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GIS APPROACH TO LAND COVER CHANGE PREDICTION IN SOUTH AFRICAN GRASSLANDS TOWARDS DETERMINING THE CATCHMENT CARBON-WATER- SURFACE ENERGY FLUX NEXUS*

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Abstract

Future land cover changes may result in adjustments to biophysical drivers impacting on: net ecosystem carbon exchange (NEE), catchment water use through evapotranspiration (ET), and even Global Circulation Models. The Land Change Modeller (Idrisi Terrset 18.08) and land cover for 2000 and 2014 is used to predict land cover for the S50E catchment in the Eastern Cape Province for the year 2030. In 2000, grasslands represented 61.5% of the total catchment area with this figure predicted to decrease to 52.1% by 2030 with losses likely to favour a gain in woody plants and cultivated land. The results show that the total change (gain and loss) in the landscape over all land cover classes was 21% for the period between 2000 and 2014 and 23% from 2014 up to the prediction for 2030, with the change intensity remaining constant at 1.5% per year. It was determined that the probability of grasslands persisting is around 80% with the highest probability of grasslands being lost to woody encroachment (~4.5%) and cultivation (~6.6%). Fraction of photosynthetically active radiation (fPAR) and leaf area index (LAI) measured and used in NEE and ET modelling respectively, indicate that both fPAR and LAI are lower for grasslands than for their transition classes. This transition thus represents a gain in both catchment NEE and ET, resulting in increased carbon storage, which from a climate change perspective can be seen as a positive change. However in an already water scarce catchment, further water demands by the vegetation will result in a decrease in the availability of water for other land covers. Finally, carbon offsets from sequestration may be counterbalanced by temperature increases linked to lower albedo increasing net surface radiation. This carbon-water-surface energy flux nexus requires further research in quantifying impacts.

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1. Introduction

Land use and land cover change (LULCC) has been suggested to be the most important anthropogenic disturbance to the environment at a local level, causing various microclimatic changes, and has been studied as a 20th century global phenomenon (Mishra & Rai, 2016) with implications for the 21st century and beyond. Anthropogenic influences on the landscape such as alteration in land use through agriculture, forestry, urbanisation and the introduction of invasive alien plant (IAP) species have a profound effect on the functioning of the landscape and ecosystems.

The storage of carbon in the landscape is driven by biophysical parameters associated with each land cover type and thus changes in land cover proportions across a catchment will impact on the net ecosystem carbon exchange (NEE) of the catchment as a whole. Similarly, the ecophysiology of the individual land covers affects the water use of the vegetation within that land cover and changes in land cover proportions within a catchment impact on the hydrology of the catchment as a whole. Palmer et al. (2017) determined, through field measurements and satellite imagery, statistics around two biophysical parameters – leaf area index (LAI), and fraction of photosynthetically active vegetation (fPAR) – which are used in NEE and evapotranspiration (ET) modelling. This knowledge, combined with predictions of how the land cover will change in the future, precipitates the estimation of future carbon storage and water use within the catchment, which have application to the broader context of climate change.

There have also been suggestions that land use changes will result in changes to the drivers of earth surface conditions that force General Circulation Models (Cao et al., 2015; Pelletier et al., 2015). These changes include variations that are linked to surface albedo; that is the earth's ability to absorb or reflect heat energy. For the southern African region, carbon offsets from sequestration may be discounted from the consequences of temperature increases linked to higher albedo. In global change science it is vital to consider surface albedo and surface area of a range of different land cover classes, and to recommend policies that will change albedo to further promote the improvements being offered by carbon off-sets. Thus for each land cover transition the shift in surface albedo should also be considered with corresponding changes in land surface temperature.

This paper builds on previous work (Gwate et al., 2016; Okoye, 2016; Münch et al., 2017; Palmer et al., 2017) by predicting land cover change for the year 2030 for a grassland-dominated catchment (S50E) in the Eastern Cape Province of South Africa following an inductive approach (Overmars et al., 2007) as a first step in determining the impact of future land cover change on catchment water and carbon fluxes. The Land Change Modeller (LCM) in IDRISI is used to predict land cover for the year 2030 and postulate preliminary consequences of this change with respect to carbon storage and water use which can ultimately be applied to climate change predictions. Rehabilitation approaches to grassland regions after clearing of IAPs may involve soil and water bioengineering techniques and practitioners should take cognisance of the wider implications of these strategies.

2. Study area

The S50E quaternary catchment is situated in the Mzimvubu-Tsitsikamma Water Management Area (WMA) in the Eastern Cape of South Africa (Fig. 1). The vegetation of the study area is predominantly grassland interspersed with IAPs (Mucina and Rutherford 2006). The soils comprise mostly deep clayey loams to rocky soils. The mean annual rainfall

for the area is 772 mm (Schulze, 1997), with the majority occurring in summer particularly during January. The Ncora Dam, supplied by the perennial Tsomo River, lies within the S50E catchment and has a capacity of $150 \times 10^6 \text{ m}^3$ and a surface area of 1 392 ha.

Mixed farming under communal land tenure arrangements is practiced, including livestock grazing and crop cultivation, are the main land use practices (Kakembo, 2001) since the catchment has high grazing potential. The major users of water and carbon in this socio-ecological system are livestock and alien trees. Clearing of IAPs in this catchment has been coordinated through the Chris Hani Local District Municipality which complements the work of the Department of Environmental Affairs' Working for Water (WfW) programme for increasing water on the landscape in combination with socio-economic development, involving poor and disadvantaged people (Macdonald, 2004; Oelofse et al., 2015). Clearing IAPs that have higher water use relative to indigenous vegetation (Clulow et al., 2011) is expected to increase the proportion of water to maintain other ecosystem services provided by rangelands (Meijninger and Jarmain, 2014; Van Wilgen et al., 2008).

Analysis of the recent past (Münch et al., 2017) found that the overall observed land cover change in S50E from 2000 to 2014 amounted to 21%, dominated by increased urbanisation (Iu) and agricultural intensification (Ia). Conversion labels (Fig. 1) were assigned as indicator to describe the transition trajectory identified at each intersection of the two land cover maps (Münch et al. 2017, Pérez-Vega et al., 2012). Persistence and intensification of natural or invaded wooded areas (Pf+If), possibly IAPs, were identified as a degradation gradient within the landscape, which amounted to almost 10% of S50E. In some areas return to grassland and bare areas signified abandonment (A) and degradation (De). However, despite a net loss of 5%, grassland still dominates the landscape.

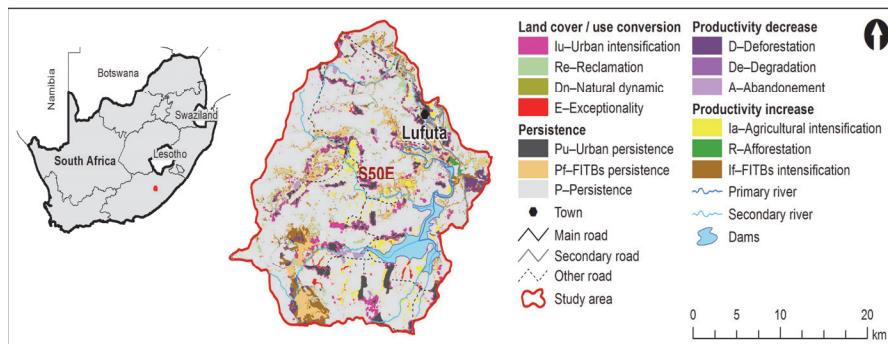


Fig. 1. Location of S30E catchment showing land cover transitions between 2000 and 2014
(adapted upon Münch et al., (2017))

3. Materials and method

3.1. Background

Land Change Modeller (LCM), integrated into IDRISI Terrset 18.08, provides tools to assess and project land cover change. In LCM, change between two past time steps (T_1 and T_2) is modelled through Multi-layer Perceptron (MLP) using mathematics and explanatory spatial variables in a trends driven approach (Perez-Vega et al., 2012) to create transition potential maps. Markov Chain Analysis assigns the probability of change determined by projecting the historic change to the future, which together with transition potential maps, predict a future land cover for some future data (T_3). Spatial analysis of land cover change using the explanatory variables identifies: 1) maps of the transition potential for each identified land cover transition, 2) a transition potential map indicating the

likelihood or vulnerability of each location in the study area to experience change and 3) a predicted land cover map for a selected future date (T_3) (Mas et al., 2013).

Land cover maps at 30m pixel resolution (Okoye, 2016), for T_1 (2000) and T_2 (2014) were used to create 1) transition potential maps for each transition, 2) a projected potential for transition map and 3) a predicted land cover map for 2030 (T_3) for S50E. An identical land cover legend consisting of eight land cover classes developed by Münch et al. (2017), including grassland (UG), natural woody vegetation (FITBs), bare (BRS), water bodies (Wb), wetlands (WI), cultivated land (CLS), plantation (FP) and urban (UrBu), was used for each time step.

Trajectories of land cover change describing both change and persistence were identified (Münch et al. 2017). Each possible transition of land cover between T_1 and T_2 was allocated to a trajectory and labelled (Table 1). According to Perez-Vega et al. (2012) land cover transitions can be grouped into sub-models if the underlying driver of change is assumed to be the same for each transition.

Table 1. Transition sub-models and descriptors for catchment S50E

Transition sub-model	Description	Land cover transitions
If: FITBs intensification	Woody natural and artificial vegetation substitutes previous land cover	UG to FITBs; FP to FITBs; CLS to FITBs
Ia: Agricultural intensification	Agricultural activities substitute previous land cover	UG to CLS; FITBs to CLS; Wb to CLS; WI to CLS; UrBu to CLS
Iu: Urban intensification	Urban activities substitute previous land cover	UG to UrBu; CLS to UrBu; FITBs to UrBu
R: Afforestation	Other land covers are converted to plantations	UG to FP; FITBs to FP
D: Deforestation	Plantations converted to other land covers	FP to UG; FP to BRS
A: Abandonment	Urban and agricultural areas converted to grassland and bare areas	CLS to UG; UrBu to UG
Dn: Natural dynamic	Areas where natural changes occurred	UG to Wb; UG to WI Wb to UG; WI to UG
De: Degradation	Shrub area converted to grassland and bare areas	UG to BRS
Re: Reclamation	Woody natural and artificial vegetation areas converted to grassland and bare area	FITBs to UG

4. Results and discussion

For S50E, the probability (Table 2) of UG persisting is approximately 80% with the highest probability of UG being lost are to FITBs (~4.5%), CLS (~6.6%) and UrBu (~8.3%), thus FITBs intensification (If), agricultural intensification (Ia) and urban intensification (Iu) are at the expense of grasslands, constituting ~12% of the catchment (5283 ha).

The probability of 34% FITBs loss to UG, possibly due to alien invasive clearing programs, may seem high, but in reality the number of pixels that can in fact transition are limited and the change represents only 4% (1800 ha) of the total area (44640 ha) in 2030 (Table 3). It is, however, interesting to note that the probability of persistence of FP is low (24%) with a likelihood of transition to FITBs (42%) and UG (34%), which clearly reflects the changes from 2000-2014. Classes WI and BRS also show a very low probability of persisting. It was determined that the total change (gain and loss) in the landscape for catchment S50E over all land cover classes was 23% for predicted period 2014 to 2030, compared with 21% for the period between 2000 and 2014 (Münch et al., 2017). The change intensity (defined as the change per year) remained constant at 1.5% per year. UG, the largest class, also has the largest loss (Table 3), though this relatively large dormant class,

shows a higher change intensity during the modelled period with the loss intensity increasing from 1.27% to 1.34%. The predicted change mimics the pattern of the measured change except for FITBs where a net loss in this class is predicted, possibly an indication of reduction in IAPs. Fig. 2a shows the spatial distribution of the probabilities mapped in Table 2, while Fig. 2b shows the predicted land cover map for 2030 and the classified transitions (Fig. 2c).

Table 2. Probability of land covers in S50E transitioning or persisting from 2014 to 2030

	<i>UG</i>	<i>FITBs</i>	<i>BRS</i>	<i>Wb</i>	<i>Wl</i>	<i>CLS</i>	<i>FP</i>	<i>UrBu</i>
<i>UG</i>	0.801	0.0451	0.0013	0.0006	0.001	0.0662	0.0013	0.0834
<i>FITBs</i>	0.3435	0.5788	0.0008	0.0005	0.0003	0.015	0.0179	0.0432
<i>BRS</i>	0.4295	0.0466	0.0013	0	0.0005	0.015	0.0141	0.4929
<i>Wb</i>	0.0323	0.0023	0	0.926	0	0.0383	0	0.001
<i>Wl</i>	0.5226	0.0138	0.0008	0.0001	0.0012	0.4329	0	0.0285
<i>CLS</i>	0.1074	0.0266	0.0003	0.0002	0.0002	0.8392	0.0001	0.026
<i>FP</i>	0.3377	0.4198	0.0043	0	0.0003	0	0.2361	0.0017
<i>UrBu</i>	0.0252	0.0027	0.0007	0	0	0.0539	0.0015	0.9161

Table 3. Modelled land cover change in S50E as a percentage of the study area.

<i>Change</i>	<i>UG</i>	<i>FITBs</i>	<i>BRS</i>	<i>Wb</i>	<i>Wl</i>	<i>CLS</i>	<i>FP</i>	<i>UrBu</i>	<i>Total 2014</i>	<i>Loss</i>	<i>Net</i>
UG	44.7	3.2	0.1	0.1	0.1	4.0	0.1	4.7	56.9	12.2	-4.8
FITBs	4.0	5.5	0.0	0.0	0.0	0.3	0.2	0.5	10.5	5.1	-0.6
BRS	0.0	0.0	0.1	0.0	0.0	0.0	0.0	0.0	0.1	0.1	0.1
Wb	0.1	0.0	0.0	2.6	0.0	0.1	0.0	0.0	2.9	0.3	-0.2
Wl	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.1	0.1	-0.01
CLS	2.2	0.5	0.0	0.0	0.0	14.8	0.0	0.7	18.2	3.4	1.7
FP	0.6	0.7	0.0	0.0	0.0	0.0	0.4	0.0	1.8	1.4	-1.1
UrBu	0.3	0.1	0.0	0.0	0.0	0.6	0.0	8.5	9.5	1.0	4.9
Total 2030	52.1	9.9	0.2	2.7	0.1	19.8	0.7	14.4			
Gain	7.4	4.4	0.1	0.1	0.1	5.1	0.3	5.9		23.4	
Change per year										1.5	

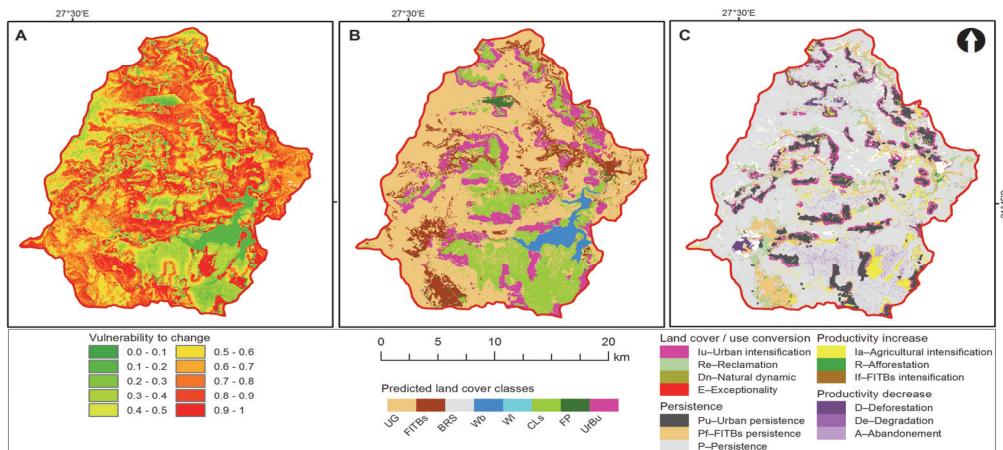


Fig 2. (a) Projected potential to transition map; (b) predicted land cover for 2030;
(c) predicted transitions for S50E

The motivating factor in predicting land cover change in the future is to acquire an understanding of how these changes may impact upon catchment run-off (Piao et al., 2007), NEE and ET as indicators of future carbon storage and water use potential (carbon-water nexus). Our research shows that there are several important transitions that have occurred and are likely to continue into the future. In 2000, UG represented 61.5% of the total catchment area, and this figure is predicted to decrease to 52.1% by 2030 (Table 3), with losses likely to favour a gain in FITBs and CLS. fPAR and LAI measured by Palmer et al. (2017) and used in NEE and ET modelling respectively, indicate that both fPAR and LAI are lower for un-improved grasslands than for both potential transition classes. This transition will thus represent a gain in both catchment NEE and ET, and a concomitant decrease in run-off. From a carbon storage perspective, the transition will result in more carbon storage, which from a climate change perspective may be seen as a positive change, however in an already water scarce catchment, further water demands by the vegetation will result in a decrease in the availability of water for other land covers.

The changes to surface albedo that will accompany these land cover trajectories are less certain. Given that there is a general increase in woody green biomass as a result of both afforestation and continued invasion by IAPS, the findings of Rotenberg and Yakir (2010) make it likely that the decrease in surface albedo from these cover classes will result in an increase in the absorption of energy, with the resultant rise in temperature. This decrease in albedo may however be counteracted by an increase in degraded surfaces associated with rural housing and in the unimproved grasslands where continuous grazing by livestock changes species composition and cover. Rangeland degradation is commonly associated with the changes in land tenure that are occurring in this catchment (Bennett et al., 2012), and a reduction in the basal cover of herbaceous plants (mainly grasses) is the first noticeable change. This results in a surface with higher albedo.

The land surface reflectance (albedo) is used in energy balance calculation to estimate net surface radiation. Dark vegetation with a high LAI will have a lower albedo than open grasslands and it can be postulated (however this must still be measured) that the transitions predicted in the S50E catchment will lead to an overall lowering of albedo in the catchment. Gibson (2013) showed that varying albedo from 0.07 to 0.15 decreased net radiation at the surface by 10% and an increase in net radiation is thought by some to be a driver of global warming. However, Bonan (2008) states that surface warming arising from the low albedo of forests is offset by strong evaporative cooling, particularly in deciduous broadleaf forests (Zhao and Jackson, 2014). The impact of a change in albedo in this catchment remains speculative but is a research avenue which should be pursued.

6. Conclusions

In 2014, grasslands represented 56.9% of the total catchment area, predicted to decrease to 52.1% by 2030 with losses favouring woody plants and cultivated land. The probability of grasslands persisting is ~80% with the highest probability of grasslands being lost to woody encroachment ~4.5% and cultivation ~6.6%.

Since fPAR and LAI are lower for grasslands than for their transition classes, this transition will result in increased carbon storage and water use. These carbon offsets from sequestration may be counterbalanced by temperature increases linked to lower albedo and this carbon-water-surface energy flux nexus requires further research.

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