant targets (ERTs) and to achieve cost effective outcomes. The two scenarios result in different catchments being selected based on how the analysis is completed. The first scenario identified catchments that have a high capacity to change relative to the loads and cost of sediment reductions. The second scenario identified areas closer to the coast, which have higher rainfall intensity and higher levels of gullying and streambank erosion. The ERT scenario identified further neighbourhood catchments than the total loads scenario to achieve the higher targets. Finally, the cost effective scenario identified a mix of Scenarios 1 and 2 neighbourhood catchments.

This analysis has focused on achieving sediment reductions as it is considered a high priority; however, it must be noted that there are also multiple benefits in terms of particulate nitrogen and particulate phosphorus reductions that inadvertently occur due to the binding of particulate nutrients to soil particles. These are further discussed in the gaps and recommendations report.

The results identify neighborhood catchments in the Fitzroy Basin that have a high ranking across the five parameters of loads, residual cover, effectiveness, cost and delivery ratio. The NC are spatially spread across the catchments with clear groupings identified. The difference between the four scenarios demonstrates the complexity of the issue and analysis highlights a number of key considerations for FBA.

- Strategies to implement these programs in the current El Niño climate need to be developed.
- Opportunities of new programs for monitoring and stakeholder engagement are available.
- There is the need to continue close liaison with research institutions in regard to the future data becoming available and continuous refinement of the prioritisation approach and hence analysis outcomes.
- Future funding and design of programs to achieve outcomes for sediment reductions can be targeted for maximum cost.

A number of the selected NCs have large proportions of highly erosive soils. Given the state of current El Niño, ground cover needs to be taken into consideration with landholders to develop strategies that maintain ground cover. These NCs that contain erosive soils *and* are relatively low deliverers of sediments, are prime candidates for this and include: D7, D6, D8, D43, D42, T15 and T16. Results of previous LiDAR studies have identified that larger gullies may be driven by episodic or event-based localised rainfall events and possibly exacerbated by low ground cover. This highlights that maintaining good ground cover at the end of a drought or the break of a dry season is important to avoid large sediment loss (Tindal et al. 2014).

Similarly, although mining only occupies 1% of the catchment, mining companies have grazing lease agreements in place for 4% of the catchment (Appendix D). Given that cattle enterprises are not their primary business there is the potential scope for engagement of mining companies to achieve mutually beneficial outcomes. There are two NCs (T31, T35) that have ranked highly in this prioritisation, which also have substantial areas of mining lease agreements. Given the large areas involved, there is potential for low risk engagement with mining companies to facilitate low cost, large impact sediment reductions. Mining companies may be receptive to improved environmental management without reliance upon incentives, and income from livestock is likely to be unimportant to their business.

Cropping areas have been identified with the potential to achieve sediment reductions with low cost and high adoption rates of supporting management practices. The dominant cropping soils also have very high fractions of particle size below 4 µm, which are increasingly understood to be extremely important in terms of the damage done to reefs. In a number of the NC selected there is the opportunity to work with growers to achieve sediment reductions and achieve corresponding cumulative benefits through herbicide reductions and the applied DIN reductions. There are a range of interventions that may have an impact but the most important will be (See Appendix B):

- the adoption of minimum tillage systems, which result in less soil disturbance and more groundcover
- the installation of professionally designed contour banks, which can greatly reduce generation and transport of sediments from the farm (see Appendix B)
- the implementation of controlled traffic farming systems, chiefly as an enabler of reduced tillage. The other significant benefits associated with adoption of controlled traffic is that it achieves nutrient and pesticide reductions due to the elimination of machine overlap.

In some NC such as D12 and D13 these cropping areas are on a smaller scale and therefore BMP support and extension is likely to be required. Advantages of investing in change in the grains industry is that the actual impacts of the change are realised virtually immediately, and the changes are relatively easy to verify. This may be in contrast to interventions in the grazing industry where benefits are likely to be realised over long time periods.

The identification of priority NC for sediment reduction in the Fitzroy Basin implies that funding sources and appropriate interventions (e.g. ongoing maintenance of infastructure and extension) need to be revised. A mix of mechanisms that includes both financial incentives with direct extension to support the infrastructure and management changes is required. Given that the production margin from cattle grazing in the Fitzroy Basin will decline further with the likely progression of an El Niño, private funds for infrastructure and improved soil management are limited. Higher levels of co-investment on a sliding scale may be required; this would result in funding up to 75% of on-ground works in some instances. The impending reduction in incentives funding associated with the closing of Reef Programme may be a serious impediment.

The prioritisation approach presented in this study is relatively simple and only the first attempt to rank neighborhood catchments. This approach has some caveats, for example, the units of the decision variables are not directly comparable as they have not been standardised. The development of advanced prioritisation techniques could provide more robust results compared to what is presented in this study. For example, an index-based prioritisation approach allows linking decision variables directly to the neighborhood catchment index. The advantage of an index over the simple ranking approach chosen in this study is that it produces a single, unit-free number based on a number of decision variables. This single number can be used to compare different regions. However, it must be noted that the current approach allows field officers and staff utilising the prioritisation process to understand the layers of data implemented and how it applies to selecting projects and on-ground works.

The costs of erosion management have not been estimated in the literature before. Hence, the cost function presented in this study is novel and universally applicable to erosion processes. However, assumptions made for the management costs of soil erosion are comprehensive and need to be refined based on a range of local case studies. It should also be mentioned the simplest management scenario that was chosen in this study for grazing and cropping (Table 6) may not be appropriate for every site or neighborhood catchment.

Furthermore, while mapping soil erosion in the Fitzroy Basin using remote sensing technologies and expert expertise may not be completed within several years, other simpler and low cost methods to collect spatial data should be considered. For example, landholders and existing extension officers could be engaged in collecting spatial data of soil erosion in the Fitzroy Basin under the assistance from remote sensing and soil scientists (e.g. provision of a guide that outlines how to collect such data using available internet tools such as Google Earth along with local knowledge).

There are a number of caveats to consider based on gaps in the data. These include updating of data, ability to spatially understand effectiveness of management, the use of the best cover metric, account for discount rate correctly and understanding erosion process. These gaps are further explained in a separate Prioritisation Gaps Analysis Report.

11. Conclusion

The objective of the study reported in this document was to prioritise neighborhood catchments within the Fitzroy Basin for sediment reductions. A relatively simple prioritisation approach was used in this study, which identified a number of neighborhood catchments, from which clusters were derived, as focus areas for soil remediation. It provides an approach of combining a number of data sets to understand the different trade-offs and capacity to achieve reductions.

The prioritisation of neighborhood catchments was significantly affected by the limited data available about soil erosion across the Fitzroy Basin. Hence, it was suggested to invest in data collection in order to broaden the spatial and bio-physical knowledge basis about soil erosion in the Basin. At the same time, it is important to further develop the prioritisation presented here for example, by establishing an index; and that the method is refined in conjunction with the information and data as becomes available.

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Appendix A: Building the residual cover image

Below is a description of the broad methods used to construct the residual cover image in our analysis.

1. A mean cover image for the region and its surrounds was developed from all spring ground cover images 2008 to 2014 inclusive.
2. A series of random points in grazing land of the region (~15,000) were created and these were used to extract mean cover values from 1.
3. An inverse distance weighted (IDW) interpolation of mean cover across the region was developed from these points. This process was iterative, identifying optimal neighbour counts and power functions for later models.
4. Steps 2 and 3 are repeated 8 times to create 8 new IDWs using the parameters identified originally at step3.
5. A mean image of the images created at step 4 was created.
6. Approximately 20,000 random points were created within the grazing country of the region, and these were used to extract matching values from the IDW and mean cover images.
7. A beta regression model was fitted to predict the mean cover values from the IDW values generated in step 6.
8. The fitted model in step 7 was applied to the full mean cover and IDW images to create a deviance residual image of the region. This is indicative of the difference between mean cover and IDW values, where smaller residuals indicate mean cover was lower than expected (IDW value).

Appendix B: Grazing management practice framework

	Weighting	Indicators & Associated Practices		Question	Weight	Allocated score				
						Low	Low-Mod	Mod	High	N/A
Hillslope erosion	20%	**Performance Indicator 1: Average stocking rates imposed on paddocks are consistent with district long-term carrying capacity benchmarks for comparable land types, current land condition, and level of property development**								
		High-level actions	There are realistic expectations of the average stocking rate each paddock will likely carry over a number of years (long-term carrying capacity or LTCC).	11	10%	10	7	4	0	
		Supporting actions	Property mapping and inventory of natural resources enables objective assessment of long-term carrying capacity and stocking rate.							
			Land condition is assessed and taken into account when estimating LTCC and when planning grazing management.	10	10%	10	6	3	0	
	40%	**Performance Indicator 2: Retention of adequate pasture and ground cover at the end of the dry season, informed by (1) knowledge of ground cover needs and (2) by deliberate assessment of pasture availability in relation to stocking rates in each paddock during the latter half of the growing season or early dry season.**								
		High-level actions	Balance between stocking rate and pasture quantity in each paddock, and implications for ground cover, are objectively evaluated.	12	20%	20	12	6	0	
			Records and analysis of stock numbers allow planning and management of stocking rate.	9	10%	10	6	3	0	
		Supporting actions	Ground cover monitoring	8	5%	5	3	1.5	0	
			Ground cover thresholds inform paddock management	13	5%	5	3.5	2	0	
	25%	**Performance Indicator 3: Strategies implemented to recover any land in poor or very poor condition (C or D condition).**								
		High-level actions	Management is tailored to encourage recovery of land in declining or poor (C) condition.	22	7.5%	7.5	5	3.5	0	
			Management is tailored to encourage recovery of areas in very poor (D) condition.	23	10%	10	7	4	0	
				18	7.5%	7.5	5	2.5	0	
	15%	**Performance Indicator 4: The condition of selectively grazed land types is effectively managed**								

		High-level actions	Where there has been, or is, strongly selective grazing of land types within a paddock, management actions are in place to maintain/recover land condition of those land types.	6	7.5%	7.5	3.5		0	
				14	7.5%	7.5	5	2.5	0	
Streambank	100%	**Performance Indicator: 5. Timing and intensity of grazing is managed in frontages of rivers and major streams (including associated riparian areas) and wetland areas.**								
		High-level actions	Grazing pressure on frontage country is able to be effectively managed (enabled by infrastructure).	7	100%	100	66	33	0	
			Grazing pressure on frontage country is managed carefully (where fencing allows control).							
Gully	30%	**Performance indicators 1-4: Hillslope erosion assessment.**								
	30%	**Performance Indicator 6: Strategies implemented to remediate gullied areas.**								
		High-level actions	Where possible, remedial actions are taken to facilitate recovery of gullied areas.	23	30%	30	20	10	0	
	40%	**Performance Indicator 7: Linear features (roads, tracks, fences, firebreaks, pipelines and water points) located and constructed to minimise their risk of initiating erosion.**								
		High-level actions	Planning.							
			Managing risk of erosion associated with roads and tracks.	16	25%	25	16	8	0	
			Managing risk of erosion associated with fences.	17	15%	15		0		
	0%	**Performance Indicator : 8. Use of agricultural chemicals**								
		High-level	Use of Tebuthiuron (where used)							
			Application of fertilisers (where used on significant areas of perennial pasture)							
			Application of phosphorus (P) fertiliser							
			Application of nitrogen (N) fertiliser							

Appendix C: Grains management practice framework

Management (weighting)		Outdated	Minimum Standard	Best Practice	Innovative, may not be economic in all situations	Not Applicable
		High Risk	Moderate Risk	Moderate - Low Risk	Lowest Risk	
Runoff & Soil Loss	Use of Tillage (40%)	Tillage is frequently used for weed control and/or managing stubble.	Efforts are made to maintain stubble cover during fallows. Stubble usually needs to be cultivated to allow for planting and/or fertilising.	Crops are planted into standing stubble from the previous crop/s. Tillage is only used when required to deal with severe compaction, nutrient stratification, or as part of a strategy to manage certain difficult weeds.	Strategy to control certain difficult to control weeds may involve occasional zonal tillage.	

Management (weighting)		Outdated	Minimum Standard	Best Practice	Innovative, may not be economic in all situations	Not Applicable
		High Risk	Moderate Risk	Moderate - Low Risk	Lowest Risk	
	Wheel Traffic (30%)	Farming equipment has different widths and wheel spacing.	All farm equipment except headers and mobile grain bins operates on the same wheel spacing and consistent implement width.	A controlled traffic system is in place with all tractors and implements, headers and mobile grain bins operating on the same set of wheel tracks. Spraying and planting occurs under machine guidance of at least 10cm pass-to-pass accuracy.	A controlled traffic system is in place with all tractors and implements, headers and mobile grain bins operating on the same set of wheel tracks. All machines operate under RTK guidance of at least 4cm pass-to-pass accuracy.	

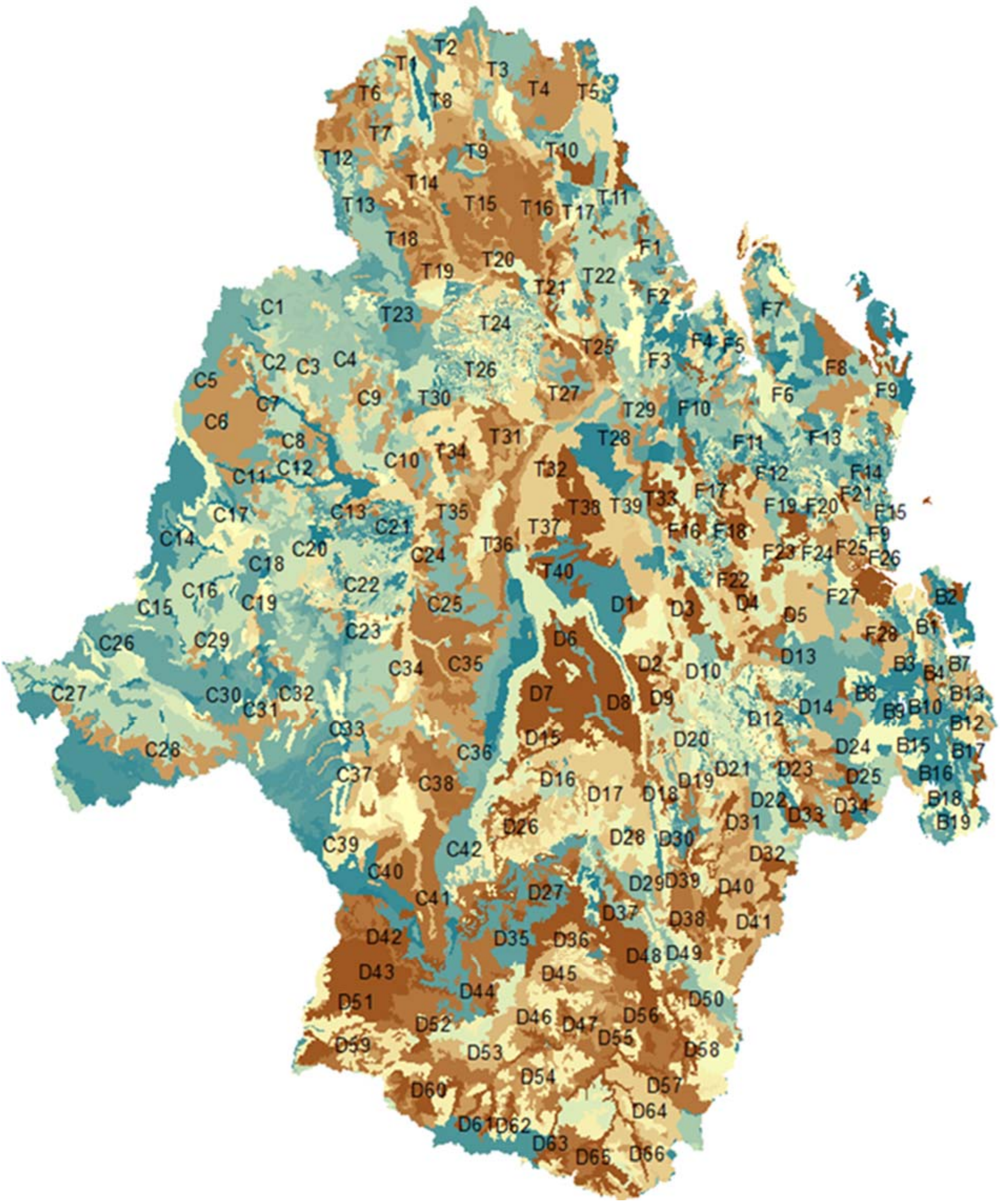
Management (weighting)		Outdated	Minimum Standard	Best Practice	Innovative, may not be economic in all situations	Not Applicable
		High Risk	Moderate Risk	Moderate - Low Risk	Lowest Risk	
	Erosion Control (30%)	Contour and diversion banks not present or not maintained in functional state.	Contour and diversion banks are present and regularly maintained	Contour and diversion banks are present and regularly maintained. The placement and design of banks is informed by a skilled third party.	Contour and diversion banks are present and regularly maintained. The placement and design of banks is informed by a skilled third party. Secondary forms of sediment control (such as sediment traps) are in place.	All farmed land has a slope lower than 1%
Nutrients	Determining nitrogen (N) requirements (40%)	Fertiliser N rates are based on historical rates or rules of thumb for particular crops.	Regular soil analysis, in conjunction with yield/protein information, is used to make N management decisions.	Yield and protein data is matched to crop performance zones to formulate soil sampling strategies and N management	Yield mapping data informs precise variable fertiliser rate control.	Do not use nitrogen fertiliser.

Management (weighting)		Outdated	Minimum Standard	Best Practice	Innovative, may not be economic in all situations	Not Applicable
		High Risk	Moderate Risk	Moderate - Low Risk	Lowest Risk	
				decisions for individual zones.		
	Influence of stored soil moisture on yield and nitrogen (N) fertiliser decisions (40%)	Stored soil moisture is not considered when selecting fertiliser application rates.	Stored soil moisture is monitored throughout the fallow and informs decisions on yield potential and appropriate fertiliser rates.		Stored soil moisture is monitored throughout the fallow and decision support tools are used to indicate yield potential when selecting fertiliser application rates.	Do not use nitrogen fertiliser.
	Application timing to minimise potential losses and maximise	Fertiliser is applied when it is most convenient to do so, usually well	Fertiliser application is carried out as close to planting as possible.	Fertiliser is applied as split applications (e.g. during the fallow, at planting and/or in crop).		

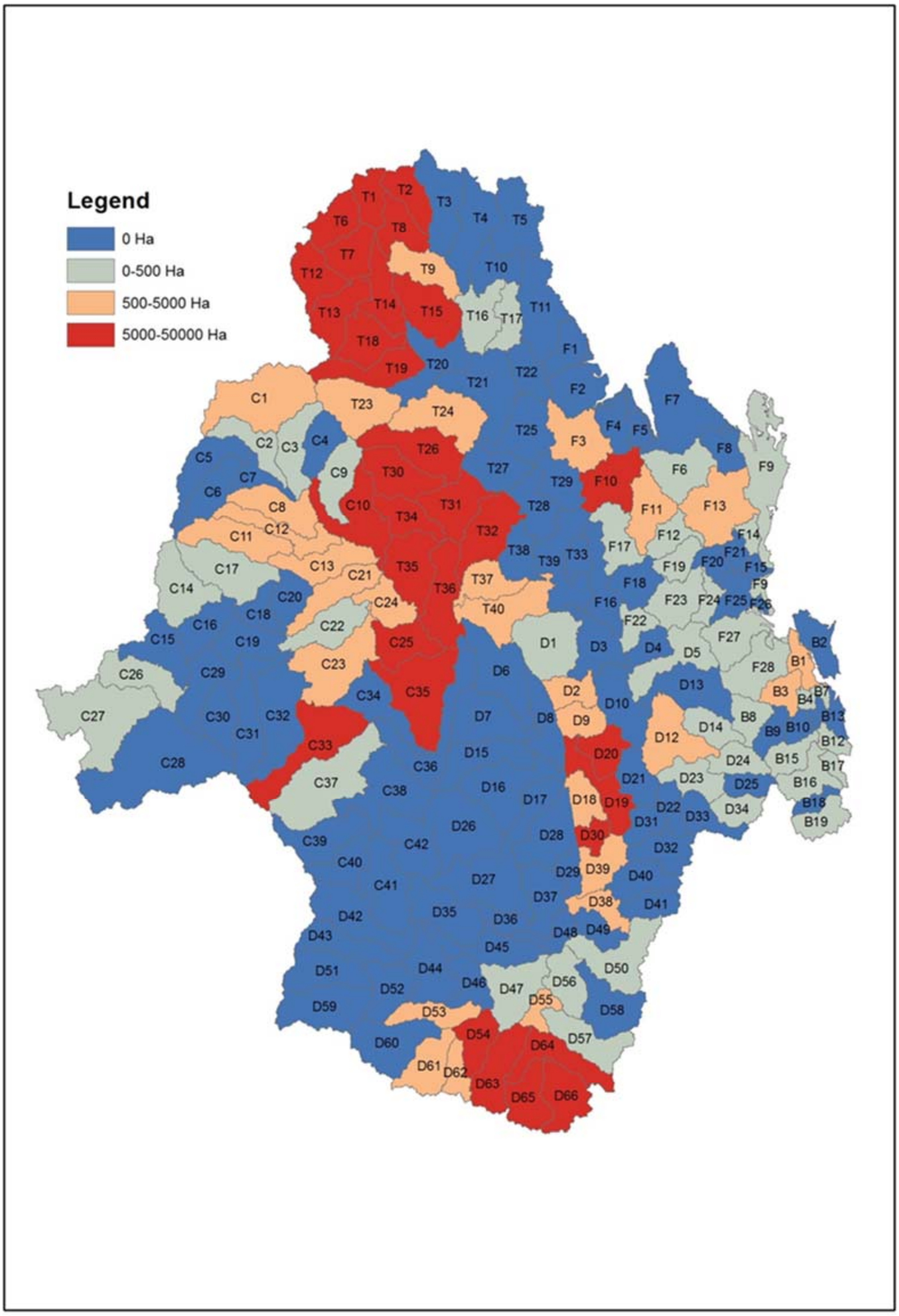
Management (weighting)		Outdated	Minimum Standard	Best Practice	Innovative, may not be economic in all situations	Not Applicable
		High Risk	Moderate Risk	Moderate - Low Risk	Lowest Risk	
	uptake of N fertiliser (20%)	in advance of planting.				
Pesticides	Targeting herbicide application (50%)		Knockdown and residual herbicides are usually applied through conventional boomspray with 100% paddock coverage.	Efforts are made to bandspray residual herbicides, and/or target specific zones within paddocks rather than apply to 100% of the paddock.	Volumes of herbicide applied are minimised through use of weed-detecting technology.	Rarely use herbicides. Usually rely on tillage or livestock for weed control.
	Efficient herbicide application	Boomspray does not operate in a controlled	Boomspray operates in a controlled traffic system to minimise overlap.	Boomspray operates under machine guidance of at	Boomspray operates under machine guidance of at least 10cm pass-to-pass accuracy in a controlled traffic system. Boom has automated section and	Rarely use herbicides. Usually rely on tillage or

Management (weighting)		Outdated	Minimum Standard	Best Practice	Innovative, may not be economic in all situations	Not Applicable
		High Risk	Moderate Risk	Moderate - Low Risk	Lowest Risk	
	(50%)	traffic system or with GPS guidance.		least 10cm pass-to-pass accuracy in a controlled traffic system. Boom has automated section control to further minimise overlap.	individual nozzle controls to further minimise overlap.	livestock for weed control.

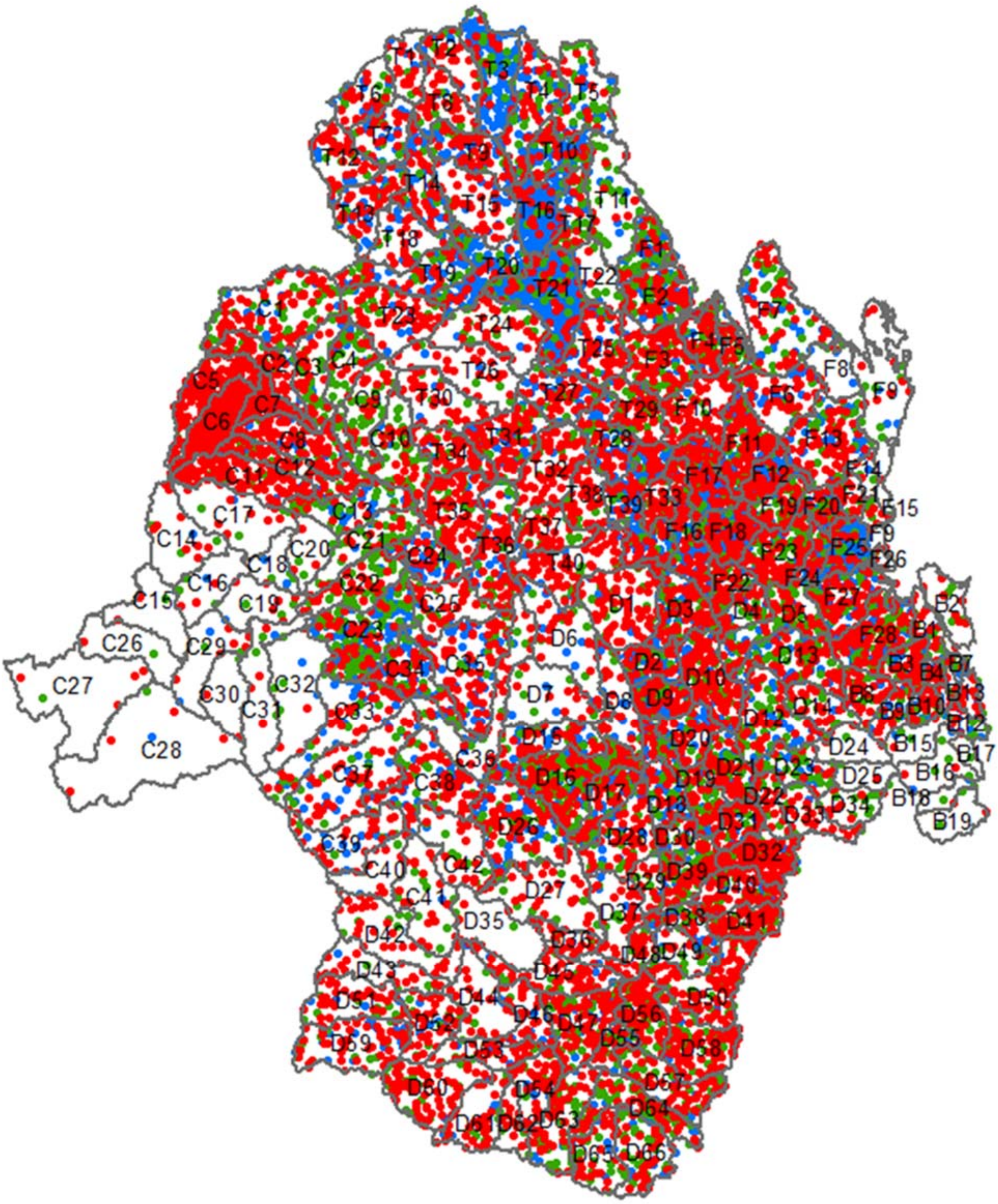
Appendix D: K- factor mapping (erosivity)



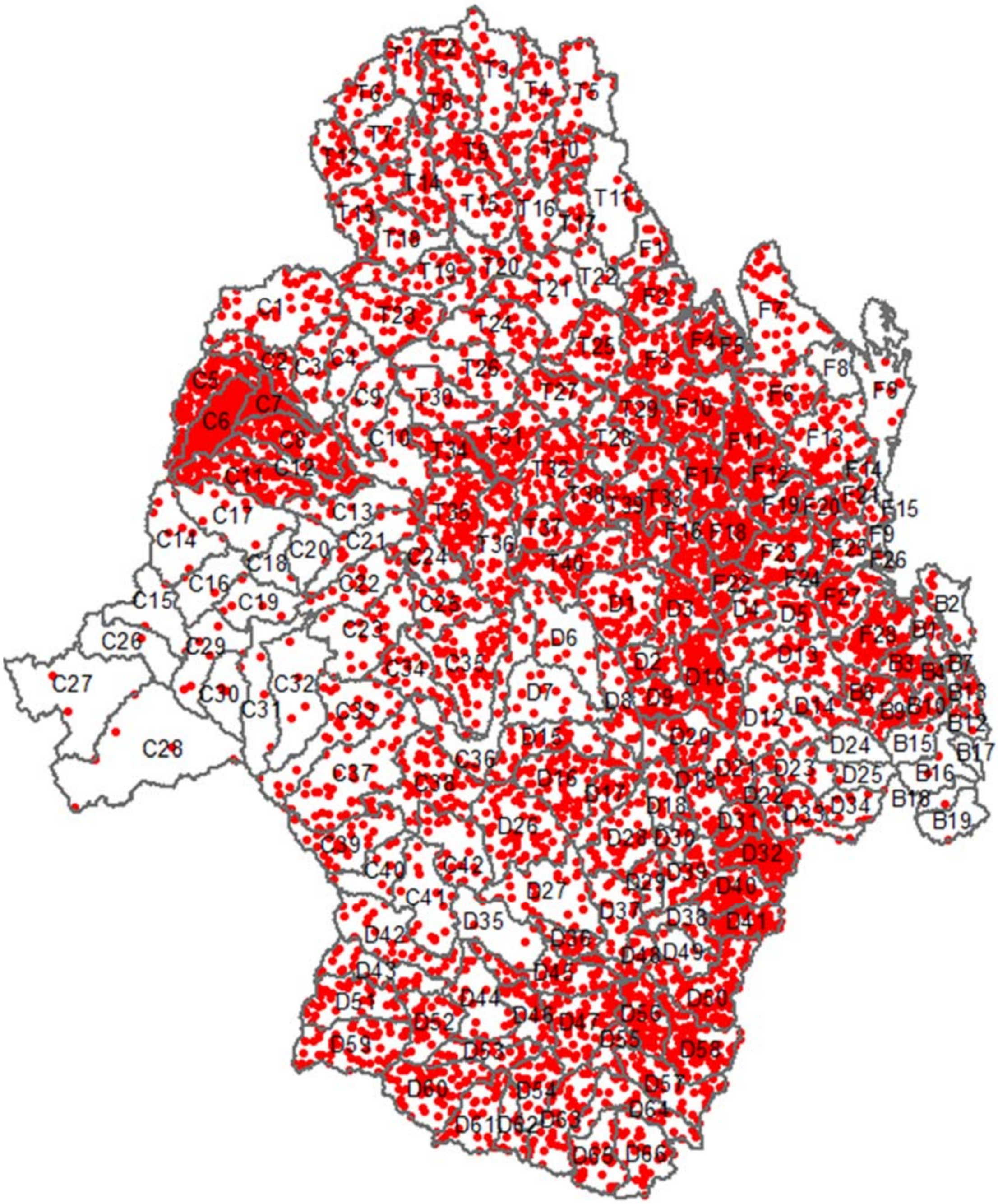
Appendix E: Area of mining owned grazing enterprises



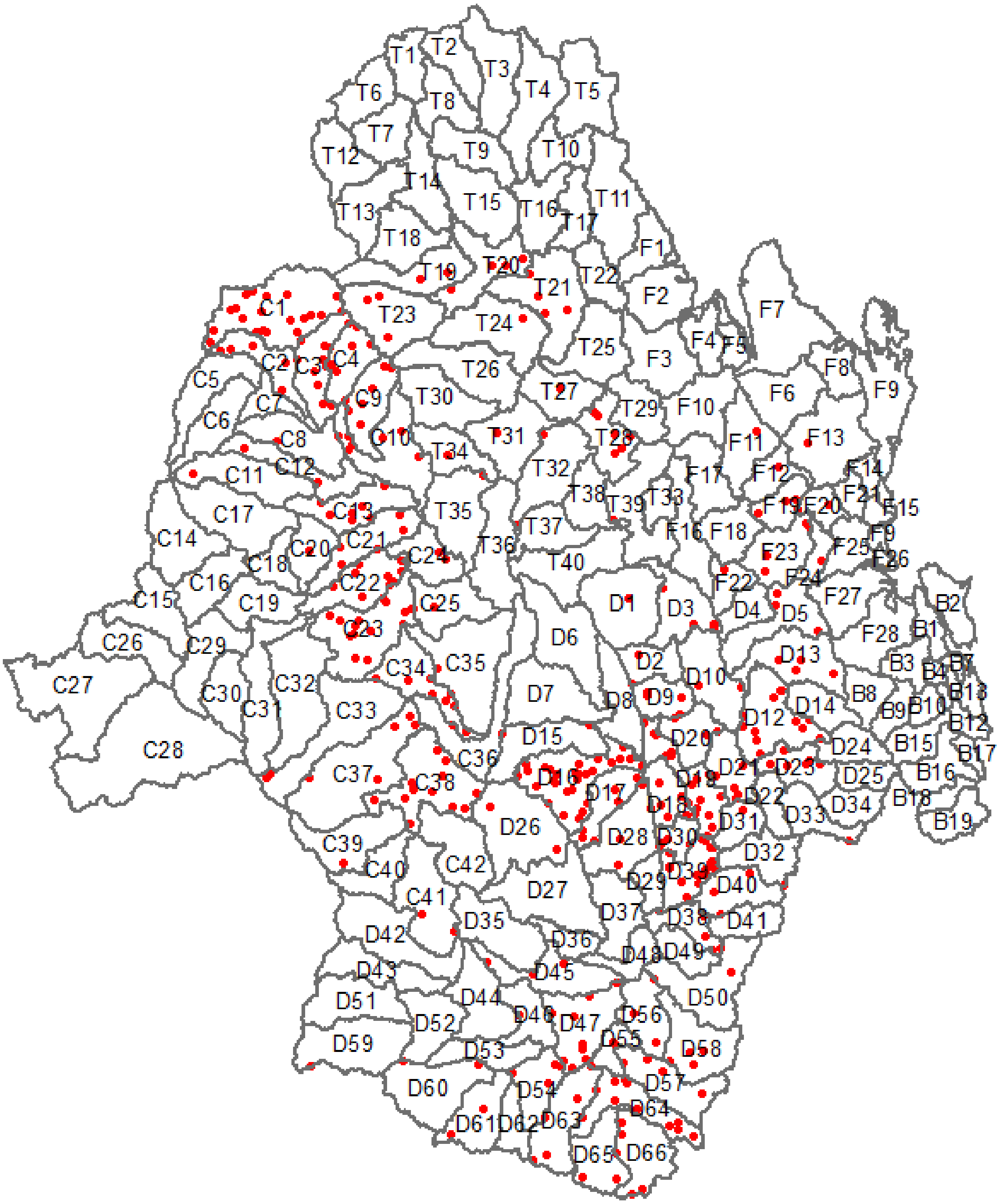
Appendix F: Total sediment load from grazing and grains across all erosion processes



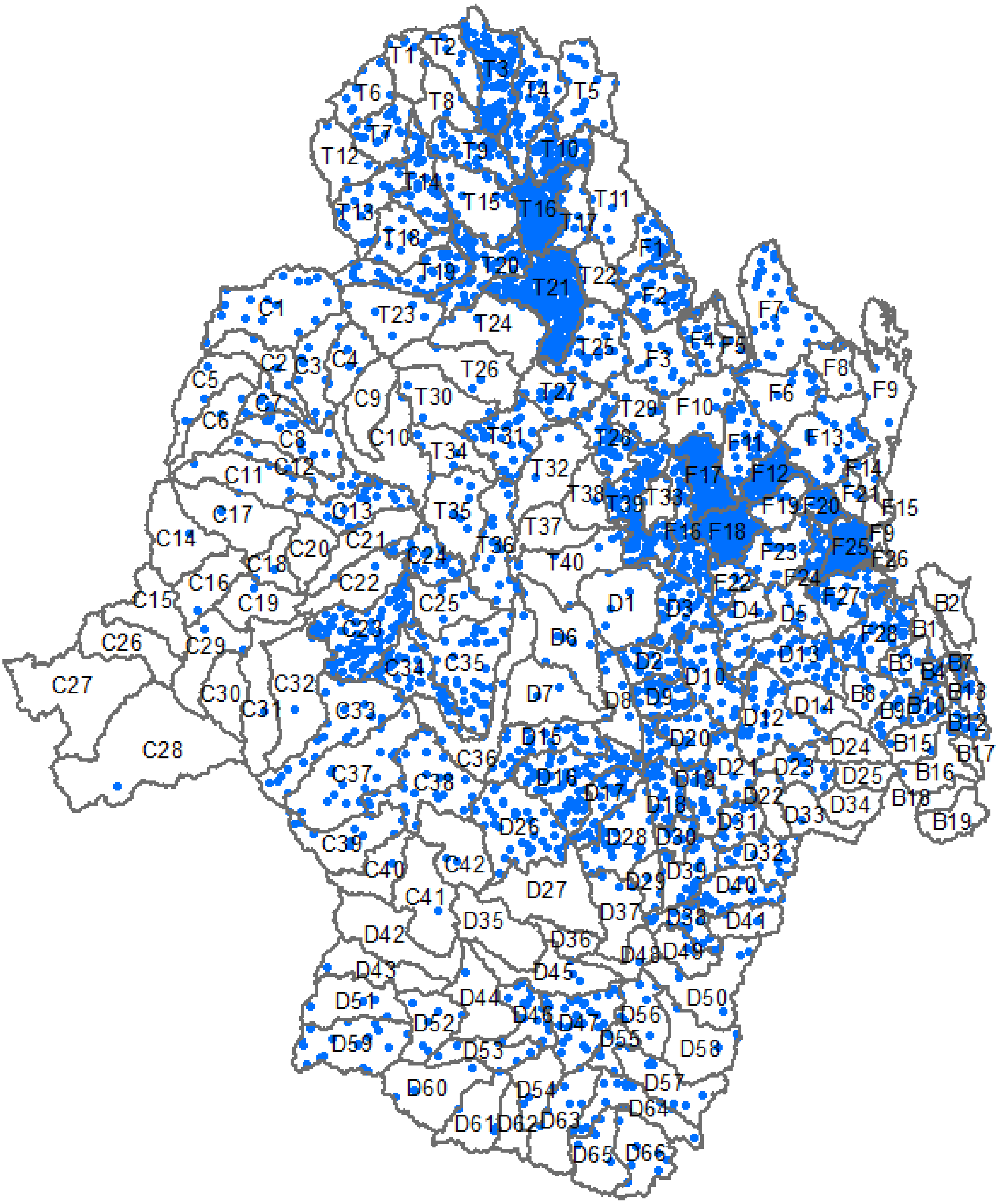
Appendix G: Total sediment from gullies in grazing lands



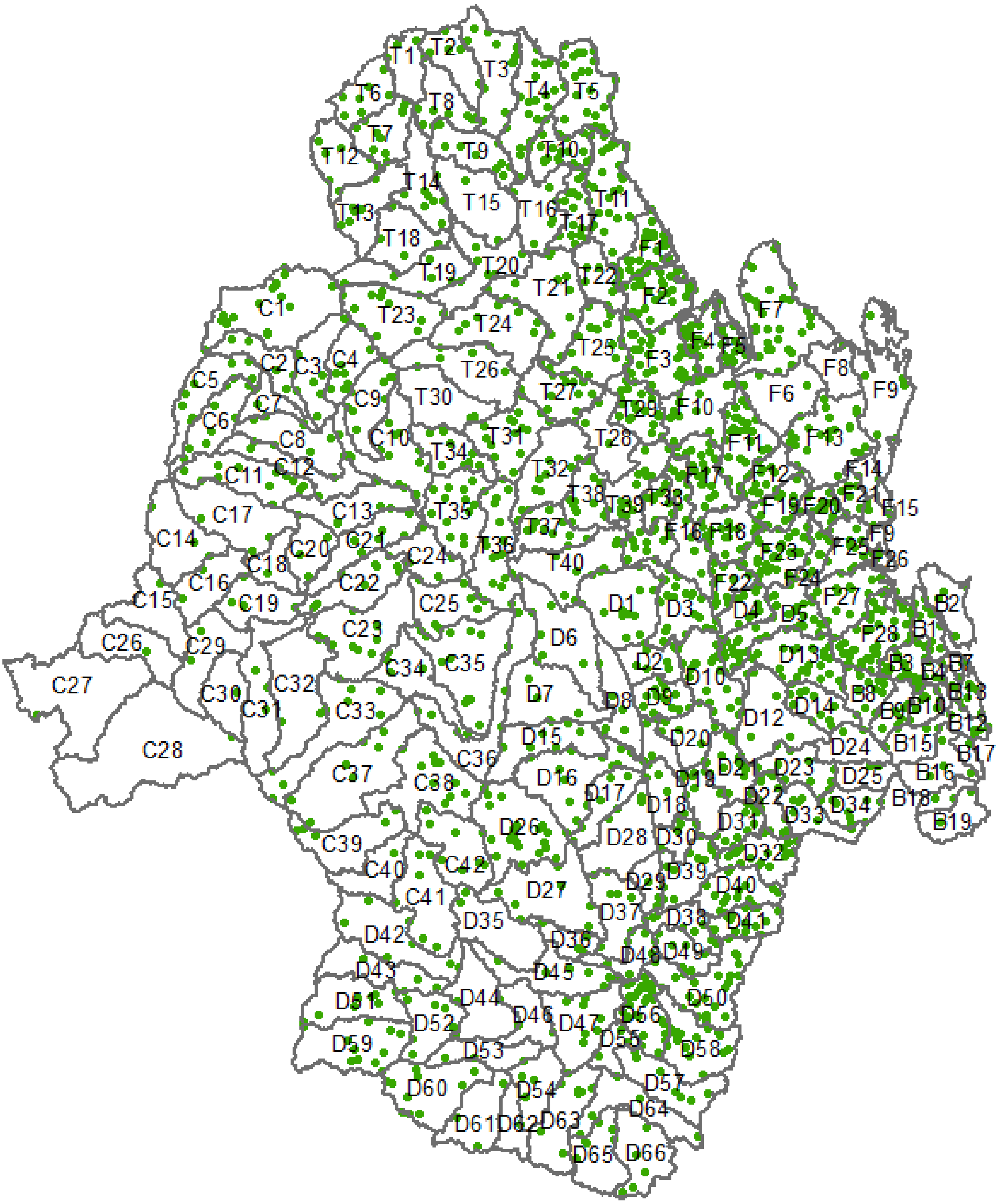
Appendix H: Total sediment gullies in grains



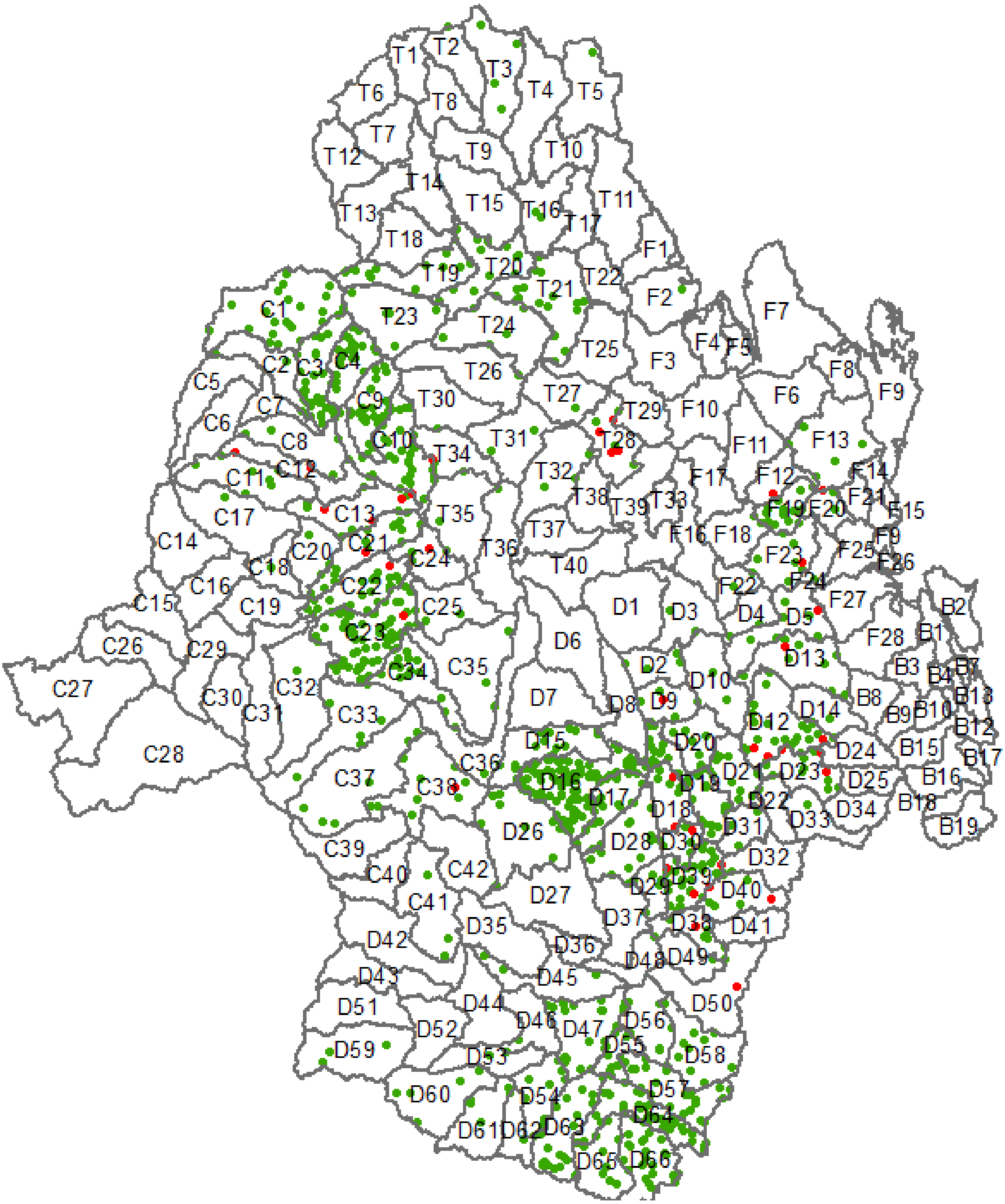
Appendix I: Total sediment from streambank



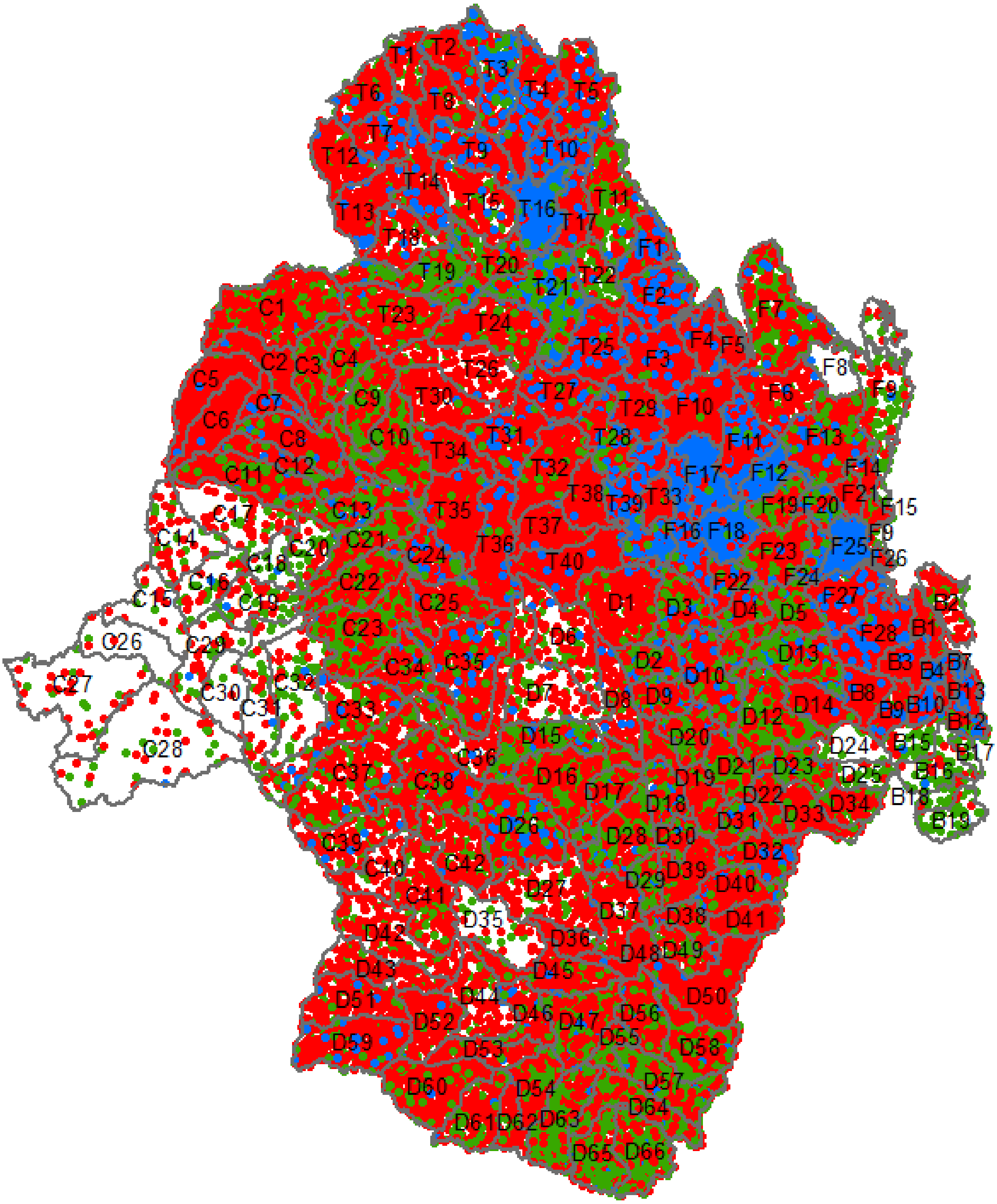
Appendix J: Total sediment from hillslope in grazing lands



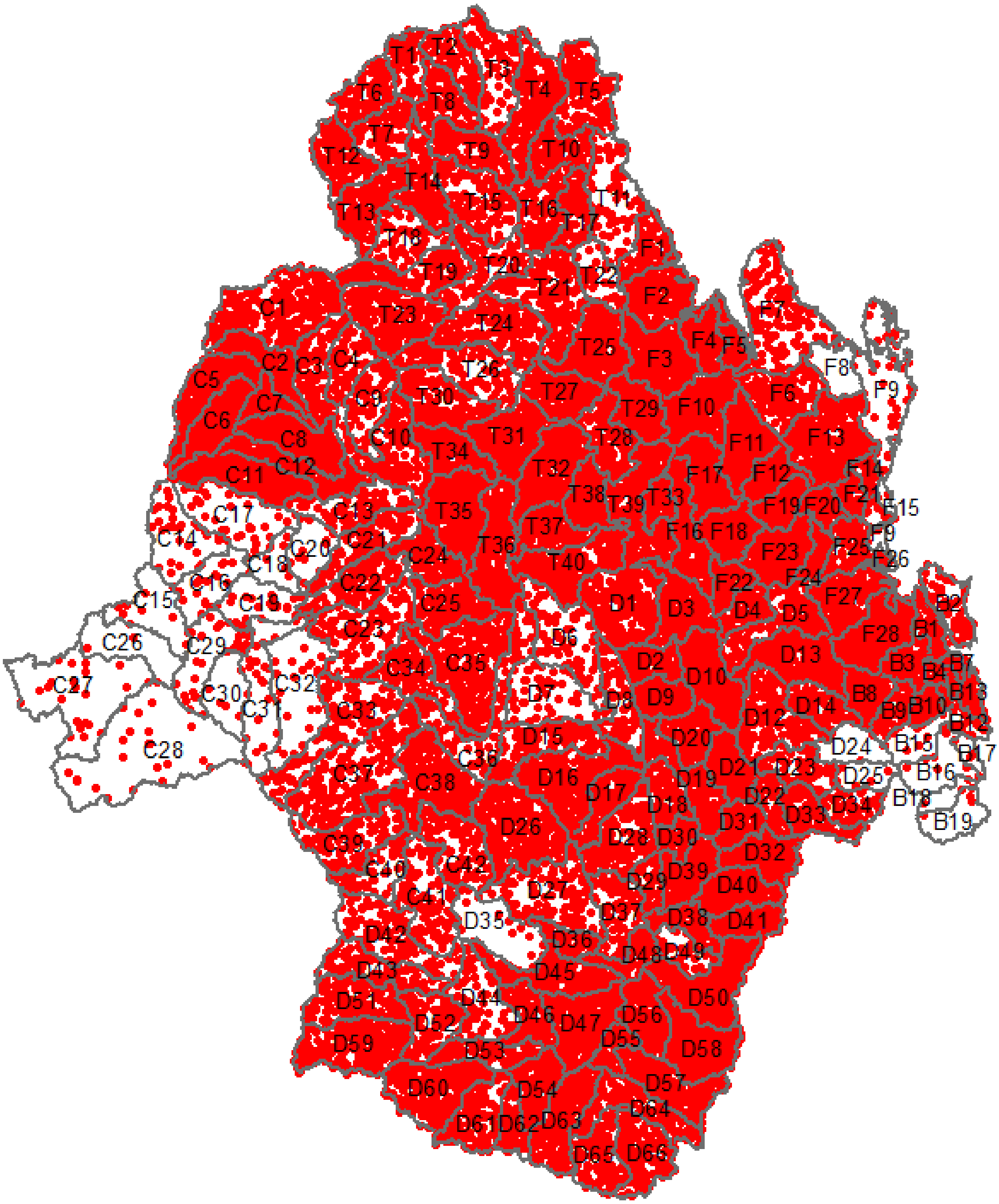
Appendix K: Total sediment from hillslope in cropping lands



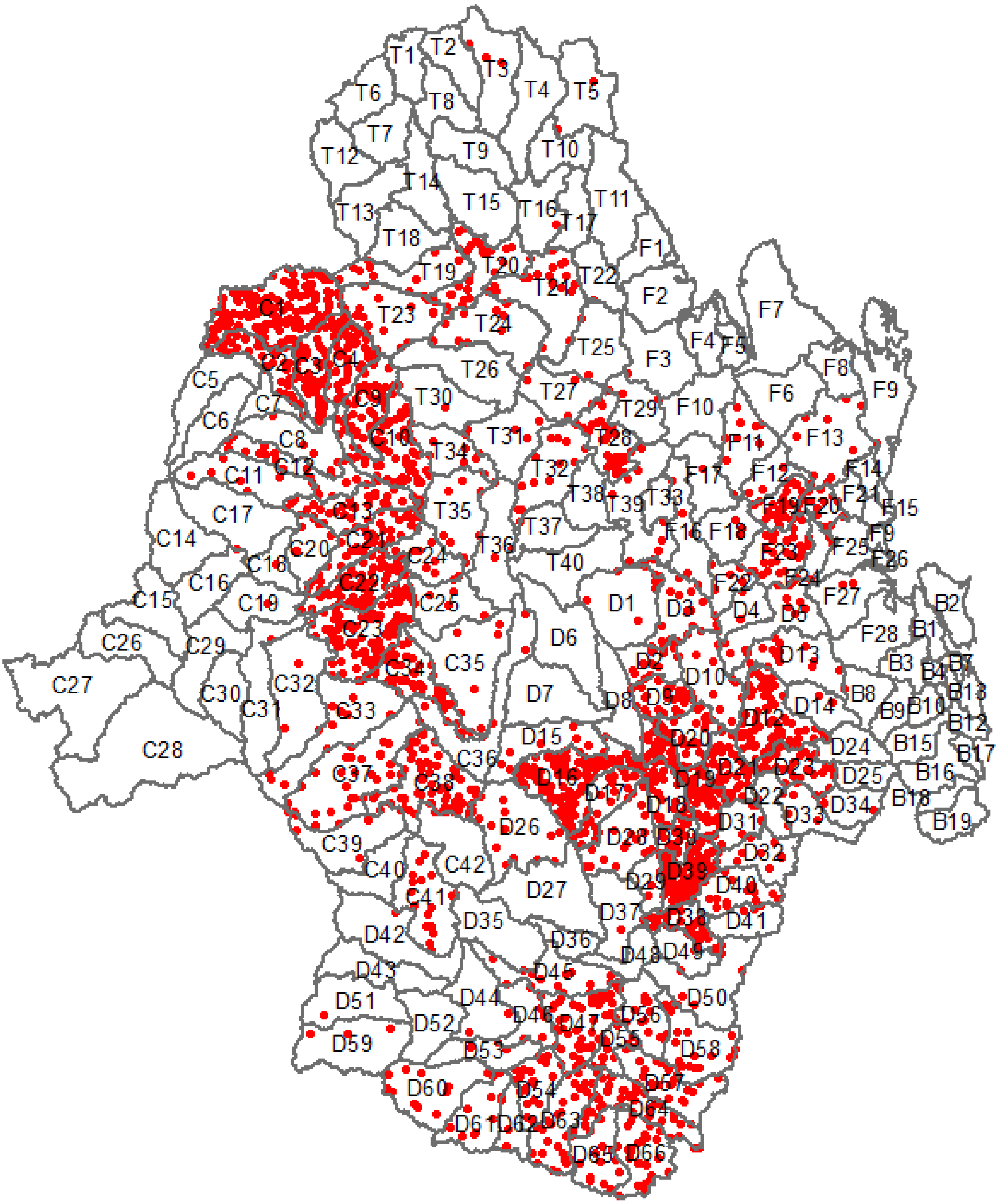
Appendix L: Total particulate nitrogen from all erosion processes both grains and grazing



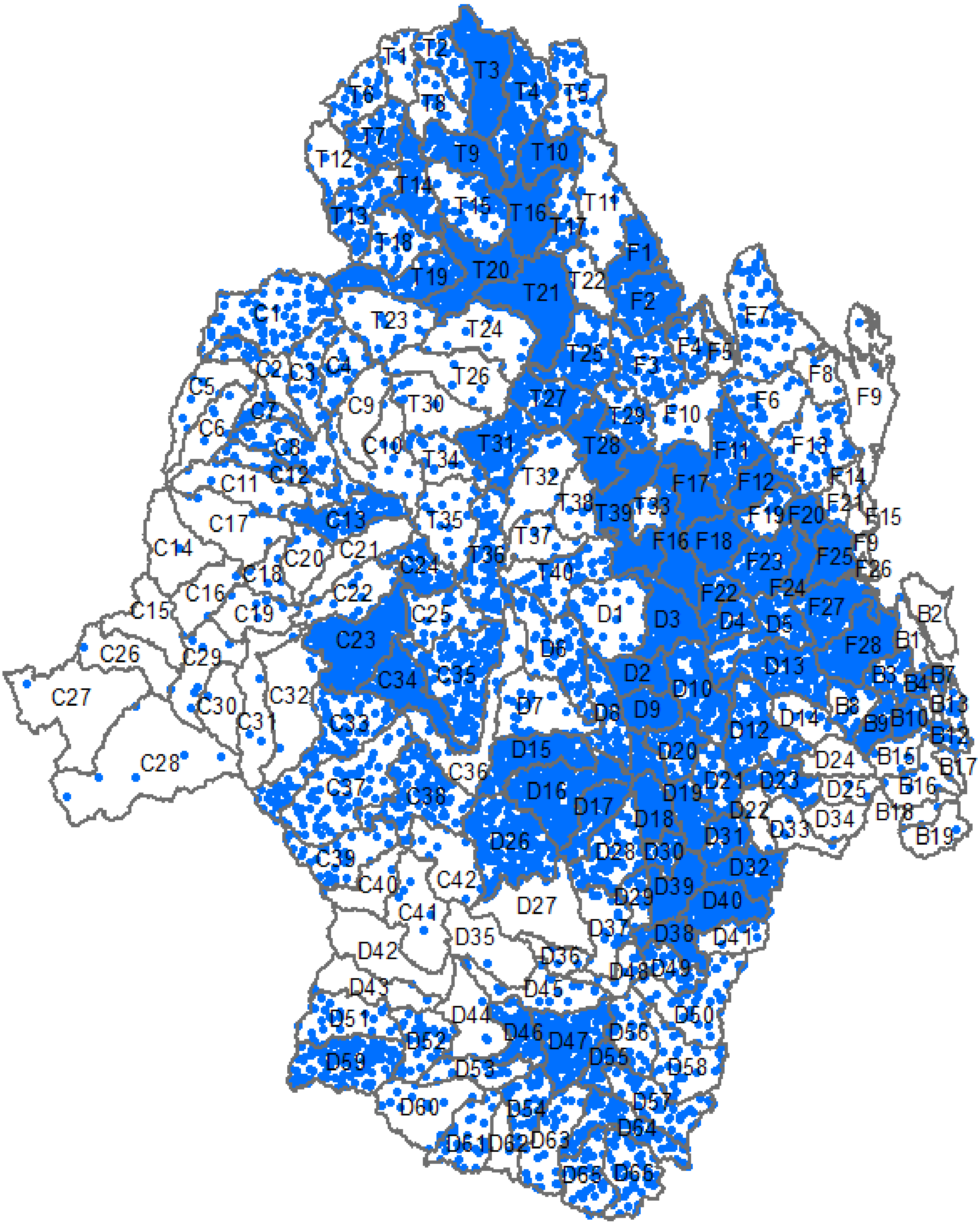
Appendix M: Particulate nitrogen from gullies in grazing



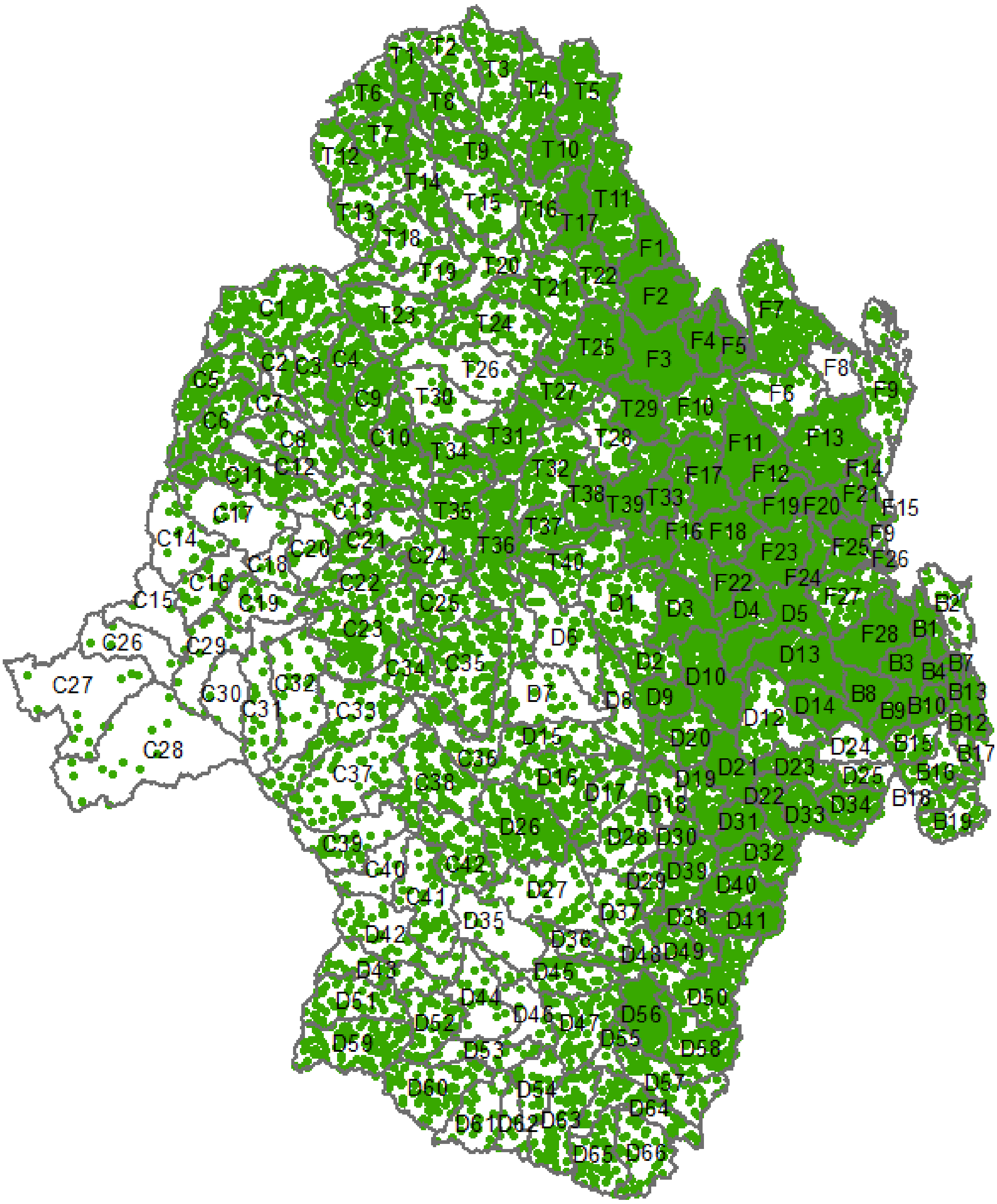
Appendix N: Particulate nitrogen from gullies in grains



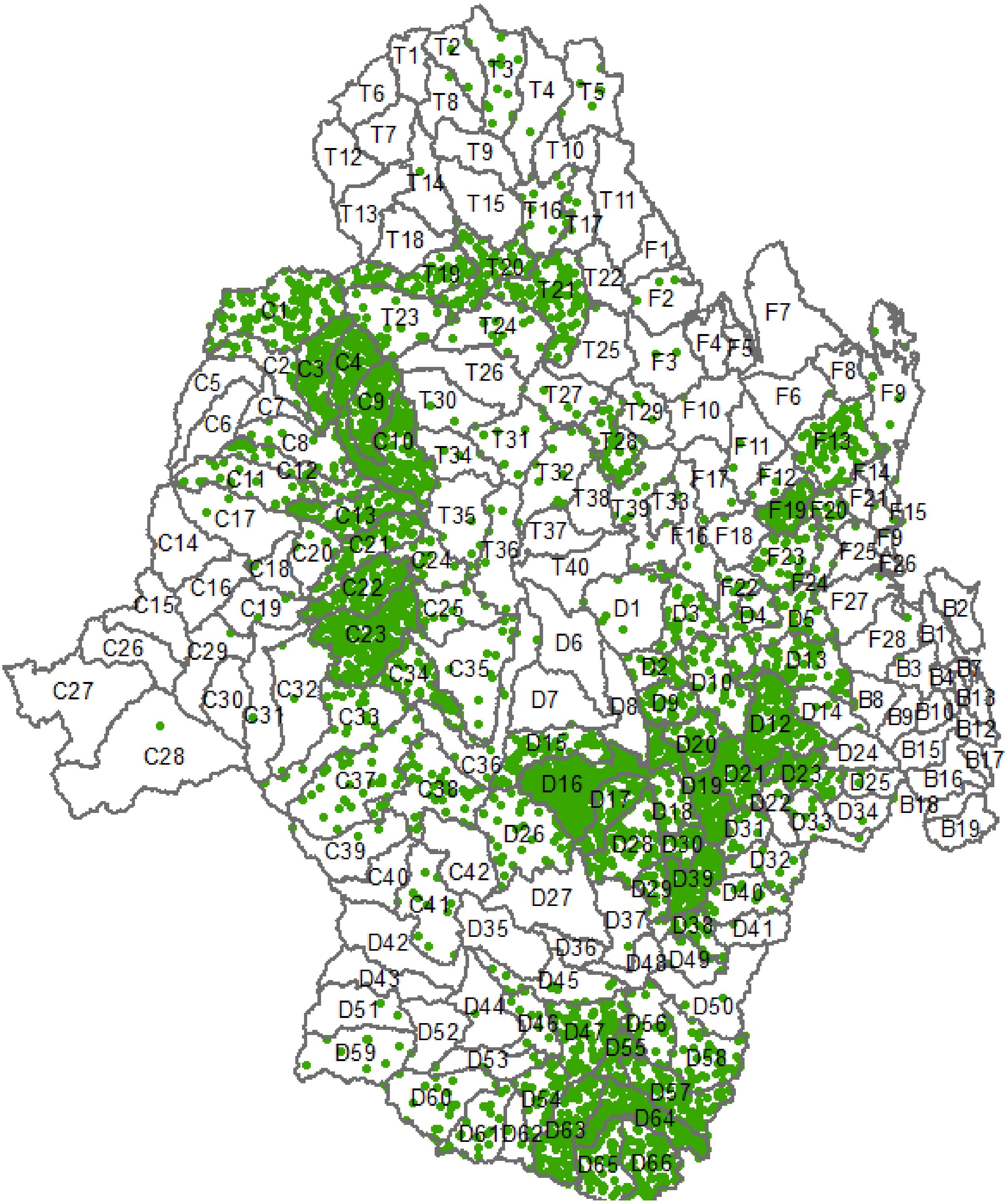
Appendix O: Particulate nitrogen in streambank



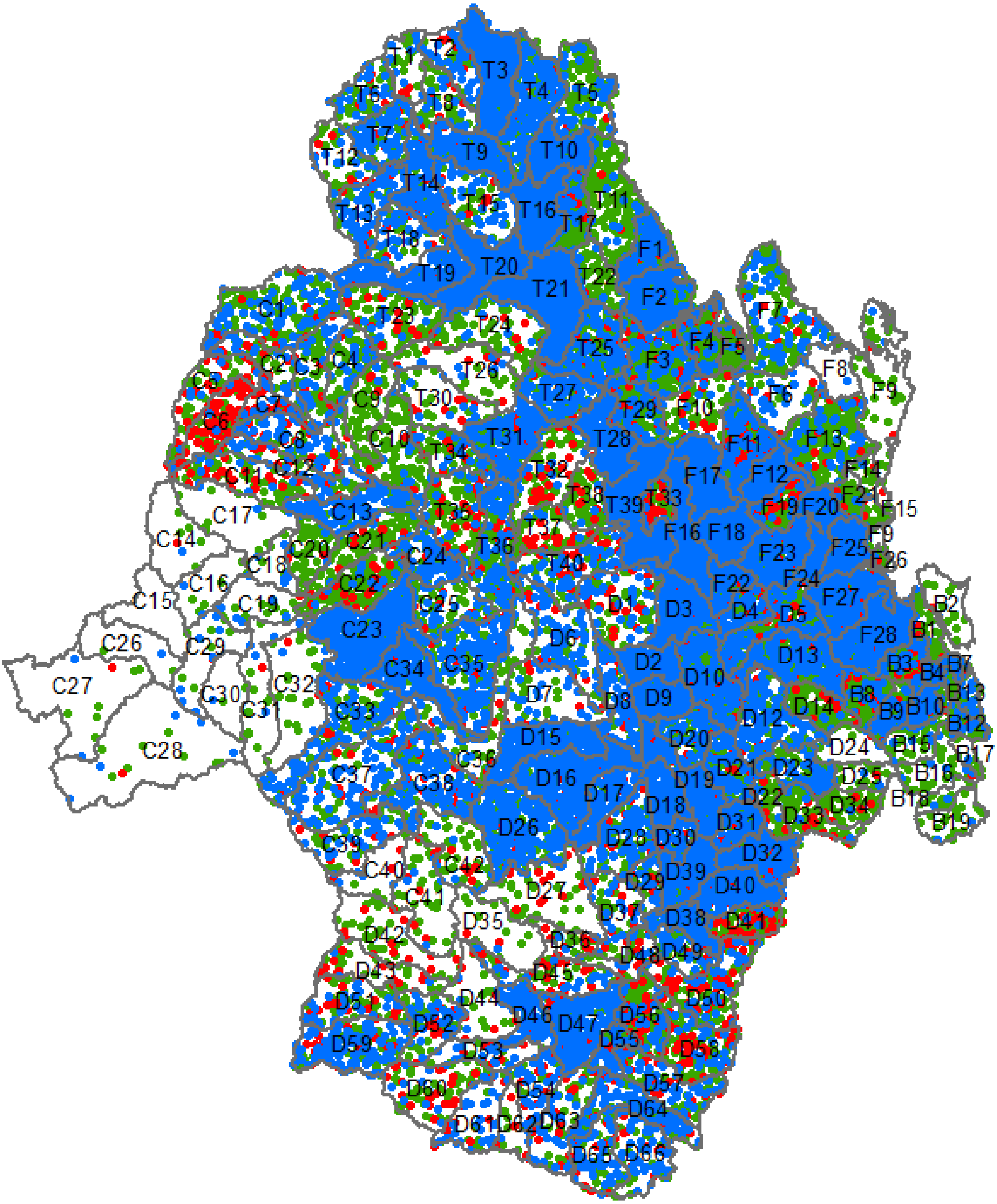
Appendix P: Particulate nitrogen in hillslope on grazing lands



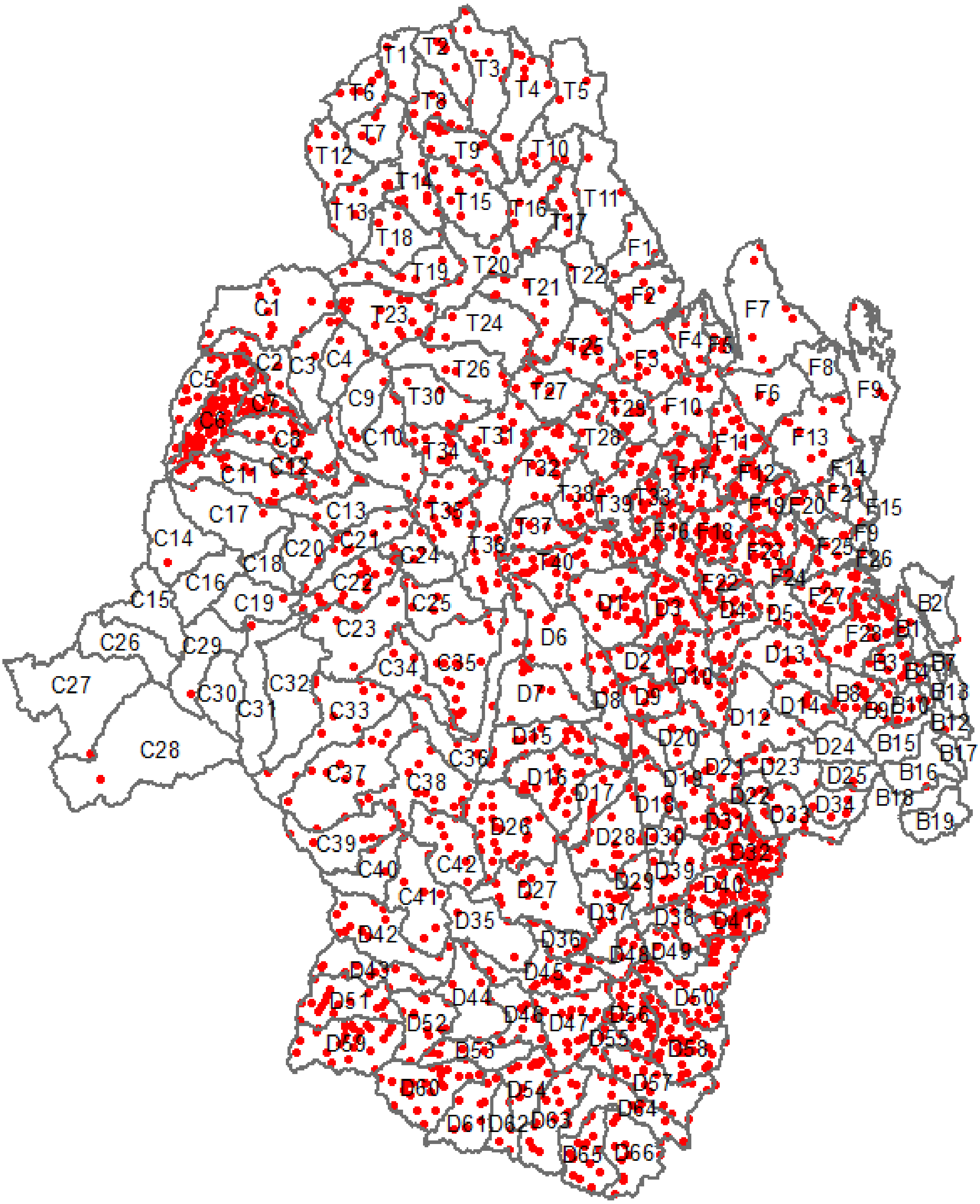
Appendix Q: Particulate nitrogen in hillslope on grains



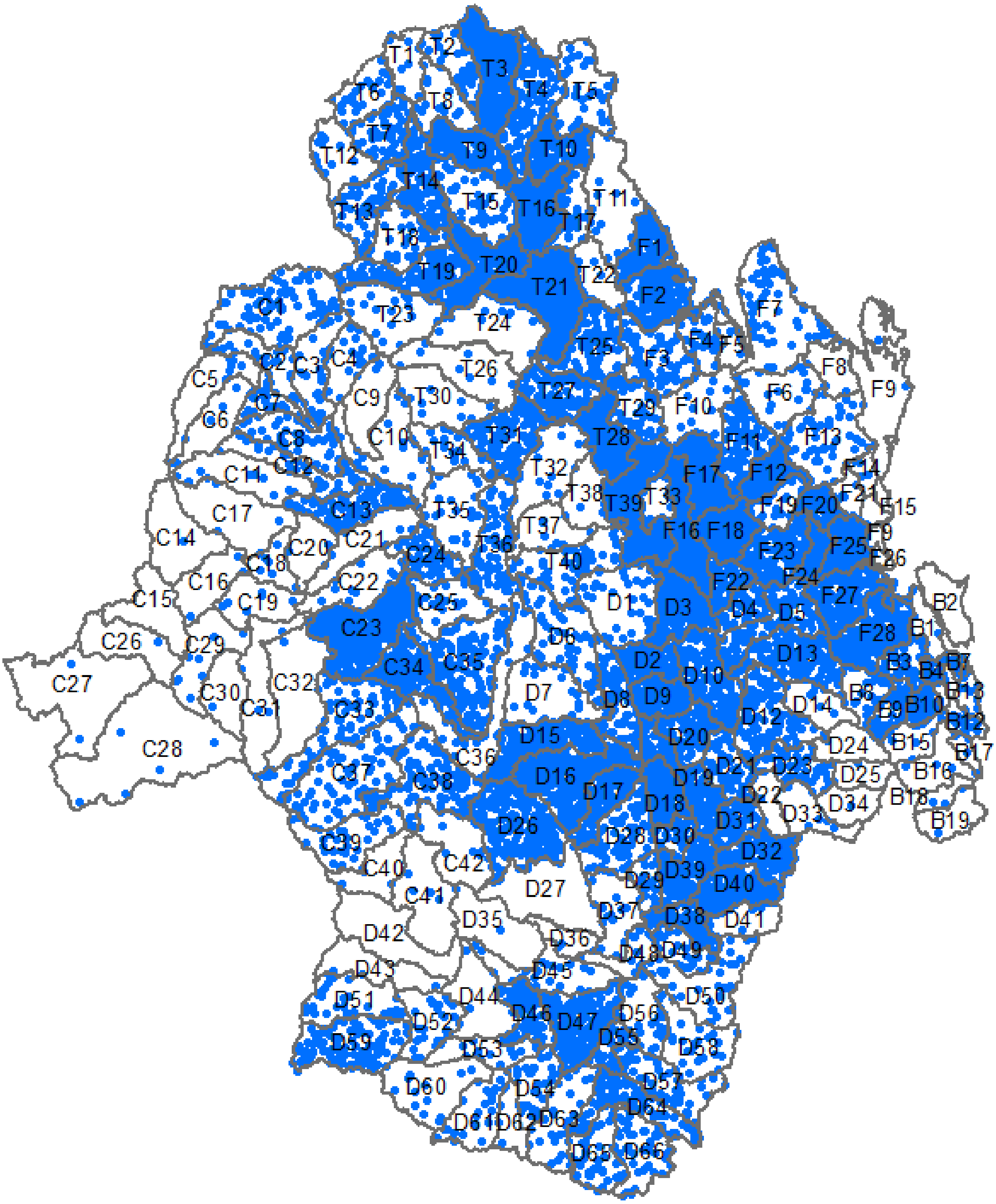
Appendix R: Particulate phosphorus in grazing lands from all erosion sources



Appendix S: Particulate phosphorus from gullies in grazing lands



Appendix T: Particulate phosphorus from streambank in grazing lands



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