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Tradeoffs between soil, water, and carbon – A national scale analysis from New Zealand

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ABSTRACT

The tradeoffs between the regulation of soil erosion, provision of fresh water, and climate regulation associated with new *Pinus radiata* forests in New Zealand are explored using national models. These three ecosystem services for which there is strong demand are monetised as commodities (avoided soil erosion is NZ $1 per tonne; water is NZ $1 per cubic metre; and sequestered carbon is assumed to be NZ $73 per tonne). This permits their summation on a spatial basis to produce a national map of the net benefit of these ecosystem services. Net benefit is spatially variable depending primarily on the relative mix of forest growth rates and demand for irrigation water. New *P. radiata* forests (once mature) generally reduce mass-movement erosion by an order of magnitude. This provides significant benefits for erosion control where there are high natural rates of erosion. Benefits are especially large in catchments where high sedimentation is increasing flood risk and degrading aquatic ecosystems. The generally high growth rates of *P. radiata* in New Zealand (8.5 tonnes C ha^{-1} yr^{-1} on average for existing forest) add significant environmental benefits of carbon sinks to climate regulation. However, the reduction of water yield associated with new forests (between 30% and 50%) can neutralise these benefits in catchments where there is demand for irrigation water, such as the eastern foothills of the Southern Alps and the tussock grasslands in the South Island.

1. Introduction

In 100 years following the beginning of European settlement in 1840, much of the original indigenous forest in New Zealand has been converted to pasture (Cumberland, 1947; MfE, 2010a,b reported 30% remaining). In hill country, where tree roots are important for stabilising slopes, deforestation has led to increased soil erosion and reduced productivity. There has also been increased sedimentation in waterways, which has detrimental effects on aquatic ecosystems by smothering habitat and reducing penetration of photo-synthetically active light (Ryan, 1991). Turbid water also reduces recreational values (Jowett and Mosley, 2004). And the flood capacity of rivers has reduced (Krausse et al., 2001). The remedy for soil erosion in hill country is tree planting: reforestation or shrubland reversion on steep slopes; and agro-forestry or soil conservation planting (usually poplar trees planted about 15 m apart) on less steep slopes (Hicks, 1995; MAF, 2010e).

Tree planting has the additional benefit of sequestering carbon from the atmosphere and thereby helping to regulate the climate. Indeed, reforestation on marginal land may be justified on the basis of carbon sequestration independent of soil erosion mitigation. Soil conservation plantings such as space-planted poplars on slopes or pair-planted poplars on gullies store little carbon per hectare. But production forestry can sequester carbon at high rates – up to 14 tC ha^{-1} yr^{-1} for *Pinus radiata* forest in New Zealand. And these high sequestration rates can be maintained over several rotations of planting, growth, and harvesting. Indeed, the New Zealand Government is currently claiming that 566,000 hectares of new forest (since 1990) will offset some 6.6 million tonnes of carbon dioxide emissions over the 2008–2012 Kyoto commitment period (Ministry for the Environment, 2009a,b).

The New Zealand Government has recognised public good services, in addition to private good, provided by afforestation in a number of schemes. The Afforestation Grant Scheme operates by tender for landowners to establish new forests in return for carbon credits (MAF, 2010a). The East Coast Forestry Scheme provides subsidies to owners of new forests on erosion prone land in the East Coast region where anthropogenic erosion rates are the highest in New Zealand (MAF, 2010a). The Emissions Trading Scheme devolves carbon credits (and liabilities) from the New Zealand Government to owners of new forests (MAF, 2010b).

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The Permanent Forest Sink Initiative devolves carbon credits from the New Zealand Government to owners of new permanent forests (MAF, 2010a). There are also central government and local government subsidies for soil conservation planting of erosion prone land (MAF, 2010c), which can include forestry less than 5 ha in area.

While these schemes seek to achieve a better balance between economic returns from pastoral agriculture and environmental benefits for the community, there are other important ecosystem services to be considered, such as the provision of fresh water. The demand for irrigation water is rapidly increasing as pastoral agriculture intensifies and horticulture expands. Despite generally large water yields in New Zealand rivers due to high rainfall in the hills and mountains, much of this water races quickly to the sea during flood and mean flow conditions (Waugh, 1992). At low-flow conditions, usually at the end of summer, water available for run-of-river extraction is limited. Historically, rights to extract water from rivers were granted on a first-come-first-served basis as total consents rarely exceeded extraction limits set through environmental considerations (Ministry for the Environment, 2004). Recently however, there are catchments in New Zealand where applications for water consents are exceeding the amount of water deemed to be available (Ministry for the Environment, 2009a,b). Therefore the basis for allocating consents is having to be rethought (Land and Water Forum, 2010). There is also increased consideration of using water storage through engineering solutions to regulate water supply more evenly through the year.

In addition to erosion control and climate regulation (through carbon sinks), forests also have significant effects on the provision of fresh water. Several case studies in New Zealand have shown that forests reduce water yield (Dons, 1987; Smith, 1987; Duncan, 1995). The reduction is thought to be controlled by the increased interception of rainfall and subsequent evaporation. This reduction of water yield with afforestation is observed commonly throughout the world (Jackson et al., 2005) even though there are also some instances where low flows in large river systems increase with afforestation (Zhongwei et al., 2000; Nyangaga, 2010). With the increasing importance of water in New Zealand for irrigation it is expedient to consider the effects of afforestation on the provision of fresh water in addition to erosion and climate regulation.

There is increasing recognition worldwide that ecosystem services should be incorporated into resource management decisions (Daily et al., 2009; MA, 2005; Boody et al., 2005). From the perspective of collective humanity, the argument basically comes down to common sense – we want to maximise human well-being, and the best way to do that is to maximise all those contributing services, not just the provisioning services of food and fibre. However, evaluation of all ecosystem services is a demanding task for the science community. Some researchers have identified subsets of critical services (for the resource management decision in question) and evaluated these in detail (Grêt-Regamy et al., 2008; Chisholm, 2010). Even then evaluation of tradeoffs is complex, because there are still multiple dimensions (several services) with different physical units and with spatial variation. Transformation of physical units to dimensionless units can help (Nelson et al., 2009), but the scale of transformation can be somewhat arbitrary depending on whether a goal-based or limit-based approach is adopted (Ausseil and Dymond, 2010).

Landcare Research has begun a major research program to characterise ecosystem services throughout New Zealand (Landcare Research, 2010c). Regulation of soil erosion, provision of fresh water, and climate regulation are three services considered critical for reasons already given here. In this paper, we present nationally applicable models for quantifying these services in spatial detail. The concurrent use of these models permits a more complete investigation of ecosystem services associated with afforestation. At the national scale, we suggest that co-benefits and tradeoffs of these three services are usefully evaluated by quantifying the commodities of avoided soil erosion, water, and sequestered carbon. Monetisation of these commodities, for which there is demonstrated demand, transforms a three-dimensional problem to one dimension, and also enables comparison with monetary values of food and fibre.

2. Methods

To evaluate the tradeoffs between soil, water, and carbon, we simulate a land-cover scenario where all presently non-forested areas (15 m by 15 m grid cells) are planted with forests, called the “all forest” scenario. We assess the change in erosion, water yield, and forest carbon for every grid cell as follows.

2.1. Net environmental benefit

The net environmental benefit of afforestation, ΔV, was calculated as:

$$\Delta V = \Delta S + \Delta W + \Delta C \tag{1}$$

where ΔS, ΔW, and ΔC are the environmental benefits from changes in erosion, water yield and carbon storage, respectively, expressed in units of \$NZ ha^{-1} converted.

In particular, they were calculated as:

$$\Delta S = k_s\left(\bar{e}_p - \bar{e}_f\right) \tag{2}$$

$$\Delta W = -k_w\left(Y_p - Y_f\right) \tag{3}$$

$$\Delta C = k_c\left(C_f - C_p\right) \tag{4}$$

where $\bar{e}$, Y and C are the respective erosion rates (tonnes km^{-2} yr^{-1}), water yield (mm yr^{-1}), and carbon storage (tonnes ha^{-1} yr^{-1}) for pasture (subscript p) and forest land (subscript f), respectively, and k_s, k_w and k_c are conversion terms to convert from units of the physical quantities to their monetary equivalents. Equation (1) was evaluated for every 15 m by 15 m grid cell in New Zealand.

2.2. Erosion model

High tectonic uplift in New Zealand combines with high precipitation (more than 1000 mm for most of New Zealand and up to 15,000 mm per year on top of the Southern Alps) to produce naturally high erosion rates. Erosion processes are dominated by mass-movement, including shallow and deep-seated landslides, debris avalanches, large gullies, and earthflows (Eyles, 1983). As such, models of surficial erosion commonly used internationally (e.g. USLE, WEPP), are not generally applicable in New Zealand, except for lowlands. Dymond et al. (2010a) developed an empirical model (NZeem®) of all erosion processes in New Zealand. The model is based on measurements of suspended sediment yields throughout New Zealand which are attributed to the landscape on the basis of known relative relationships with mean annual rainfall (including snowfall) and landcover. The inputs to the model exist in spatial data layers (at scales of approximately 1:50,000) with national coverage. The model is written

$$\bar{e}(x,y) = a(x,y)K(x,y)R^2(x,y) \tag{5}$$

where $\bar{e}(x,y)$ is the mean annual rate of erosion in tonnes km^{-2} yr^{-1}, $a(x,y)$ is the erosion coefficient which depends