Modelling tropical landscapes for ecological management: what can we learn from preliminary Savanna.au simulations?

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EXTENDED ABSTRACT

Landscape scale modelling incorporates complex spatial and temporal processes (e.g. soil hydrology, runoff and sediment loss) operating at finer spatial resolutions than the model. It is important that these processes are accurately incorporated into larger scale models either intrinsically or extrinsically. Such hydrological factors ultimately determine plant production important for land use practices such as cattle grazing which occupies vast areas of northern Australia.

Sustainable management of pastoral properties to meet both economic and environmental targets requires an understanding of key ecological processes. Computer models can be used to explore the complex interaction of factors operating in the landscape, and also provide a useful management tool to improve both enterprise production and maintain landscape health and system outputs to other areas (i.e. runoff and sediment loads).

This preliminary simulation study uses the Savanna.au model to investigate the extent to which fine scale seasonal runoff and sediment loss can be simulated; using field based hydrological monitoring as validation. The Savanna.au model has been specifically designed to consider a range of spatial scales. Important hydrological and ecological processes operate at the fine patch scale of square metres, whereas management questions refer to paddocks of several square kilometres and properties of many paddocks. The model is also developed to provide easy parameterization using readily available ecological field data.

In this study we will determine to what extent the fine scale ecological processes are understood and incorporated in the model before we scale to larger areas and whether these processes can simply be scaled up, or whether additional relationships are required at larger scales. Also, we find that it is often necessary to account for important, but rare, events experienced in the field such as cyclone driven rainfall. In this situation it may be necessary to ask, at what point should model complexity be limited and rare events ignored, thus providing an exploratory model.

The site chosen for this study is a pastoral property in North Queensland. We show that the spatial arrangement and amount of cover over a 1.19 hectare hillslope modelled at 4 metre square resolution will influence the amount of seasonal runoff over a three year simulation using actual rainfall data. This study also shows that data available to parameterise models is often lacking in the details required for accurate simulations.

This study also highlights where model changes or more data are required to improve simulation results, and how some previously unconsidered aspects are important for accurate simulations. The results also point to the difficulties in determining cause and effect in complex models.

1. INTRODUCTION

Due to the vast scale of land use practices in northern Australia, there is a need for large-scale ecological studies. However, as field trials are usually expensive and impractical over such areas, point based trials are often extrapolated to landscape scales, for example the case of estimating biomass for carbon accounting (Hutley *et al* in press). Remote sensing and simulation modelling have been invaluable in describing large scale landscape processes, changes in land condition (Ludwig *et al* 2005) and tracking fires (Russell-Smith *et al* 1997). However, much is being asked of models that may not have been developed for such scales.

Before we can consider the applicability of scaling up models, we need to ensure that the models can capture the complexity of ecological systems and that data sources are available. This study will look at the ability of a process based model to simulate complex ecological processes at a fine scale (16m^2 cells over 1 hectare) which is a scale not considered by many models.

Tropical landscapes are typically characterized by a dynamic mosaic of patches of trees and grasses interdispersed by bare areas, the scale of which ranges from grass clumps of a few centimetres to units of several hectares. Resources in the form of water and nutrients move between these areas and are retained by patches, leading to increased plant production and landscape function. Bare areas capture less water and lose nutrients and sediments, thus resulting in a decline in plant production and further degradation, in turn increasing the area occupied. This complex system of ever changing landscape patchiness is dependent on a large number of ecological and hydrological factors such as soil properties, slope, macroinvertebrate activity, grazing and plant production. The ability to simulate these spatial processes is important to capture changes in landscape condition. Many landscape factors critical to enterprise management such as pasture biomass, nutritional quality and sediment retention rely on the maintenance of patch heterogeneity in the landscape.

In this paper we use the soil water and plant production components of the Savanna.au model to explore the various hydrological processes, such as “seasonal” runoff and sediment loss. Simulations on a small hillslope will use hydrological monitoring for validation. We will consider the applicability of the spatial and temporal scales used and the level of model complexity considered necessary.

2. METHODS

2.1 The Savanna.au Model

The Savanna.au model was developed to explore the impacts of land management on vegetation dynamics, animal production and landscape processes over periods from a few years to a century. Savanna.au is a grid-based, spatially explicit, process orientated model, developed from the Savanna model (Coughenour 1992, 1993). Savanna was originally devised to study large nomadic pastoral ecosystems (500m cells) in arid east Africa, and has also been used in the savannas of northern Australia (Liedloff *et al* 2001, Ludwig *et al* 2001). While Savanna.au shares much of the plant production and general model concepts with the Savanna model, it has been re-developed to address a range of management questions relevant to northern Australia, and to allow for the inclusion of smaller scale simulations to understand fine scale processes and how these may change with increasing spatial scales. For this modelling exercise, only the landscape hydrology component (Liedloff *et al* 2003) will be discussed in detail.

Accurate modelling of soil water is considered critical for simulating plant production, as plant available water directly relates to plant growth and therefore pasture production, nutritional value and stocking rates. Savanna.au simulates soil water processes using a tipping bucket soil water model, which can be easily parameterised using available field data. As this model has a management focus, the landscape hydrology processes used are not as detailed as for other models such as PERFECT (Littleboy et al., 1992), WEPP (Laflen et al., 1991) and GUEST (Misra and Rose, 1996).

Savanna.au runs on a daily time step using daily rainfall records. It is recognised that rainfall intensity and duration are critical to understanding infiltration, soil water and runoff. Generally, daily rainfall totals are the finest resolution of rainfall data available. For this reason, daily rainfall is divided into rainfall events of defined duration and amount that can provide the storm driven rainfall intensities of northern Australia. The model assumes the first daily event is of one hour duration accounting for a given proportion of the daily rainfall previously calculated from finer resolution rainfall data. The duration of the second event is determined from either a cumulative probability curve or a rainfall duration equation provided for the site.

Rather than calculate runoff from a range of landscape variables (i.e. slope, litter etc) and assume the remaining water infiltrates, Savanna.au uses soil characteristics to determine infiltration rates. The model distributes water through the soil profile based on rainfall amount and duration. The soil properties required can be easily obtained from soil maps providing the depth and texture of soil layers (sand, silt and clay percentages) from which saturated capacity, wilting point and base infiltration rate can be estimated (Bristow et al 1997). Infiltration and percolation into the various layers is further enhanced by eco-hydrological processes such as the development of macropores from macroinvertebrate activity (Liedloff *et al* 2003, Dawes-Gromadzki in press), soil surface condition (Tongway and Hindley 1995) and the feedback to factors such as plant biomass, litter production and cover. Additional processes such as evaporation, plant transpiration and deep drainage determine the final amount of soil water stored in the soil.

Water that does not infiltrate or that is surplus to soil water holding capacity, is routed between cells as sheetflow. A digital elevation map (DEM) provides the height differences between adjacent cells, that in turn determines which cells receive runon, and what proportion is sent to adjacent cells as runoff, using the basic approach used in the model T-HYDRO (Ostendorf and Reynolds, 1993). An additional creek map can be used to specify when a proportion of sheetflow is channelled into creek flow and lost from the system.

A relatively simple sediment movement component is included based on research conducted in the Burdekin Basin, Queensland (Scanlan et al 1996). This component tracks the uptake and deposition of sediment from each cell as a function of runoff volume and grass cover. The DEM is used to determine the volume of water moving across each cell, but this model does not specifically consider the fine scale soil particle physics and water velocity relationships.

2.2 Model parameterisation

This simulation exercise uses the field results from a hillslope runoff study (1.19 hectares) undertaken in the Weany Creek catchment on Virginia Park Station, Queensland (Bartley *et al* 2005). The site is an open eucalypt savanna with the ground cover dominated by low biomass of the stoloniferous Indian couch (*Bothriochloa pertusa*). These study data in the form of plant cover maps, a digital elevation map and soil descriptions were used to parameterise the model. Infiltration data were used to validate the model equations.

A 4×4 metre grid was chosen which was considered an appropriate scale to capture both the vegetation patchiness of the hillslope (i.e. grass clumps and bare ground patches) and the hydrological processes. Future studies will need to use larger cells sizes (e.g 1 hectare) to consider management of paddocks many square kilometres in size. Each grid cell was assigned an elevation from the DEM and a patch type based on the ground cover conditions at the start of the field trial using three levels of cover (0-20%, 20-40%, and 40-100%) of *Bothriocloa pertusa*.

Soil data were based on the Dalrymple soil type (Rogers *et al* 1999) and field based measurements of the A horizon depth. The cover to infiltration relationship was based on the association of macroinvertebrate activity with cover (Dawes-Gromadzki in press), where high cover provides infiltration rates 10 times that of soil base infiltration alone.

Daily rainfall data were provided from the site rain gauge over three tropical wet seasons from November 2002 to February 2005. Other climate variables for plant growth such as temperature and solar radiation were provided from long-term records for Charters Towers (Bureau of Meteorology). It is acknowledged that the runoff and erosion behaviour of the different vegetation patch types depends on rainfall intensity (Reid *et al* 1999). The modelling work currently presented assumes that each grid cell of the hillslope site receives the same amount of rainfall at the same intensity at the same time as only data from a single rain gauge in this catchment was available. Given the small size of this hillslope, this is not an unreasonable assumption. All runoff was assumed to be sheetflow in the absence of creeks. The model assumed no grazing, which was the situation for the period 2003 to 2005 when the paddock was spelled.

In addition to the field-based cover reported in October 2002, 2003 and 2004, four synthetic cover layers were also used in simulations with the same rainfall and soil settings; high cover (initial biomass of 100g m^{-2}) over the entire hillslope, low cover (initial biomass of 10g m^{-2}) in the top 50 percent of the catchment with high cover near the runoff measuring flume, high cover in the top 50 percent of the catchment with low cover near the flume and a bare soil slope.

3. RESULTS

3.1 Modelling outcomes: comparison of measured and modelled data

The measured runoff as a proportion of total rainfall exhibited ranged between 9.5% and 13.3% (Table 1). Modelled runoff consistently underestimated the measured runoff ranging from 3.9% to 7.5%. As sediment loss was dependant upon the number and magnitude of rainfall events, modelled sediment loads varied across the three years with the 2002/03 estimate below the field measurement and the 2004/05 estimate above the field measure.

Table 1. Comparison of measured field data with modelled data for runoff (mm) and sediment loss (tonnes) from the large flume (Bartley *et al* 2005) over three wet seasons.

	Season		
	Wet 2002/03	Wet 2003/04	Wet 2004/05
Rainfall (mm)	168.2	238.2	298.8
Runoff (mm)			
Measured	16.00	31.87	32.47
Modelled	11.43	9.45	22.61
Sediment lost (t)			
Measured	0.270	0.250	0.094
Modelled	0.083	0.253	0.150

Table 2. Comparison of measured field data with modelled data for individual runoff (mm) events using measured plant cover to initialise model each year.

	Runoff (mm)	
Event Date	Measured	Modelled
13-14/12/2003	22	6.77
8-9/1/04	0.02	0.55
12-13/1/04	4.63	2.31
14-15/1/04	4.8	0.54
30-31/1/04	0.098	0.00
2-5/2/04	0.08	0.00
11-12/2/04	0.12	0.54
13-15/2/04	0.017	0.01
Other	0	0.05
Total 03/04 Wet	31.88	10.78
9-12/12/04	0.89	0.68
22-24/1/05	31.58	49.30
Total 04/05 Wet	32.47	52.78

Table 2 shows that most runoff events in the 03/04 and 04/05 wet seasons were small and most were captured by the model. Two reasons are suggested why the simulated data did not match the field data (Table 1). Firstly, the plant production component did not predict the plant cover changes witnessed in the field over the study. This was most likely due to the initialisation of the grass component and the lag period for the plant component to settle. Therefore, the subsequent years (03/04 and 04/05) were modelled with different plant cover than was experienced in the field. Secondly, the modelled runoff from large storm events were most different to that recorded in the field. This accounted for the major seasonal differences reported in Table 1 and is clearly evident for the period 22-44 January 2005 where a cyclonic event caused large runoff volumes (31.58mm) which were over estimated by the model (Table 2, Figure 1). Also, the model underestimated the first large runoff event of the season (see 13-14 December 2003, Table 2).

Figure 1 shows the spatial model output from the simulation. Storm driven runoff is produced, based on rainfall intensity and the elevation of cells in the hillslope catchment (Figure 1b). This sheetflow moved sediment downslope from areas with low cover (Figure 1a) where sediment loss was observed, to be collected at vegetation boundaries where infiltration was higher and vegetation could capture sediment. Sediment loss appeared to be localised, with much retained by neighbouring cells and remaining within the hillslope catchment (Figure 1c). Therefore the reported sediment loads from the study may originate from close to the flume.

3.2 Modelling outcomes: the effect of spatial arrangement of patches

Savanna.au simulations showed that runoff was dependent upon the distribution of cover. The results indicated we could expect large differences in total runoff from the hillslope catchment based on the amount and spatial arrangement of cover on the slope (Table 3). The greatest runoff was predicted when no plant cover was present. Similar trends were reported by Liedloff *et al* (2003), where low/no plant biomass produced the lowest infiltration rates as a result of limited macroinvertebrate activity and lack of litter and plant basal area to slow the movement of water.

Table 3. Simulated total hillslope runoff across the flume (mm) over three wet seasons (2003-2005) based on different levels of initial plant cover and spatial arrangement.

Initial cover	Hillslope runoff (mm)
All high (100%)	71.31
Top half low (10%) – lower half high (100%)	88.52
Top half high (100%) – lower half low (10%)	100.60
No cover (0%)	263.08
2002 measured (61%)	73.73
2003 measured (34%)	78.60
2004 measured (24%)	79.63

The location of areas of high cover influenced total runoff. Where there was high cover around the flume area, the total runoff over the three years was lower than when there was high cover at the top of the catchment. Runoff was also more sensitive to

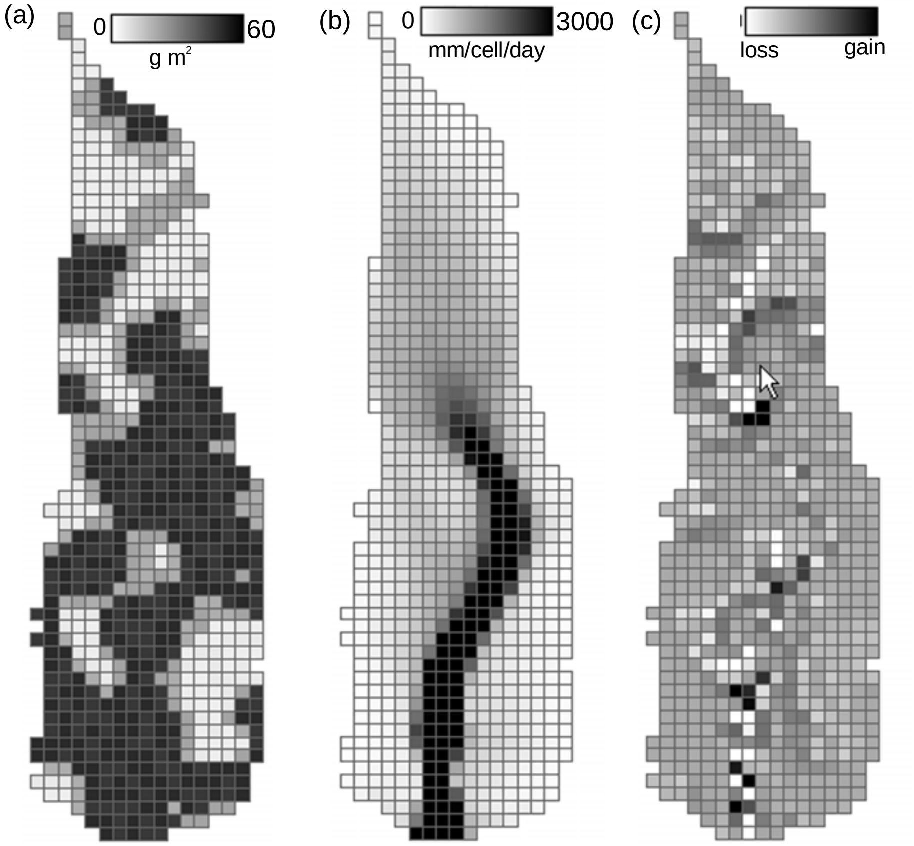

Figure 1. Model output showing (a) live, above ground biomass of grass based on 2004 field measurements, (b) water lost from each cell for one rainfall event (23 January 2005) and (c) the movement of soil sediment over the 3 year simulation.

low cover than high cover (Table 3). The difference between 100% cover and 61% cover (2002 measured) was only 2mm whereas the difference between no cover and 50% low cover resulted in a 160mm difference in total runoff.

4. CONCLUSIONS

These results suggest that preliminary simulations of the Savanna.au model can model eco-hydrological processes and provide estimates of runoff. However, further refinements of the model and data collection are required, especially to capture the outcomes of large rare events (i.e. cyclone associated rainfall). We will discuss a number of areas that may have led to differences between the measured and modelled data. In doing so, we raise some important factors which need to be considered in any landscape hydrological model, regardless of scale.

- It was not possible to provide the model with the rainfall intensities experienced in the field given only daily rainfall totals. As rainfall intensity is critical to infiltration and runoff it was necessary to estimate these values from the daily rainfall totals as the seasonal distribution of rainfall (storm event, shower or continuous rain) influences the runoff simulated. Unfortunately, hourly rainfall data is not readily available and most datasets consist of monthly or annual rainfalls. The alternative is to generate sub-daily rainfall intensity as performed in Savanna.au or to use more general equations that can relate runoff, sediment loss and pasture growth to monthly or annual rainfall. These equations will introduce more variation into the simulations when their level of uncertainty is considered.

- The dynamic modelling of grass biomass is dependant on a large number of interdependent factors. It is difficult to simulate exact field conditions, where the initial states of many factors are largely unknown. This was highlighted in this study where the distribution of grass biomass modelled in 2005 after three years did not match field measurements. This was most likely because of the uncertain history of grazing and initial parameterisation (below ground root biomass and distribution). Using 2002, 2003 and 2004 cover maps to initialise the grass biomass produced more comparable simulated runoff and sediment loads. When the model was supplied with cover representative of the 2004 field measurements, the resulting simulated 0.09 tonnes of sediment loss in

2004/05 was much closer to the field observations than when the simulated plant growth after three years was used (0.15 tonnes).

- Certain critical variables are difficult to measure across the flume catchment. These include the depth of the soil A horizon, which directly determines the soil water-holding capacity which in turn influences runoff relations and plant production. Ideally, these should be known for each grid cell. The study site has lost much of the A horizon revealing a clay based soil type. Modification of the depth of the A horizon around the field estimated 8cm, produced variation in simulated runoff. The ability to accurately represent this parameter over larger areas with scaling up must also be considered.

- The first rainfall events of the season produce increased runoff due to hydrophobic crusting and hard setting characteristics of the study site soil types (Bartley *et al* 2005). This is addressed in the model via a crusting algorithm whereby the period without rain decreases the soil surface condition thus reducing infiltration until crusting is broken by rainfall. However, further research is required in this area. The effects of crusting were clearly seen in December 2003 where the model did not account for a large runoff event at the start of the season based on soil infiltration rates alone.

Any model designed to be used as a management tool requires a number of key of features. The model must be able to handle a scale relevant to the questions being asked and must be easily parameterised with available data. The Savanna.au model has been designed with these criteria in mind and found that available data may be a limiting factor in providing simulations capable of incorporating the range of variation experienced in the field.

The Savanna.au model is not designed to be a predictive model, but to be used as an exploratory tool explaining trends and outcomes of various management scenarios. For this reason the results provided by the model give an indication of how the system is expected to operate including an indication of variability. While accurate values of runoff and sediment loss can be simulated for individual years using all available data, extended periods of simulation will only provide a representation of the landscape being considered.

As seen in the field, variation in critical factors led to large changes in run off, and so accurately describing even a small flume catchment prior to modelling is difficult. Nevertheless, it is important to validate the model simulations with field data. This produces some problems with scaling up as data for much larger catchments than reported here is difficult to obtain.

Both the modelling exercise and field measurements show that the spatial arrangement of cover within a small hillslope influences the soil water and run off. The ability of processes such as grazing and macro-invertebrate activity to influence infiltration, soil water, run off and sediment loss means hydrological processes at a landscape scale can change rapidly. Therefore, this understanding must be incorporated into large scale hydrological models and considered within a land management context.

Given the difficulties in simulating only the soil hydrology of a small hillslope with a detailed process model, simulating larger landscape scales at the same level of detail must be approached carefully. Either the processes discussed here need to be considered extrinsically in landscape-scale models, all areas need to be considered at the level of detail of the hillslope or the differences between the two modelling scales compared and used to justify simulation outcomes at various scales.

This study did not consider the extra complexity introduced by other landscape processes such as fire, grazing and climatic variability and yet several challenges for modelling complex systems were encountered. As the level of complexity increases in the model it becomes increasingly difficult to isolate cause and effect due to feedback mechanisms. Also, the data required to accurately explain the hydrological processes at the scale and time step considered useful by ecologists and land managers may not currently exist for a wide range of locations.

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