Modelling Scale-dependent Processes and Impacts of Agricultural Disturbances on Tropical Savanna Ecosystems in Northern Australia

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Abstract Tropical savanna ecosystems of northern Australia are being cleared for agricultural developments such as cropping, orchards and pastures. This tree clearing disturbs the natural structures and processes which function to capture and conserve limited resources such as soil nitrogen. Tropical savannas have a patchy structure which occurs at multiple scales in space. Our field data from these savannas suggests a scaling rule: the concentration of resources in patches is progressively greater as patch scale (size) increases. Larger landscape patches of savanna trees have greater concentrations of soil nutrients than smaller grass patches which occur between the trees. Thus, it seems logical that a disturbance such as tree clearing will have a greater scale-dependent effect than the grazing of grass patches. A savanna ecosystem model was used to estimate how these different landscape disturbances affect resource conservation. This model used scaling functions to relate differences in soil fertility within and between patches to patch size. Model simulations were then used to investigate the impacts of grazing and tree clearing on a 10 square-kilometer area of savanna. Simulation results suggest that if a grazing disturbance resulted in a 20% loss of fine-scale grass patches a loss of 4.2 metric tons of soil N could occur. If an equal area of larger tree patches were cleared, this potential loss could be as high as 7.0 metric tons of soil N. Thus, model simulations predict that the disturbance of larger patches results in a greater loss of resources than the disturbance of an equal area of smaller patches. Of course, these estimates of potential losses must consider time-lag, down-slope cascading and patch over-load effects.

1. INTRODUCTION

Tropical savannas occur around the world in wet-dry tropical climates, that is, where rainfall is high in summers and winters are dry, and where temperatures are high year round [Huntley & Walker 1982]. In Australia, savannas cover about 25% of the continent and generally occur in the tropical north above the 500 mm rainfall isohyet. This includes parts of the northern half of the Northern Territory, north Queensland and northern Western Australia [Mott et al. 1985]. The savannas of northern Australia include open forest and woodland vegetation [Gillison 1994]. A discontinuous tree layer dominated by Eucalyptus spp. over lies a more continuous, but patchy, grassy ground layer dominated by annual and perennial C4 grasses. A few broad-leaf trees and shrubs occur in the mid-layer.

Around the world, savannas occur over a wide range of climates, from humid to arid, and on soils, from light to heavy textures. Variations in savanna structure and composition may depend on plant available moisture (PAM) and available nutrients (AN) [Walker & Menaut 1988]. Tropical savannas are shaped by both natural forces (e.g. climate and soil type) and disturbances (e.g. fire and grazing).

1.1 Fire in Savannas

The impacts of fire are particularly important in the savannas of the Northern Territory, Australia. Fires are frequent because of a highly predictable wet season (i.e. one that occurs every year) followed by a distinctive 5-8 month long dry season. During this dry season, the grass fuels produced during the wet season cure and become highly flammable. Fire can occur in different parts of the dry season. Late dry season fires are generally 3-4 times more intense than early dry season fires [Williams et al 1997]. This is because weather conditions tend to be more extreme late in the dry season (September /October) and fuel loads also tend to increase due to leaf litter from drought deciduous trees.

It is estimated that tens of thousands of square kilometres of the Northern Territory burn each year [Russell-Smith 1995]. Fire frequencies are approximately one year in two or two years in three. Although frequent, fires in northern Australia are of relatively low intensity compared to the wildfires in the forests of southeastern Australia. Crown fires do not occur in the savannas because fuel loads are only about 2-10 t per ha [Williams et al 1997]. However, these fuel loads can build to maximum levels within a few years, compared to decades for southeastern forests.

1.2 Grazing in Savannas

The impacts of grazing by cattle in savannas of the Northern Territory is increasing due to growing markets for live-cattle exports to Indonesia. In fact, grazing by cattle is the most wide-spread land use within the savannas of northern Australia [Winter & Williams 1996]. The main impacts of grazing are on the grass layer in these savanna landscapes. In terms of the conservation of limited soil resources, the effects are mediated through the native perennial tussock grasses, which control how these scarce resources - water and nutrients - are redistributed in these landscape systems. Soil nutrient concentrations and soil moisture levels are higher within and near grass tussocks than in the inter-tussock spaces. In other words, perennial grasses regulate scarce resources within landscape systems [Tongway & Ludwig 1997]. Grass tussocks form obstructions to water, litter and soil sediments flowing in runoff, thereby capturing and concentrating these resources. Thus, soil C, N and P concentrations are all higher under tussocks than in the open gaps between tussocks.

The utilization and disturbance of the grass tussocks by livestock can lead to a decline in tussock vigour, an increase in tussock mortality, an expansion of the inter-tussock spaces and, eventually, to land degradation (e.g. soil erosion)[McIvor et al. 1995]. Of course, at high stocking rates the intensity of utilization increases, forage quality declines, as does forage yield, and the risk of land degradation increases [Scanlan et al. 1994]. Grazing utilization, hence impacts, have also increased through the use of improved breeds of cattle and by using 'improved' pasture species [Gardener et al. 1990]. The long-term sustainable use of savannas for livestock grazing will depend on maintaining perennial grass tussocks such that the basic landscape function of resource conservation is maintained.

1.3 Aims

We begin by describing how spatial patchiness in tropical savannas occurs at multiple scales, and how patches are linked to the conservation of vital resources such as soil nutrients. We then suggest a scaling rule where the concentration of resources in patches is progressively greater as patch scale or size increases. A model using this scaling rule in a mathematical function is then described: it relates patch--inter-patch differences in soil nitrogen to patch scale. This model is then used to illustrate how different land-use disturbances affect resource conservation.

The model predicts that the disturbance of larger patches results in a greater loss of resources than the disturbance of an equal area of smaller patches. The implications of maintaining landscape patchiness for sustainable land management are also discussed.

2. MULTIPLE SCALES OF PATCHINESS

At a large spatial scale, tropical savannas can be classified into vegetation types or patches related to underlying geology and soils [Wilson et al. 1990]. At a smaller scale, these types can be sub-divided into landscape units reflecting topographic position (e.g. ridges, mid-slopes, toe-slopes). At an even smaller scale, clumps of trees occur within savannas and woodlands [e.g. Ludwig and Tongway 1995]. At the smallest spatial scale, clumps and tussocks of perennial grasses contribute to the structure of savannas [Tongway and Ludwig 1994].

3. A LANDSCAPE SCALE APPROACH

The importance of scale in ecology and how it relates to issues of land management has grown dramatically in recent years [e.g. Wiens et al. 1993]. In this paper we examine how scale interacts with landscape patchiness and provide an example of how this understanding could improve our management of savanna landscapes. There is a close relationship between landscape patchiness and scale. For example, the sizes of landscape patches and the spaces or distances between these patches influence the way materials move over the landscape and how these materials become concentrated within patches [Tongway and Ludwig 1997]. Although how concentrated materials are utilized, retained and recycled within patches is difficult to measure, differences in concentration of materials (e.g. soil N) within patches versus between patches reflects the long-term actions of these landscape processes. It is these differences that we will use to illustrate landscape scale effects.

The concentration of soil N within and between patches of different sizes documents that resources can be captured, and with time, concentrated within landscapes (Table 1). Note that the concentration within patches is significantly greater than between patches. Further, this difference becomes greater as patch size increases.

Table 1. The concentration of soil N in tropical savanna patches of different types and sizes.

Landscape Patch Type	Patch Scale or Size sq.-meters	log 10	Soil Nitrogen Concentration (%) Within-patch	Inter-patch	Difference
Grass Clumps versus Inter-clumps	0.1	-1	0.094	0.065	0.029[a]
Tree Clumps versus Inter-clumps	10	1	0.175	0.125	0.050[b]
Dry Monsoon 'Islands' versus Dry Savanna	30,000	4.4	0.28	0.14	0.14[c]
Wet Monsoon 'Islands' versus Dry Savanna	40,000	4.6	0.23	0.12	0.11[c]
Coastal Monsoon versus Dry Savanna	1,000,000	6.0	0.38	0.19	0.19[d]

[a] Tongway and Ludwig 1994; [b] Burrows et al. 1988; [c] Bowman 1992; [d] Bowman and Fensham 1991

4. A SCALING RULE AND FUNCTION

Although more data is needed, the data presented in Table 1 for savannas suggests the following scaling rule: the concentration of resources in patches is progressively greater as patch size (scale) increases. Note that this rule is for resource concentration, that is, the amount of resource (soil N) per unit area (of patch), not total resource for the patch which, of course, would increase with area. In other words, the scaling rule states that resource concentration is disproportionally greater for larger patches.

A scaling function can be dereived from this rule by plotting the differences in concentration for soil N against patch size (Fig. 1). This function is appears to be approximately linear when differences are plotted against patch area transformed as log base 10. Additional data on concentration differences between and within patches is needed, particularly at small scales, before functional forms can be determined more accurately.

5. MODELLING IMPACTS OF SAVANNA DISTURBANCES

The scaling function for soil N can be built into a simulation model to simulate the potential impacts of different disturbances on savannas.

5.1 A Typical Tropical Savanna

For simulating the potential impacts of disturbances, let us assume that an undisturbed area of savanna, 10 km^2 in size, is fenced for use as a paddock for cattle grazing. Let us also assume that the tree layer in this savanna is dominated by eucalypts and that the grass layer is dominated by perennial tussock grasses, as is typical for many of the savanna vegetation types in northern Australia [Wilson et al. 1990]. We will set the savanna tree density at 200 tree per ha (10,000 m^2), with a mean canopy cover of 25 m^2 per tree and a mean tree basal area of 0.025 m^2 per tree. With 200 trees per ha and 25 m^2 per tree, the total canopy area is 5,000 m^2 per ha or 50% tree canopy area. These are typical values for savanna trees occurring at about the 1000 mm annual rainfall zone on sandy-loam soils in northern Australia [Williams et al. 1996]. A typical tussock grass density for these savannas is about 5 individual tussocks per m^2. The average canopy size of a tussock is about 0.1 m^2.

5.2 Modelling a Grazing Disturbance

As an example of a simulation run, let us assume that the grazing management aim is to sustain a stocking rate that will utilise the perennial grass forage such that tussock density is only reduced by 20% over the long-term. In other words, over the years, the density of grasses would only be reduced from 5 tussocks per m^2 to 4 per m^2, or 1 tussock per m^2 would be lost. From the scaling function (Fig. 1), this represents a potential loss of 0.03% soil N per tussock or a total of 4,200 Kg N (4.2 metric tons) for the 10 km^2 paddock (Fig. 2).

The simulation model computes this total given three facts: (1) 0.03% N is 0.3 mg N per g soil, (2) a typical bulk density for these savanna soils is about 1.4 g per cm^3 of soil [McIvor et al. 1995], and (3) 1 cm of soil is eventually lost from the soil mound formed under each grass tussock. Thus, the model computes: (0.3 mg N/g soil) x (1 kg/1,000,000 mg) x (1.4 g soil/cm^3) x (1,000 cm^3/tussock) x (1 tussock lost/m^2) x (1,000,000 m^2/km^2) x (10 km^2/paddock) = 4,200 kg N for the paddock.

5.3 Modelling a Tree Clearing Disturbance

Another simulation run assumed that the paddock was treated by clearing 20% of the trees, that is, tree density was reduced from 200 trees per ha to 160 trees per ha, or 40 tree patches were disturbed per ha within the 10 km^2 paddock. In other terms, clearing 40 trees per ha would reduce the tree canopy cover from 5,000 m^2 per ha to 4,000 m^2 per ha. From the scaling function, where each tree patch is 25 m^2 (250,000 cm^2) in area, the model would estimate a potential loss of 7,000 kg soil N for the 10 km^2 paddock (Fig. 2).

Model computations are: (0.5 mg N/g soil) x (1 kg/1,000,000 mg) x (1.4 g soil/cm^3) x (250,000 cm^3/tree patch) x (40 patches lost/ha) x (100 ha/km^2) x (10 km^2/paddock) = 7,000 kg N for the paddock, or 7 tonnes of soil N. Again, this assumes that 1 cm of soil is eventually lost from under the area of cleared tree canopies. In the short term, it is know that tree clearing increases forage yields in the area of the removed tree [Burrows et al. 1988]. However, if one assumes that with this tree removal disturbance some soil is eventually lost from the paddock, then this loss could be as much as 7 tonnes of N. Of course, more than 1 cm of soil could eventually be lost from where the tree patches were cleared.

5.4 Savanna Management Implications

Although these model estimates involved making a number of assumptions based on little firm data, the implications for land management are clear. Applying the scaling rule demonstrates that if a landscape disturbance impacts large patches, these impacts will be far greater than if these disturbances impact on an equal area of smaller patches. As indicated above, time-lag effects will need to be considered. Also, if most of the disturbances (e.g. tree clearing) occurred at the top or on the upper slopes of the landscape, then these impacts could cascade down-slope, perhaps causing greater damage than if the disturbances were more uniformly applied over the entire landscape. This cascading effect could occur because down-slope patches would have a finite capacity for capturing the soil resources (e.g. sediments) released from disturbance up-slope, thus becoming over-loaded and impacted themselves. The sustainable management of tropical savannas will depend on having an understanding of potential impacts of different kinds of disturbances [e.g. Ash 1996]. This modelling study, and many others to follow, will hopefully contribute to this understanding.

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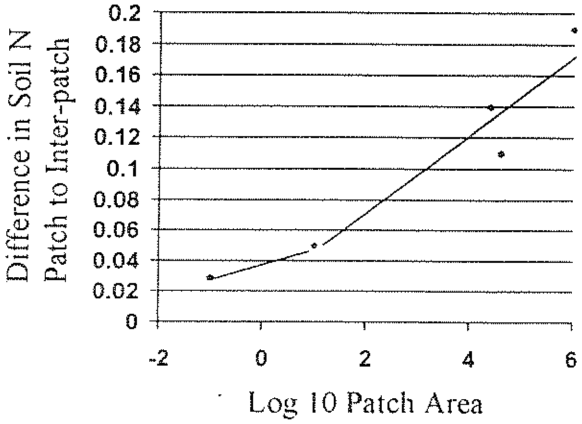

Figure 1. Scaling function of the differences in concentration in soil N with patch area (log 10).

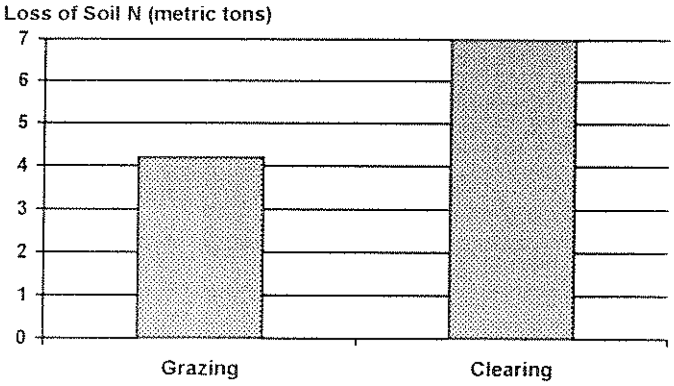

Figure 2. The potential loss of Soil N (Metric tons) in a 10 km^2 paddock with disturbances.