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Impacts of mass movement erosion on land productivity: a review

Paul M. Blaschke,[1] Noel A. Trustrum[2] and Douglas L. Hicks[3]

[1]Boffer Miskell Ltd, PO Box 11 442, Wellington, New Zealand
[2]Landcare Research New Zealand Ltd, Private Bag 11-052, Palmerston North, New Zealand
[3]Ecological Research Associates (NZ) Inc., PO Box 170, Orewa, New Zealand

Abstract: Wherever people gain their livelihood in mountains and steeplands, the productive capacity of the soils they use is likely to be affected by mass movement erosion. The impacts of mass movement erosion on land productivity are significant but under-rated in the scientific literature. Impacts on cropping are here reported from 15 countries in south and southeast Asia, east Africa, the Caribbean and Melanesia, but accounts are generalized or anecdotal, and do not quantify crop loss or damage attributable to mass movement separately from that due to surface or fluvial erosion. Impacts on pastoral grazing have been studied in New Zealand, where production losses of up to 80% at field scale, and up to 20% at farm scale, have been measured. Studies in the Pacific Northwest coastal forests of North America show plantation forest wood volume declines by 35–50% on eroded sites. Mass movement impacts on production from tropical forests or agroforestry appear to be as yet undocumented.

The reasons for lack of documentation are, first, that most soil erosion–productivity research has been done on gently sloping cropland, which is subject to surface rather than mass movement erosion. Secondly, geomorphological research in steeplands has dealt with mass movement as a hazard to human life, settlements and infrastructure – with limited identification of its contribution to sediment loads in rivers, and disregarding its impact on land productivity.

We suggest there are many other countries where significant impacts are likely to occur, and that erosion–productivity studies should pay more attention to this type of erosion. Studies should not be restricted to cropland, but also extend to grazing land, plantation forestry, agroforestry and traditional uses of natural forest as mass movement appears to affect all these forms of land-based production, particularly in densely populated steeplands whether tropical or temperate. Topics needing study are the documentation and costing of productivity losses, ways to reduce mass movement impacts on productivity, and ways to enhance recovery of soil on eroded areas (e.g., revegetation with fertility-building shrubs and legumes).

Key words: erosion, land productivity, landslides, mass movement, off-site impact, on-site impact, primary production, production loss, soil degradation.

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I Introduction

Erosion is one of the most pervasive forms of soil degradation and is the subject of increasing concern because of its implications for food production for a rapidly increasing world population. The impacts of erosion on land productivity are particularly significant because losses are generally cumulative and, on a human timescale, permanent. On the other hand, any cause-and-effect relationships between soil erosion and reductions in productivity are complex and often indirect. Accordingly, erosion–productivity relationships have been the subject of considerable research. Searches of the Commonwealth Agricultural Bureau's (CAB) Geobase abstracts database, undertaken between 1993 and April 1998, revealed nearly 5400 items which combined the key words *production* (or *productivity*) and *erosion*. In the last 15 years, a number of global or regional reviews of the subject have been carried out, including those of Crosson (1984), FAO (1984), Follett and Stewart (1985), Larson *et al.* (1983; 1985), Lal (1986; 1987), Lal and Stewart (1990), Roberts (1992) and Dregne (1990; 1992; 1995). However, this literature reveals marked geographical unevenness in coverage. Stocking (1985) has estimated that 60% of the literature comes from the USA, which has only about 5% of the world's potentially cultivable land. On the other hand, a number of authors have commented that the subject is considerably under-researched in tropical environments (Dregne, 1990; Lo, 1990; Bojö, 1991), although this situation is improving (Lal, 1990; FAO, 1991; Stocking and Saunders, 1992).

There are further inconsistencies in the topics researched. In line with the geographical dominance of USA-based research, most of the literature deals with impacts on crop production on gently sloping, mechanically cultivable land, principally subject to *surface forms of erosion*. Other land types have received much less attention, notably large areas of steeplands used for crop production in several climatic zones, whether through terracing or through manual cultivation of natural slopes. Other productive land uses, such as grazing or forestry, also tend to be overlooked. Steeplands are commonly subject to *mass movement* erosion types, such as landslides, debris flows and slumps. Sidle *et al*. (1985: 1) noted that 'mass movements can decrease primary land productivity and thus may be one of many factors preventing sustained land use'. They also noted in their conclusion (p. 119):

> We think we have identified major gaps in knowledge concerning soil mass movement . . . which deserve concentrated attention in future research . . . At the broad regional and national levels, too little is known of the effects of mass movement erosion on the productivity of pastoral, agricultural and forest land. These persistent on-site costs of mass movement erosion have received much less emphasis than have off-site impacts and costs . . .

Of the 5400 literature items concerning erosion and productivity in our CAB searches, 175 also contain the key words *mass movement*, or *landslide*. Of those items, only about 25 contain information substantially drawn on in the present review. This confirms that a gap in the literature, previously detected by the reviews of Sidle *et al*. (1985), Trustrum and Hawley (1986) and Blaschke and Trustrum (1996), still persists.

In this article we review the literature available to us (predominantly English language) about worldwide impacts of mass movement on land productivity. We wish to show that these impacts are both significant and under-rated in a range of environments, tropical and temperate, and warrant further research.

II Terminology

In this review, the treatment of mass movement as a type of erosion largely follows that of Crozier (1986). Mass movement is defined by Crozier (1986: 6) as 'the outward or downward gravitational movement of earth material without the aid of running water as a transportational agent'. *Mass wasting*, *slope movement* and slope failure are commonly used synonyms. In Crozier's treatment, mass movement includes the processes of subsidence and creep which lack discrete failure boundaries, but as landforming processes these two are insignificant in comparison with *discrete slope movements*, for which Crozier (1986) and Brabb and Harrod (1989) use the general term *landslide*. In some classifications of discrete slope movements (e.g., Varnes, 1978), a subdivision is made between *slides* and *flows*. Slides are in turn subdivided into rotational and translational, and flows into rapid or slow failures. For the purpose of this review, we prefer to retain mass movement as a term which designates the process, defined by Crozier without further subdivision. We regard mass movement as a type of *land degradation*, here defined (after Dudal, 1982) as a loss of land productivity through various processes such as erosion, salinization, waterlogging, depletion of nutrients, deterioration of soil structure or pollution.

Mass movement processes essentially feature catastrophic *removal* or *displacement* by gravity of the whole soil body from a slope. This is in contrast to fluvial and aeolian erosion processes which feature progressive removal of soil particles by water or wind, from either sloping or level surfaces. Mass movement grades into both fluvial and coastal erosion types (Crozier, 1986). In the case of coastal erosion, the areas of overlap are geographically very limited, but could potentially have impacts on land productivity (although none have been noted in our literature review). In the case of fluvial erosion, areas where mass movement spatially coincides with gullies are widespread and erosion–productivity impacts are the subject of significant literature coverage but usually without acknowledgement of the mass movement component of erosion. Fluvial and mass movement erosion can also be closely linked in a temporal sense, for example when surface erosion occurs from unconsolidated sediments resulting from mass movement erosion.

Land productivity is defined (following Dudal, 1982) as the amount of primary production per unit of land area. It should be noted that our definition departs from the conventional economic definition of productivity (the price received per unit of output relative to the cost of inputs used to produce it). The principal reason for this departure is that our literature review reveals remarkably little available data about impacts of erosion on *economic productivity* of land. Most published data are expressed as crop yields, livestock numbers carried or similar.

III Why have mass movement impacts on land productivity been neglected?

Most of the early erosion–productivity research was carried out in temperate croplands, especially cereal croplands in North America (Bennett, 1939; Baver, 1952). In these regions, cropland is generally gently sloping, i.e., typically < 5 degrees but not steeper than 15 degrees. Mass movement is so infrequent in these environments that it is not commonly recognized as an erosion problem. While gully and streambank erosion are significant, sheet and rill erosion are thought to account for almost 80% of total sediment yield (Nowak *et al*., 1985).

In the 1980s several reviews (e.g., Hudson, 1982; Lal, 1985) pointed out that the environments where this research had been carried out were not typical of much of the world's croplands, in particular steep land in the tropics used for a large variety of crops. In recent years, many runoff plots and crop trials have been established to measure surface-erosion-induced loss of land productivity in tropical countries (Stocking and Saunders, 1992). However, these plots and trials still do not represent the range of slopes cultivated in the tropics. Those described by Stocking and Saunders are situated on 3–28% slopes (with only one exception at 55%). Another compilation of runoff-plot-derived erosion rates in tropical regions (El-Swaify, 1990) refers to slopes ranging up to 30%. At all these sites surface erosion processes apparently predominate, particularly sheetwash and rilling of topsoil. Some gully erosion also occurs but researchers have found it difficult to measure (Foster, 1988). There is little or no reference to mass movement in the above citations.

The runoff plots and crop trials, whether temperate or tropical, undoubtedly measure one form of erosion-induced decline in land productivity: that due to surface erosion. Equally undoubtedly, surface erosion on these types of sites is geographically widespread and occasionally severe. On the other hand, reports of crop cultivation on slopes of 30 degrees or more are common in geographical and agricultural literature – particularly in the tropics and under shifting cultivation (Blaikie and Brookfield, 1987). While the threshold slope steepness for mass movement varies considerably, the geomorphological literature indicates that it is relatively common on slopes greater than about 30 degrees (Crozier, 1986).

Mass movement has been explicitly excluded from some definitions of soil erosion and implicitly excluded from commonly accepted concepts of *soil degradation* which emphasize loss of soil quality rather than loss of soil (e.g., Klock, 1982; Lal and Stewart, 1990). In much of the literature on erosion–productivity impacts, the type of erosion process involved is unspecified or inadequately described. It is often simply categorized as 'water' or 'wind' (fluvial or aeolian) erosion. Mass movement is sometimes mentioned as a form of water erosion. Neither of these approaches is satisfactory, as mass movement and fluvial processes are fundamentally different (Crozier, 1986). The difference in processes is very significant for erosion–productivity studies because it means that mass movement erosion cannot be modelled or predicted by surface soil loss models such as the Universal Soil Loss Equation (USLE) and its derivatives which have been the subject of a large proportion of all erosion–productivity research. Nor can mass movement generally be investigated using bounded runoff plots, the most common technique in erosion–productivity research (Mutchler *et al*., 1988; Pla Sentis, 1997).

A reason for inadequate recognition of mass movement impacts may be that much agriculture in steeplands is made possible by terracing. Terrace systems have often been maintained continuously for hundreds of years and give the impression of stability and sustained agricultural productivity, with little obvious signs of mass movement. Well maintained terrace systems can indeed enhance stability against mass movement erosion. However, the impression of stability can sometimes be superficial, with old mass movement features evident on closer inspection (Figure 1). Because terraced land is usually managed by small-holders, any mass movement damage has a very

Figure 1 Mass movement collapse of rice paddy terraces, Ubud, Bali, Indonesia.
Photo taken by N.A. Trustrum, April 1995

immediate impact on the farming family. The damaged area is repaired, reterraced and restored to production as speedily as possible. Both the visual impact and the direct production impact are thereby reduced. The principal short-term impact is indirect, through diversion of labour to repair the damaged agricultural infrastructure.

A further factor in previous neglect of the topic is that although there is an extensive literature on the impacts of mass movement erosion (e.g., Crozier, 1986; Bonnard 1988; Brabb and Harrod, 1989; Hewitt, 1997), this has concentrated heavily on mass movement as a hazard either to human life or to human settlements and their infrastructure (roads, bridges, dams, irrigation schemes, etc.). This is understandable in view of the tremendous destructive force of many mass movements. However, this emphasis means that the loss of agricultural land, which is occasionally listed among the impacts of a particular mass movement episode, *is treated as a loss of infrastructure rather than a loss of productive capacity*. The emphasis on mass movement as a hazard has also led to an emphasis on its off-site impacts, as opposed to land productivity impacts, which are largely on-site (see below). Exceptions to this treatment are the extensive studies (summarized and referenced in section VI) of the effects of landslides on pastoral production in New Zealand.

Mass movement erosion is often thought of as a natural process, and as such appears to have been judged outside the sphere of erosion–productivity researchers who assumed that all erosion occurring on agricultural land was anthropogenic (e.g., Lal and Stewart, 1990). However, almost all forms of erosion, whether fluvial, aeolian or mass movement, occur naturally as well as resulting from human activity (Young and Saunders, 1986). It follows that productivity impacts can be caused by natural or induced erosion. Furthermore, although mass movement is a common natural process, its rate is often influenced significantly by human activity, particularly by changes to the amount or quality of woody vegetation cover (Sidle *et al*., 1985; Young and Saunders, 1986; Trustrum and Page, 1992).

The above points also reveal a final reason: the subject of mass movement as a cause of lost land productivity has fallen through a gap between two largely nonintersecting areas of research: erosion–productivity research carried out by agricultural scientists or soil scientists, and mass movement hazards research carried out by geomorphologists, hydrologists or engineers.

IV On-site and off-site effects of mass movement

Lal (1987) discusses the following erosion-induced causes of *on-site* decline in land productivity: decreases in plant rooting depth, alterations in plant-available water reserves, degradation of soil structure, loss of organic matter, and loss of plant nutrients and soil fertility. Lal appears to refer only to fluvial or aeolian erosion, but these factors all apply to mass movement at least equally. Loss of productivity due to mass movement is commonly more extreme at the affected site than that due to surface erosion, because the former often removes the entire soil profile in one event, whereas the latter normally takes many years to remove an equivalent depth. Even if mass movement removes only part of the soil profile, that part almost always includes the organic matter and nutrient-rich A and upper B horizons. The only exceptions to this are in highly weathered regolith with few nutrients remaining in the topsoil, where weathering can relatively rapidly produce a more fertile soil after erosion.

Off-site declines in land productivity occur through excessive sedimentation or inundation of agricultural land downstream from eroded areas (Trustrum *et al*., 1999). These can occur downstream of mass movements, just as they can downstream of fluvially eroded land, in both cases contributing sediment to river networks. Indirect off-site impacts also occur through damage by sediment to production infrastructure such as transport routes and irrigation systems. Sediment derived from mass movement is just as likely to cause such off-site effects as an equal amount of sediment derived from surface erosion.

This leads to an important question: does mass movement (or surface erosion for that matter) in fact have a serious net impact on land productivity if debris is deposited within the same land management unit (whether this be hillslope, farm, district or watershed)? The answer is time-dependent according to what changes occur in soils formed from both the eroded and the deposited material; and also on the sediment delivery ratio, i.e., amount of sediment loss out of the land unit under examination. As already mentioned, the remaining eroded subsoil is not always stony or infertile; rapid weathering may release nutrients and form a good medium for plant growth. Organic material and nutrients eroded by mass movement are not necessarily lost from a slope. Some mass movement forms (e.g., earthflows) carry soil blocks only a short way downslope, and may even leave them more or less intact. Others (e.g., shallow landslides) break up soil as they transport it, but generally deposit the debris as colluvium on footslopes. Even where soil is removed from slopes entirely, for instance by gullying of mass movement debris, much may be redeposited on stream terraces within the same field or farms (Page *et al*., 1994). Such processes may even be deliberately induced by cultivators causing the collapse of small banks, etc., as observed by one of the authors (NAT) in Indonesia.

On the other hand, plant growth conditions at depositional sites (whether colluvial or alluvial) are often unfavourable for many years afterwards. Organic- and nutrient-rich topsoil is buried; soil structure and drainage may deteriorate. Clearly mass movement can either reduce or increase land productivity on different parts of a land management unit, but always alters the *pattern* of land productivity within the unit (Trustrum and Stephens, 1981) or within a region (Wright and Mella, 1963).

V Environments in which mass movement has significant productivity impacts

Several monographs (e.g., Sidle *et al*., 1985; Crozier, 1986) have reviewed the influence of natural factors, such as rock type, tectonic environment, climate and slope, on the incidence of mass movement; this topic will not be covered in this review. Cultural factors which influence mass movement's incidence, specifically the effects of agriculture and timber production, are also touched on by these authors. However most reviews of cultural factors influencing erosion discuss their impact on surface erosion (e.g., Blaikie and Brookfield, 1987; Lal, 1990, Dregne, 1990; 1992. A handful of contributions make reference to the combination of natural and cultural factors influencing mass movement in specific countries, notably Caine and Mool (1982), Kienholz *et al*. (1983), Chang (1984), Carson (1985; 1989), Diemont *et al*. (1991) and Dregne (1995). However there are as yet no reviews specifically discussing the global environments where natural factors predisposing slopes to mass movement coincide with cultural pressures. This section of our article constitutes a tentative attempt to do so.

It is an obvious point that in considering the impacts of mass movement on land productivity, the environment subject to mass movement impacts must be one that is used for land-based production. It need not be used continuously or intensively; it could be a montane area used for summer pasturage but here the impact is likely to be small. For example, although the Southern Alps of New Zealand have very high rates of mass movement erosion, and this erosion has significant off-site impacts in terms of sediment yield and associated damage (Griffiths, 1981), on-site land productivity impacts are insignificant because a large proportion is unoccupied or grazed at low intensities (Whitehouse, 1985). In other regions, particularly where there are growing or displaced human populations, high mountains may be subject to intense uses that are severely affected by mass movement (Messerli and Ives, 1997). Examples are the Himalaya foothills of Nepal (Kienholz *et al*., 1983), the New Guinea Highlands (Blaikie and Brookfield, 1987) and the High Andes (Kojan and Hutchinson, 1978).

Our indicative map (Figure 2) is based on the FAO/Unesco 1:25 000 000 *World soil resources map* (FAO, 1990), interpreted with reference to our literature search. We identified soil groups susceptible to mass movement as those which tend to be relatively shallow, with clayey subsurface horizons, occurring on steep slopes in continually moist or seasonally wet climates (Table 1). The FAO/Unesco 1:5 000 000 *Soil map of the world* (FAO-Unesco, 1978) distinguishes three slope classes. Class C (steeply dissected to mountainous: dominant slopes over 30 degrees) provides some guidance as regards regions where a high proportion of soils within each group are susceptible to

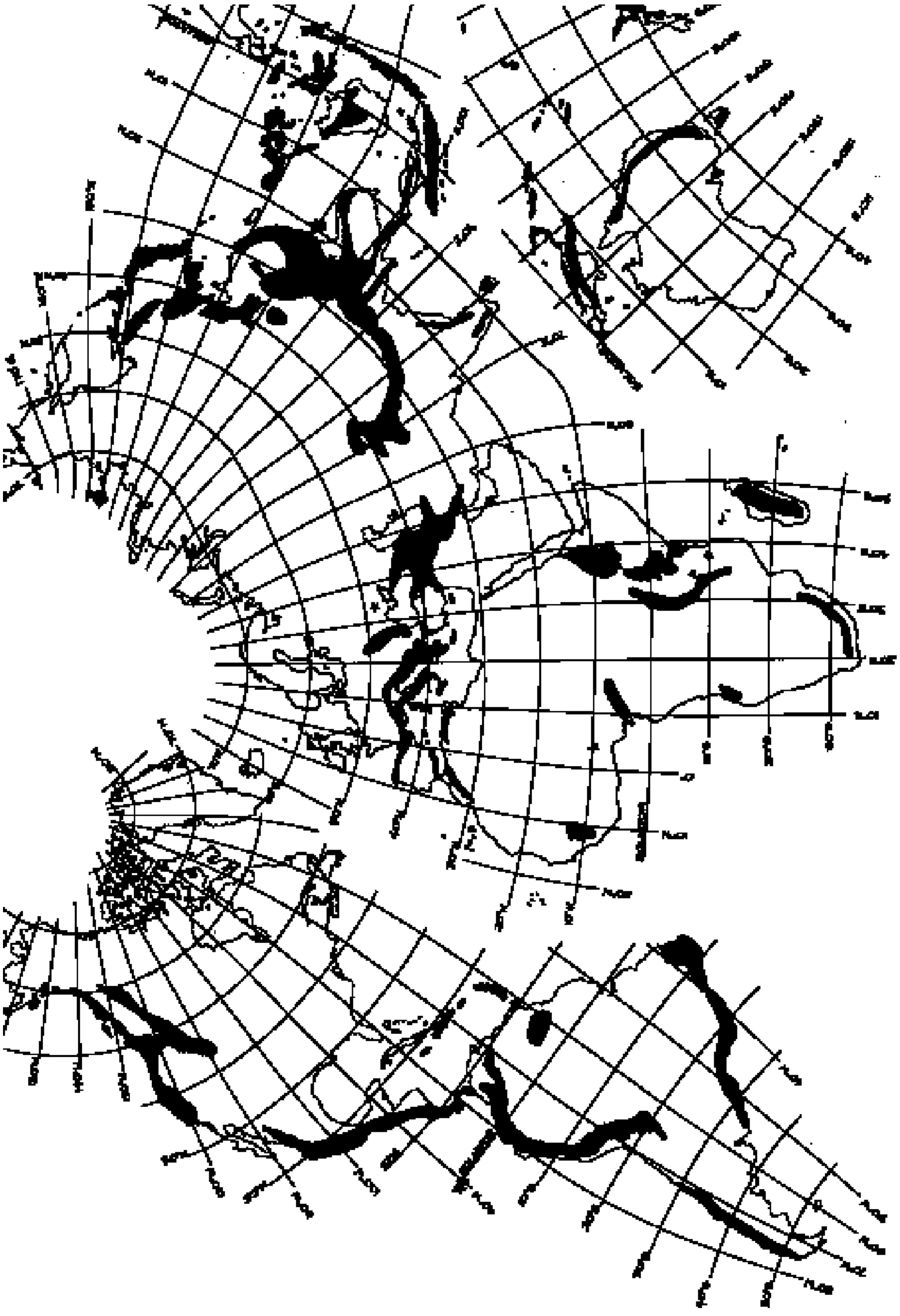

Figure 2 Approximate extent of regions where mass movement erosion affects land productivity (excluding areas where cropping, pastoralism or forest harvesting are of low intensity) (▲ localities noted in Table 2; ★ localities noted in database)

mass movement. Finally, from these areas of steepland with susceptible soils were excluded some areas of high mountains, deserts and subpolar regions not used intensively for production. Total areas (all soil groups) of land area steeper than 30% in

Table 1 Major soil groupings on which mass movement frequently occurs

FAO/Unesco primary map unit	Principal soil taxonomy equivalents	Brief description of soils	Significant mass movement – land productivity impacts
Lithosols (Leptosols in 1988 revision)	Entisols (mainly Orthents), Lithic subgroups of other great groups	Rocky shallow soils. Includes desert as well as mountainous regions	Major
Cambisols	Inceptisols (except Aquepts)	Weakly weathered brownish and reddish soils. Temperate and boreal climates	Some
Andosols	Andisols	Amorphous soils developed on volcanic ash	Some
Acrisols	Ultisols Alfisols (Kandi or Kandhapl subgroups)	Acid soils with argillic subsoils and low base saturation. Humid tropical climates	Some
Luvisols	Alfisols	Nonacid soils with argillic subsoils, high exchange capacity and base saturation. Humid temperate climates	Minor
Nitisols	Ultisols Alfisols	Strongly weathered basic soils developed in volcanic ash. Humid montane tropics	Minor
Podzols	Spodozols	Leached horizon, subsoil accumulation of Al, Fe and organic matter	Minor
Ferralsols	Oxisols	Highly weathered tropical soils with subsoil dominated by Al and Fe sesquioxides	Minor
Lixisols	Alfisols (Kandi or Kandhapl subgroups)	Argillic soils with low exchange capacity and high base saturation. Subhumid tropics	Minor

Source: Summarized from FAO (1990) and Richter and Babbar (1991).

tropical regions range from 8% (Africa) to 29% (southeast Asia), with an average of 16% (Lal, 1990). We believe that temperate regions would fall within this range.

Susceptible soils are widespread in the following regions: the continental rim of the Pacific lithosphere plates (including island arcs of the western and southwestern Pacific, but excluding polar and arid portions of the rim); Caribbean island arcs and Central American mountain chains fringing the Caribbean; the Atlantic coastal uplands of southern Brazil; the Ethiopian mountains; highland areas around the African Rift Valleys; the Drakensberg and Madagascar; mountains fringing the Mediterranean Basin (excluding arid parts of the Atlas mountains, Asia Minor and Caucasus); European mountains (Pyrenees, Alps, Norway); the Carpathian and Ural Mountains; steepland areas stretching through central and southern China to Tibet; the Afghan mountains, Hindu Kush and Himalayas; steeplands in Burma, northern Thailand and Indochina; much of the Philippine and Indonesian archipelagos; and central New Guinea.

It is meaningless to attempt to measure the extent of susceptible soils in these regions as, at the scale mapped, mapping units all include a mix of affected and unaffected soils. Some indication is given by statistics for individual countries. For example, 43% of Java has soils from the groups in Table 1 on slopes steeper than 30 degrees (Diemont *et al*., 1991), almost all cropped and densely settled. Of the 36% of New Zealand susceptible to mass movement erosion (Eyles, 1983), nearly half (44%) is farmed hill country or mountain land, albeit grazed and sparsely inhabited.

Even on susceptible soils, only a relatively small proportion of land is likely to be affected by active mass movement erosion at any one time. However, considering Figure 2, it is reasonable to estimate that up to 20% of the world's land area is sporadically affected by mass movement under its present vegetation cover (including natural forest) and that as much as half of this (again including forest) is used for land-based production and is thus susceptible to mass movement impacts on land productivity.

Production activities on steeplands include irrigated and rain-fed cropping, pastoralism, timber cutting and other forest uses. In many countries/regions there is little cultivation undertaken on steep land and productive land uses are generally restricted to pastoralism or timber production. However in densely populated countries not only does deforestation and extensive cultivation occur on steeplands but also fully or partly forested steeplands may be intensely used, for shifting agriculture, agroforestry or extraction of various products. All these activities are susceptible to impacts from mass movement; and those which reduce forest cover increase mass movement. Deforestation rates are generally rapid.

VI Overview of mass movement impacts on land productivity

In this section, we review the available literature about mass movement impacts on land productivity worldwide. As discussed above, our primary information source was 175 items drawn from CAB abstracts databases, containing key words *production* or *productivity* and *mass movement* or *landslide*. The majority of these references are fragmentary, spurious or generalized. Our own research database contains 60 entries, from 38 countries. Table 2 is a summary of information from 22 of the more complete and useful references, along with seven additional publications on the topic from New Zealand. These are discussed below under headings corresponding with three broad

Table 2 Survey of selected literature on mass movement impacts affecting land productivity

Country, region	Land use	Annual rainfall (mm)	Landform slope	Type of erosion	Area affected	Duration of events	Soil loss rate	Production and economic losses	Reference(s)
Asia *India* Sikkim	Tea gardens	3100	Steep hills 25–40°	Mudflows, slumps, debris slides, landslides	*c.* 1300 km^2	4 days (1968)	Slope lowering *c.* 10 cm	*c.* 20% of planted area devastated	Starkel, 1972
China Wuding River valley, northern Shaanxi	Cropping, animal husbandry	350–500 (high intensity storms in summer)	Loess-covered hills	Landfall, landslides (gully)	Catchment 30 000 km^2, 15% subject to mass movement	Multiple short events	16 600–26 500 t/km^2/yr, *c.* 25% of catchment erosion?	Production, 'low and unstable'	Jiang, 1990
China Jinsha and Minjang Basins, Sichuan, south-western China	Farming	Low, but high intensity storms occur	Dry valleys in Qinghai–Tibet Plateau; 30–50° slopes	Debris flows, landslides	Very extensive	Multiple short events	Total erosion loss, Sichuan Province 1.6 bt/yr	Much farmland affected; cost of debris flows, Sichuan Province 1991, was 350 m Yuan	Liu *et al.*, 1990
China Liaoning Province, northeastern China	Wide range of crops, some orchards and pastoral use	400–1100	Hills and low mountains	Debris flows, avalanches, rockslides, gullies	Very extensive	Multiple events	Rates up to 3000–5000 t/km^2/yr	60 000 ha cultivated land destroyed in one event; associated losses in soil fertility	Zhao *et al.*, 1992

Country, region	Land use	Annual rainfall (mm)	Landform slope	Type of erosion	Area affected	Duration of events	Soil loss rate	Production and economic losses	Reference(s)
Taiwan	Farming (cropping)	2000–> 4000	Steep slopes	Landslides, mudslides	10–40 000 ha covered by active landslides	Multiple events	NA	Loss of farmland, e.g., 3100 ha cropland, cost $0.4 m in one event (1951)	Chang, 1984 Li, 1989; Lo, 1990
Nepal Middle Himalaya Mountains	Terrace land farming	1000–> 2000	Steep mountain slopes, landslides on 32°–45° slopes	Many	NA	Multiple events	Average sediment loads for 4 catchments 7.6–38 t/ha/yr; possibly from mass movements in actively eroding areas	Considerable damage to terraced land; terraces repaired rapidly as long as soils remain productive; long-term soil productivity (all erosion) claimed to have decreased at least 20%	Kienholz *et al.*, 1984; Carson, 1985; Dregne, 1992
Indonesia Upland areas Java, Bali, Nusa Tenggara	Irrigated and rain fed crops (especially rice), home gardens, some grazing	Up to 2500	Dissected terraces to mountains	Lahars, landslides, slumps (gullies)	Very extensive	Multiple events	Average watershed sediment loads 10–81 t/ha/yr; up to 380 t/ha/yr (*c.* 2 cm/yr) on slopes > 50%	Yields generally low and declining; some of most profitable crops strongly erosive (> 80 t/ha/yr) especially on limestone soils	Carson, 1989
Africa *Tanzania* Mgeta, western Uluguru Mountains	Subsistence and cash cropping on terraced land, fallow and grazing	1065	Dissected hills and mountains 1000–2870 m a.s.l. 28–44° slopes in	Mainly debris slides and mudflows (> 1000 events)	*c.* 75 km^2, not including area of fluvial erosion and deposition	1 day, February 1970 (100 mm/24 hr)	Displacement of 270 000 m^3 in most severely affected 20 km^2 = soil lowering of 14 mm in	500 ha cultivated land destroyed; some damage on grazing land; 540 families suffered property	Temple and Rapp, 1972; Rapp *et al.*, 1991

	land		eroded areas				event	loss; total cost of damage US$90 000	
Tanzania Rungwe, southwestern region	Subsistence cropping, fallow and scrubland	2500	Broken hilly country; generally 18–30°; some debris avalanches on gentle slopes	Debris avalanches and flows, subsidence (gullies)	*c.* 1400 ha in main event	2 events April–May 1955, (425, 120 mm/ 24 hr); evidence of many older landslides	Displacement of major landslide *c.* 300 000 m^3	Considerable damage to crops and cropland, but preventative/ remedial measures not economically justified	Haldemann, 1956
Uganda Bulucheke region western Uganda	Subsistence and cash cropping, home gardens	1520	Hill country; slopes 15–45°	Landslides, undercutting	NA	3 major slides between 1920 and 1970	NA	Fertile land covered; large socioeconomic disruption (deaths, loss of food reserves) for about 5 years; perceived by farmers as major problem	Omara-Ojungu, 1978
Rwanda Ruhengeri region northwest Rwanda	Subsistence and cash cropping; very high population densities	1020–1440 (average 1340)	Heavily dissected to mountainous, many slopes > 60%	Fluvial erosion and landslides	NA but widespread	Soil loss monitored 6–12 months; concentrated in relatively short (1–6) day) periods; old landslide scars abundant	Measured soil loss (plots) ranged 91–210 t/ha, depending on cover, 30% of total loss was from single rainfall event which also caused extensive landsliding and flooding	Assumed highly significant	Byers, 1990; 1992; Konig, 1994

Country, region	Land use	Annual rainfall (mm)	Landform slope	Type of erosion	Area affected	Duration of events	Soil loss rate	Production and economic losses	Reference(s)
Australasia									
Fiji Southern Viti Levu	Shifting cultivation	*c.* 2500	Hills, mainly 28–30°	Debris slides, flows and avalanches	313 ha (catchment)	24 hours (1980) (> 900 mm rain)	110 000 m3 from 37 landslide sites	50% of garden crops from 21 villages destroyed, 20 000 people required emergency food	Crozier *et al.*, 1981
New Zealand East coast	Pastoral grazing	1000–2400	Hills 16–35°	Earthflows, landslides	8300 km^2	300–900 mm in 72 hours (1988)	7% of slopes eroded (regional average)	$43 m damage and production loss on farmland, $30 m off-farm damage	Hicks, 1992
New Zealand Wairarapa	Pastoral grazing	*c.* 1000–1200	Steep hills	Landslides, some earthflows	*c.* 800 km^2	Prolonged wet weather over 3 months (1977)	6% of slopes eroded (district average)		Lambert *et al.*, 1984; Trustrum and Hawley, 1986
New Zealand Taranaki	Pastoral grazing	*c.* 1800–2000	Steep hills	Landslides	?	150–250 mm over 48 hours (1990)	3% of slopes eroded (district average)		Hicks, 1990; Trustrum *et al.*, 1990
New Zealand Taranaki	Pastoral grazing	1200–2000	Steep hills	Landslides		Repeated rainstorms, typically over 200 mm over 48 hr	30% of slopes over 80 years	Pasture reductions increase from about 1 to 3% per decade with increasing slope angle from 28 to 42°	DeRose *et al.*, 1995

New Zealand Gisborne	Pastoral grazing	500–2500	Hills 15–25°	Earthflows	10 320 km^2 susceptible land in pasture	Prolonged wet weather (typically > 200 mm > 5 days)	Typically > 50% of slopes disturbed, < 10% disrupted	40% loss of pasture production on disturbed surfaces, 80% loss on disrupted surfaces	Miller, 1991
New Zealand Hill country, summary	Pastoral grazing	500–2500	Hills 16–35°	Landslides	32 200 km^2 susceptible land in pasture	Prolonged wet weather or intense storms (typically > 100 mm per 24 hrs)	Typically 1–10% of slope disrupted	80–100% loss of pasture production on disrupted surfaces; typically pasture recovery occurs over 20–40 years to within 60–80% of original productivity	Trustrum *et al.*, 1990; Blaschke *et al.*, 1992; Clough and Hicks, 1993
Papua New Guinea Central Highlands (*c.* 1400–2500 a.s.l.)	Subsistence agriculture	High	Long 'ridge and ravine' steep hillslopes, commonly 30–40°; intermontane valleys and basins	Shallow slumps, deep-seated slumps and slides, debris flows	General area 14 000 km^2; examples described affect 5–70 ha	Multiple events; threshold rainfall not known	Not known; largest event had volume 2.5–7.5 × 10^6 m^3	Larger events destroy dwellings, kill pigs, damage gardens and coffee trees; most garden and tree areas salvaged	Blong and Eyles, 1986; Humphreys and Brookfield, 1991
Europe *Yugoslavia* Southeastern region	Cropping and grazing	*c.* 800–1200	Hilly; slopes 17–50°	Landslides	0.2–3 km^2	3 separate events	4–20 m^3 displaced	7–15 km^2 arable land flooded or destroyed	Anagnosti *et al.*, 1989
North America *USA* Cascade Range, Oregon	Production forestry	2400	Steep hillslopes, mainly 50–80%	Shallow landslides	12 300 ha, 257 landslides inventoried	Multiple events over *c.* 20 yr	NA	Annual height growth, stocking levels and potential stocking all lower on landslide areas (see text)	Miles *et al.*, 1984

Country, region	Land use	Annual rainfall (mm)	Landform slope	Type of erosion	Area affected	Duration of events	Soil loss rate	Production and economic losses	Reference(s)
Canada Queen Charlotte Islands, BC	Production forestry, salmon fishing	*c.* 2000	Steep hillslopes; 32–68% on landslide areas	Debris avalanches	Whole island group; 49 landslides, average size 2.3 ha	Multiple events over 155 yr; mass movement associated with 24 hr 180–200 mm rainfall events	NA	Basal area height growth, and biomass all lower on landslide areas; species composition less favourable for production (see text); decline in salmon fry survival	Smith *et al.*, 1986; Chatwin and Smith, 1992
Caribbean and Latin America									
Dominica East coast	Small-holder crops and home gardens	1000–1600 on coast; more inland	Steep hills, rugged terrain	Debris slide	4 ha	1 event (1986)	17 000 m^3	Loss of cash crops $5000; total agricultural losses $8000, affecting 6 holdings (per capita income $500–$1000)	DeGraff *et al.*, 1989
Chile South-central region	Cropping and grazing	> 2000	Steeplands	Debris slides, avalanches, mudflows, slumps (all related to volcanic activity	At least 2000 km^2	2 months following earthquake in May 1960		92 000 ha affected land suited to agriculture, including 37 000 ha totally destroyed	Wright and Mella, 1963
Peru Western Andes, Huancavelica region	Cropping and grazing	735	Various mountain landforms, 9–35°	Rockslide/ debris fall	NA	1 event, April 1974	10^9 m^3 material displaced	Inundated 1270 ha agricultural land, further land destroyed by loss of irrigation canal and breaching of temporary dam	Kojan and Hutchinson, 1978

categories of land use. The unevenness of information in Table 2 will be clear. The 'Area affected' and 'Duration of events' columns were particularly difficult to compile consistently as the literature was frequently unclear as to whether single or multiple events were being described, or whether areas affected were areas of mass movement damage or area of affected district.

1 Cropping

Researchers in a number of countries have detected widespread occurrence of mass movement in cropped agricultural steeplands, notably Starkel (1972), Carson (1989), Kucera (1990), Diemont *et al*. (1991) and Rijsdijk and Bruijnzeel (1991) in Indonesia, Humphreys and Brookfield (1991) in New Guinea, Caine and Mool (1982), Kienholz *et al*. (1983) and Carson (1985) in Nepal, Simon and Guzman-Rios (1990) in Puerto Rico and Rapp *et al*. (1991) in Tanzania. They have generally done so in the course of sediment yield or sediment budget investigations, pointing out that a major source of 'missing' sediment, in budgets at catchment scale, has been mass movement erosion occurring either in catchment headwaters or downstream. Sources of mass movement-derived sediment in downstream agricultural districts include, as well as natural landslides on steep slopes, failures induced by runoff from roads or leakage from ditches, failure of artificial embankments on terraced slopes, and collapses where hillsides have been deliberately undercut to increase cultivable area of slopefoot terraces (Diemont *et al*., 1991). In the central highland valleys of Papua New Guinea, Humphreys and Brookfield (1991) state that forms of slope failure, such as shallow slumps, deep-seated landslides and debris flows, are by far the most common erosion forms in cultivated steeplands. Many mass movement scars may be more significant for their contribution to sediment loads than for production losses but, in densely populated agricultural areas such as Java, the combined area of such features is considerable (Diemont *et al*., 1991) and therefore constitutes a loss of productive area.

The references cited are mainly from tropical countries where population density forces cultivation of steeplands either during shifting cultivation cycles or through terracing or contouring. We have found no references from North America, possibly because here little land subject to mass movement is cropped (Nowak *et al*., 1985).

Documentation of impacts is poor. Some references simply note that cropland has been destroyed, as part of an account of impacts of mass movement from a geomorphology or hazard assessment perspective. Others (e.g., Temple and Rapp, 1972; Kienholz *et al*., 1983; Carson, 1985; Rapp *et al*., 1991) contain photographs or maps which show mass movement features clearly impinging on cropland. A recent article from Nepal discusses the impact of landslides on irrigation systems (Sharma and Nicholaichuk, 1996). Reported scales vary from very local events (e.g., Chang, 1984; Ovuka and Ohman, 1995), through to huge ones that affect tens of thousands of hectares (e.g., Wright and Mella, 1963) or tens of kilometres of waterway affected by sedimentation or flooding (Liu *et al*., 1990). Almost all accounts are of erosion from one storm, not the cumulative erosion resulting from successive events.

There are virtually no data on amounts of production loss or economic loss from mass movement in cropland. The reasons for this omission are methodological. First, surveys of farmers' crop losses do not indicate which losses are due to surface erosion, mass movement, sedimentation, inundation, etc. Secondly, attempts to differentiate the forms of erosion are problematic. For instance, some productivity losses are specifically ascribed to gully erosion (e.g., by Dregne 1990; 1992). However as gully and streambank erosion are frequently initiated by mass movement (Dhruvanarayana and Sastry, 1985; Llerena, 1987; Lal, 1990; Bocco and Garcia-Oliva, 1992), some of the productivity losses ascribed to gully erosion could be equally validly ascribed to mass movement. Terms such as 'debris flow gullies' (Li and Cheng, 1987) have sometimes been used to describe these complex fluvial–mass movement features.

Probably the best documented region is Java, Indonesia, where, as stated above, the proportion of land susceptible to mass movement erosion is very high, and increasing because of deforestation and artificial recontouring. The references cited above clearly show the significant contribution of mass movement to erosion rates and sediment loads. Because of the large areas of land affected and the density of the population, it is reasonable to assume that the production impacts are significant. However accounts of specific productivity impacts are at best anecdotal (Table 2) and certainly not specified in discussion of economic impacts of erosion (Magrath and Arens, 1989). Thus it is still debated whether mass movement is a factor in the low productivity of upland environments in Java (DeGraff and Wiersum, 1992).

At least one reference indicates that mass movement erosion can occasionally lead to increased rather than decreased productivity from cropland. In tropical steeplands, soils on stable sites such as ridgetops are very deeply weathered, leached and generally infertile, whereas soils on hillslopes where mass movement periodically exposes less weathered subsoils rapidly accumulate organic matter and nutrients in new topsoils which are relatively favourable for subsistence crops under a shifting cultivation regime. This has been documented in the Solomon Islands by Wall *et al.* (1979). Lal (1987) describes similar situations resulting from surface erosion where slight or moderate levels of erosion may have a positive effect on crop yield on soils because lower horizons have more favourable conditions for plant growth than surface horizons.

2 Pastoral grazing

The work summarized in the following paragraphs, on the effect of landslide erosion on pastoral use in the steeplands of the North Island, New Zealand, appears to constitute the best documented example of mass movement effects on productivity world-wide.

In New Zealand, some 7.6 million hectares of hill country and mountainland are used for pastoral grazing of sheep and beef cattle. About 44% of the North Island and 30% of the South Island are prone to mass movement, through a combination of weak, tectonically disturbed rocks, steep slopes and frequent intense rainfalls. Rates of mass movement have greatly increased by clearance of forest for pasture establishment since 1840 (Taylor, 1939; Williams, 1979; Trustrum and Hawley, 1986; Trustrum and Page, 1992; DeRose *et al.*, 1993; Glade and Crozier, 1996; Page and Trustrum, 1997). Siltation of river channels and sedimentation of flood plains have been attributed to headwaters erosion, as has loss of pastoral production and cropland (e.g., by Cumberland, 1945; Poole, 1983).

The magnitude of pasture production loss has been established by a series of trials in North Island hill country districts which have measured pasture growth on revegetating scars of different age, relative to uneroded ground (Lambert *et al*., 1984; Trustrum *et al*., 1984; Douglas *et al*., 1986; Miller, 1991; DeRose *et al*., 1995; see also Figure 3). Annual dry matter production on recently eroded landslide scars is depressed by about 80% on average, relative to uneroded ground. Much of the residual growth is of low nutritive value for fodder. Production recovers over some 20–40 years as scars regrass, but to an asymptotic level below that of adjacent uneroded ground. Longer-term declines of productivity have been measured on a whole hillslope basis at 2% per decade or a total of 18% since forest removal (Trustrum *et al*., 1984). The permanent loss can exceed 40% (on unfertilized soils re-forming from sandstone parent material), or be less than 5% (on heavily fertilized soils re-forming from mudstone). Hillslope angle influences productivity. On sandstone hillslopes permanent reductions increase from

Figure 3 Pasture measurement trials on shallow landslide scars of different age and adjacent ‘uneroded’ forest soils, Wairarapa, New Zealand. Deforestation occurred between 1860 and 1890
Photo taken by N.A Trustrum, February 1980

about 1 to 3% per decade with increasing slope angle, from 28° to 42° (DeRose *et al.*, 1995). On deep-seated earthflows, somewhat greater pasture production is obtained from remnant vegetation rafted by the predominantly subsurface movement. Production from extensively disrupted earthflow surfaces is depressed by about 80% relative to uneroded ground. Pasture that is disturbed (i.e., rumpled into hummocks and hollows) is depressed by about 40%. Old flows which have stabilized still show slight production loss as less than 10%. Pasture production recovered in proportion to increases in nitrogen, phosphorus and carbon levels in soil on revegetating scars, suggesting that loss of these nutrients partially limits plant growth (Trustrum *et al.*, 1990). The decrease in regolith depth caused by erosion (Trustrum and DeRose, 1988) implies considerable change in soil physical properties, particularly water-holding capacity, which may also limit plant growth (DeRose *et al.*, 1995).

A further aspect of the New Zealand investigations has been the measurement of pasture recovery in the presence of conservation measures. Lambert *et al.* (1993) have measured complete recovery of pasture production on shallow landslide scars within five years, where these are fertilized, oversown with grass and legume seed, and livestock are excluded. Miller (1991) has also demonstrated complete pasture recovery where earthflows are cultivated, drained and fertilized. A common stabilization technique is widely spaced plantation of fast-growing trees, mainly *Populus* and *Salix* species, which stabilize soil with a network of lateral roots and still enable land to be grazed. Where earthflows are stabilized by spaced planting of trees, Miller *et al.* (1996) report annual pasture production at around 60% of the uneroded level (i.e., stabilization is achieved with no net loss in growth relative to disturbed ground (also 60%), and with a net gain relative to disrupted ground (20%)).

Opinions differ as to the economic impact of this long-term production loss. Trustrum and Hawley (1986) postulated that, as eroding hillsides represent about 60% of total area and contribute about 45% of overall production on typical hill country farms, 18% reduction across eroding hillsides translates to about 9% loss in annual farm gross income. This interpretation must be reconciled with the fact that New Zealand's pastoral hill country has now been deforested for some 70–120 years, yet the impact of erosion on farm profits has clearly not been enough to force hill country farmers to abandon their land. Most have been able to mask the effects of erosion by amalgamating with neighbouring farms, improving utilization of the remaining pasture growth on regrassed scars, topdressing with fertilizer and lime, and resowing with higher-producing pasture plants (Trustrum *et al.*, 1984; Trustrum and Blaschke, 1992; Clough and Hicks, 1993).

Nevertheless, several surveys carried out in recent years indicate that mass movement economic impact is significant at farm scale, regionally and, perhaps, nationally (Clough and Hicks, 1993; Glade and Crozier, 1996). Hawley (1984) reported that government disaster relief payments for landslide damage had steadily increased over the previous decade. Mass movement erosion during Cyclone Bola in 1988 caused damage and production loss averaging NZ$26,000 on hill country farms of the North Island east coast (Korte, 1989). In one east coast catchment, Hicks (1992; 1995) estimated that mass movement during Cyclone Bola had caused production losses averaging $72 a hectare and damage repair costs amounting to $59 a hectare. Clough and Hicks (1993) cited figures from a number of mostly unpublished government sources, indicating that government expenditure on repair of landslide and flood damage (including disaster relief payments to farmers) could be less than \$1 million some years, but exceed \$70 million in others.

Other than the New Zealand literature, we have found only one instance where mass movement impacts on pastoral land productivity has been documented: the Uluguru Mountains in Tanzania (Temple and Rapp, 1972; Rapp *et al.*, 1991), where an intense three-hour rainstorm in 1970 caused widespread slope failures over 75 km^2. Landslides and mudflows originated about equally in cultivated cropland, fallow land and lightly grazed land. The documented economic impact in this case was confined to the cropping land only.

Even in densely populated tropical regions, uncultivated steeplands are often lightly grazed, and often covered with relatively unpalatable plant species. However, the New Zealand evidence suggests that production impacts can be expected in other steeplands, if they are erosion-prone (due to tectonic activity and/or high rainfall) and especially if they have been recently deforested. Such areas include populated steeplands under pastoral use in southern and eastern Africa, the Andes, Amazon Basin and large Pacific islands such as New Guinea.

3 Forestry and agroforestry

In general, fewer impacts of mass movement on forest land productivity would be expected because of lower rates of mass movement. In a number of temperate countries where landscape-scale analysis of mass movement has been carried out, mass movements recent enough to have discernible scars rarely cover more than 1–2% of forested landscapes (Sidle *et al.*, 1985; Crozier, 1986). Also, with much longer harvest cycles for trees than most agricultural crops, cumulative erosion impacts could be expected to take much longer to be discernible (Swanson *et al.*, 1989). However, studies of vegetation regeneration on landslide scars in areas of natural forest (e.g., Lundgren, 1978; Shimokawa, 1984; Mark *et al.*, 1989; Guarigata, 1990; Blaschke *et al.*, 1992) show that it takes many decades to centuries for site conditions and indicators such as basal area to return to similar levels as in nearby undisturbed forest. Similarly, a few studies in production forests show significant impacts of mass movement on forest productivity. The most detailed come from the Pacific Northwest region of North America. Here, widespread commercial forestry is undertaken in both old-growth and regenerated forest stretching from *c*. 37° N to 61° N. Several studies have examined the impact of erosion, specifically including mass movement erosion, on forest productivity. These studies are reviewed by Swanson *et al*. (1989) and Chatwin and Smith (1992) and discussed by a number of contributors to Perry *et al*. (1989).

The most significant are those of Miles *et al*. (1984) in Douglas fir (*Pseudotsuga menziesii*) forests in the western Cascade Mountains in Oregon, and Smith *et al*. (1984; 1986) in mixed coniferous forests on the Queen Charlotte Islands, British Columbia. Plots on landslides of different ages and adjacent noneroded areas in either old-growth or regenerated forest were selected and surveyed either by paired comparisons (Miles *et al*.) or general survey (Smith *et al*.). Stocking rates, species composition, height growth, basal area and biomass were among the vegetation factors sampled, as well as soil properties.

Together, their results show a significant reduction in all productivity-related properties sampled on landslide areas compared with either comparably aged regenerating and old-growth areas. The declines are accompanied by significant changes in species composition in the study of Smith *et al*., chiefly a large increase in the relative importance of red alder (*Alnus rubra*) at the expense of the more commercially valuable conifer species. In Miles *et al*. (1984), the dominant Douglas fir is also a predominant colonizer of eroded surfaces, reducing the impact of species composition change. The composition changes are related to different parts of the landslide area, principally between the upper scar (bedrock) area and the lower depositional portion. The reductions are age-dependent: both studies suggest there is a recovery in height growth, basal area and biomass increase over time (after 60 years in the study of Smith *et al*.). Miles *et al*. (1984) suggest that a recovery of height growth rate on landslide scars is possible within the period of one timber rotation. However the results of the same authors, indicating decreased stocking potential, suggest that mass movement impacts are very long-lasting in the absence of management intervention.

It should also be noted that much sediment resulting from mass movement entered streams which in British Columbia are important habitat and spawning ground for commercial and recreational fisheries. Concern about this impact was a primary reason for the above studies being carried out (Chatwin and Smith, 1992; Hartman *et al*., 1996). Increased fine sediment levels and physical catchment changes caused by mass movement reduced the quality of salmonid habitat and caused a significant decline in coho salmon egg survival rates, but it was apparently not possible to separate the effects of logging from those of mass movement in causing increased fine sediment levels.

A further type of productivity impact which is unique to timber production areas is nonlethal damage to trees by mass movement events which affect timber quality or growth rates. Such damage may be distortion or lean in trees affected by slow mass movement events such as earthflows (Vest, 1988), or abrasion caused by rapid regolith movements.

Swanson *et al*. (1989) conclude that mass movement productivity impacts in production forest are not large because of the small areas generally affected. However, they note that when mass movement rates are increased by management activities such as logging, roading or yarding, or where erosion acts in combination with other factors on already severely disturbed sites, productivity may be reduced on the scale of decades to centuries. On the other hand, Miller *et al*. (1989), in the same volume, concluded that net long-term loss in site productivity from erosion had not been demonstrated with certainty, and also mentioned the possibility of depositional material enhancing growth locally to offset upslope losses.

A difficulty with these studies is the long production and growth cycles of forests compared with herbaceous crops, making prediction of long-term trends difficult. In New Zealand, the exceptionally fast growth of *Pinus radiata* stands may enable trends to be detected earlier. Although no studies comparable with those discussed above have been undertaken, modelling of tree growth in relation to environmental factors had indicated some unexplained variability in stands on shallow steepland soils, which may be attributable to the previous effects of mass movement erosion in reducing soil rooting volumes (Hunter and Gibson, 1984). Surveys by Phillips *et al*. (1990), Marden *et al*. (1991) and Kelliher *et al*. (1992) indicated that in young pine plantations (less than about 8 years old), mass movement damage after a severe storm in 1988 was just as severe as in adjacent grassland. Under growing trees which had established a continuous root network (8–24 years), mass movement affected less than 1% of plantation area. Under mature trees close to harvest (25–30 years), damage was typically less than 0.5%. Two surveys by Hicks (1990; 1991) indicated that the levels of mass movement under both growing and mature *P. radiata* plantations were comparable with undisturbed natural forest cover and lower than under regenerating scrub.

Mass movement impacts on forests that are not used for timber harvesting are scarcely documented. Due to the lower rate of mass movement under forest, such impacts could be expected to be small, especially in industrialized temperate countries, where little productive use of forests other than timber harvesting occurs. However, in third-world countries numerous other productive uses take place (e.g., harvesting of nontimber products, fodder and fuel gathering, and charcoal production). Any such activity is disrupted to some extent by mass movement, whether the mass movement is 'natural' or enhanced by human activity. Such disruption is likely to be more severe in exceptional events which are generally less affected by the type of vegetation cover. If natural forest or induced grassland has been recently replaced by planted trees and a new tree root network not yet established (O'Loughlin and Ziemer, 1984), impacts can also be severe, as occurred in Thailand in late 1988 when widespread severe landsliding, as well as downstream flooding and sediment damage, occurred on young rubber tree plantations on steep slopes (Hamilton, 1992).

Mass movement productivity impacts on tropical agroforestry systems have not yet been documented to our knowledge. Lal (1990) notes that studies of the impact of erosion on agroforestry systems are very limited for any kind of erosion.

VII Minimizing the impacts of mass movement on land productivity

A fundamental difference between surface and mass movement erosion from a land productivity perspective concerns the strategies available to minimize the impacts. Surface erosion rates are greatly increased (relative to natural rates) by inappropriate agricultural managements such as excessive cultivation, overgrazing of ground cover, or repeated burning of vegetation. It follows that the impacts can be very largely mitigated by sensitive land husbandry techniques, as described for a number of years by many authors e.g., FAO, 1977; Hudson, 1982; Lal, 1986; Carson, 1989). In contrast, the rate of mass movement is not responsive to changes within an existing agricultural management regime (e.g., more careful cultivation. It does either increase or decrease with change from one type of agricultural regime to another – e.g., shifting cultivation to cash cropping (increase) and livestock grazing to a mix of livestock grazing and agroforestry (decrease). Similarly it can either increase or decrease if land use is entirely changed from agriculture to something else – e.g., plantation forestry (decrease) or urban (increase). Therefore, minimization of mass movements impacts on land productivity has to be achieved by different strategies from the land husbandry techniques applied to control surface erosion. Examples include mechanical or biological techniques for restoring productive capacity of affected terrain, or zoning techniques aimed at avoidance of areas particularly prone to mass movement erosion.

A voluminous literature on these types of strategies already exists. To review it is beyond the scope of this article whose principal theme is the nature and magnitude of impacts – a topic which is not so well documented. Readers seeking further information on strategies for counteracting mass movement impacts are referred in particular to Schiechtl (1980); Hathaway and Van Kraayenoord (1987) and Hicks (1995) as comprehensive sources of information.

VIII Conclusions

1 Where impacts have been demonstrated

Impacts of mass movement erosion on land productivity have been comprehensively documented in a few environments, notably New Zealand steeplands, and the Pacific Northwest coast of North America, and more anecdotally discussed in a wider range of tropical environments (Table 2).

2 Likelihood of impacts elsewhere

There are a number of regions worldwide, particularly in tropical steeplands, which have large agricultural populations and where mass movement is likely to impact on production, but which are poorly reported in the English-language international literature. Richter and Babbar's (1991) analysis of soil variability in the tropics clearly shows there are far larger areas of soils affected by and susceptible to mass movement erosion than has been indicated by soil maps and classifications current until recently. Particular gaps appear in the following areas: much of China, northern Burma and Indochina, Madagascar, the east African highlands (other than Tanzania), the Mediterranean mountain fringes, the Caucasus, the Caribbean, the Andes, the Brazilian uplands and New Guinea.

Land productivity impacts of mass movement will increase over the next few decades, as a simple consequence of increasing populations expanding on to steeper and more marginal land for food, fibre and fuel production. Such expansion will inevitably mean more severe impacts, even if considerable progress is made with the various strategies for minimizing impacts. Another reason is the likely prospect of future climate change resulting in more storminess in many regions of the world (Lal, 1990).

3 Significance of the impacts

Perceptions of impacts vary widely among different groups of farmers and land managers around the world, and are probably closely linked with the degree to which mass movement's impact on land productivity is masked by other factors. Some writers (e.g., Gurung, 1988) assert that farmers, with few options for resettlement, accept mass movement as part of their natural environmental variability, and simply adapt to it as best they can. However, Omara-Ojungu (1978) finds that farmers in eastern Uganda regard landslides one of their most pressing problems, second only to land shortage and fragmentation, and well above 'soil erosion' (presumably surface erosion) in importance. Cost-benefit analyses in the Pacific Northwest indicate that on a long-term basis, productivity loss in forested temperate watersheds may be of little economic significance (Beuter and Johnson, 1989). On the other hand, Poulin (1985) discusses how the loss of forest productivity and fish habitat to mass movement is perceived as important enough to warrant initiation of a very comprehensive programme to study further and then to ameliorate the impacts. On grazed steeplands in New Zealand, mass movement erosion mainly affects the production of individual farms, but also imposes significant 'flow-on' costs (lost processing opportunities, damage repair) on local communities (Clough and Hicks, 1993). The impacts have become more noticeable to farmers and local communities in recent years, now that losses are no longer compensated by government intervention, which formerly transferred costs to the national economy.

In view of the uneven and incomplete literature on mass movement impacts on land productivity, it is not surprising that the number of quantitative estimates of its significance through sediment budgeting is tiny. Results are contradictory. In terms of sediment load, surface erosion in some steepland regions is undoubtedly predominant (Rijsdijk and Bruijnzeel, 1990; 1991, in east Java). In other regions sediment budgets show that mass movement processes are more significant. This is clearly the case for New Zealand steeplands (Trustrum *et al.*, 1999) and parts of the Caribbean (Simon and Guzman-Rios, 1990) and likely to be so in parts of the Himalaya.

One reason for the discrepancies in perception of impacts is that it takes time for productivity loss to accumulate from successive mass movement events (Thomas and Trustrum, 1984). Another is that the impacts are often masked: for instance, by higher inputs such as increased fertilizer or more productive plant cultivars (Trustrum *et al.*, 1990; Lambert *et al.*, 1993); or by structural adjustments such as farm amalgamation or income diversification (Clough and Hicks, 1993).

4 Insufficient study and documentation

Published information about mass movement's impact on land productivity remains inadequate worldwide. Erosion–production research has historically concentrated on cropped lowlands, where mass movement is rare or absent; while more recent research has concentrated on surface erosion processes in steeplands. Enough literature exists to indicate that, in many parts of the world, production losses in steeplands do occur due to mass movement. However, few of the studies to date have quantified them, as opposed to noting their existence. There is a pressing need for researchers to take account of mass movement, if their studies are to indicate the full extent of erosion-induced productivity loss.

The nature of mass movement requires that investigations of productivity loss be conducted quite differently from those for surface erosion. Runoff-plot-scale studies are clearly inappropriate. Watershed-scale investigations are sufficiently large to integrate spatially the impact of widespread mass movements, but can be subject to difficulty in distinguishing mass movement impacts from those of other erosion processes. For instance, the techniques described for New Zealand pastoral steeplands, while appropriate for ascertaining impacts of mass movement, have largely neglected surface erosion impacts. For a comprehensive approach to assessing cumulative watershed effects and environmental risk it is necessary to employ a combination of plot observations, watershed-scale surveys, sediment budgeting and catchment modelling techniques (Reid, 1993; Luckman *et al*.,1995).

Finally, research is needed in a wider range of productive ecosystems than cropland or grazing land. In particular, much closer attention could be paid to the impacts of mass movement erosion on commercial forestry, traditional uses of forests by subsistence communities, and agroforestry systems.

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