Impact of land use and land cover transitions and climate on evapotranspiration in the Lake Naivasha Basin, Kenya

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Abstract

The Lake Naivasha basin in Kenya has experienced significant land use cover changes (LUCC) that has been hypothesized to have altered the hydrological regime in recent decades. While it is generally recognized that LUCC will impact evapotranspiration (ET), the precise nature of such impact is not very well understood. This paper describes how land use conversions among grassland and croplands have influenced ET in the Lake Naivasha Basin for the period 2003 to 2012. MODIS data products were used in combination with the European Centre for Medium-Range Weather Forecasts (ECMWF) data sets to model ET using the Surface Energy Balance System (SEBS). The results indicate that conversions from grassland to cropland accounted for increases in ET of up to 12% while conversion from cropland back to grasslands (abandonment) reduced ET by ~4%. This suggests that recently cultivated agricultural lands could increase local water demands, while abandonment of the farms could decrease the water loss and eventually increase the water availability. Also, recovery of ET following re-conversion from cropland to grassland might be impeded due to delayed recovery of soil properties since parts of the catchment are continuously being transformed with no ample time given for soil recovery. The annual ET over the 10 years shows an estimated decline from 724 mm to 650 mm (~10%). This decline is largely explained by a reduction in net radiation, an increase in actual vapour pressure whose net effect also led to decrease in the air-surface temperature difference. These findings suggest that in order to better understand LUCC effects on water resources of Lake Naivasha, it is important to take into account the effect of LUCC and climate because large scale changes of vegetation type from grassland to cropland substantially will increase evapotranspiration with implications on the water balance.

Keywords: Agricultural abandonment, Remote Sensing, Reanalysis, LUCC, SEBS

1. Introduction

At least 30–50% of global land cover has been affected by land use change, primarily for agricultural purposes to increase food production for the increasing human population (Pongratz et al., 2008; Vitousek et al., 1997). Globally, agricultural land expansion at the expense of forest and grassland has increased fivefold in the past 300 years (Goldewijk, 2001; Scanlon et al., 2007). In Sub-Saharan Africa and South America further large scale land use change for food production is projected for the coming years (Bruinsma, 2003). These land use conversions modify parts of the hydrological cycle and may eventually impact ecosystem functioning and compromise water, food, hydropower provisioning as well as regulation of climate (Inauen et al., 2013; Nosetto et al., 2012).

Evapotranspiration (ET) from land returns about 60-65% of the continental precipitation (Brutsaert, 2005) and consumes more than half of the solar radiation absorbed by the land surface (Trenberth et al., 2009) making it a major component of the climate system linking the hydrological, energy and carbon cycles (Jung et al., 2010). Therefore, accurate ET estimation is crucial to better understand the climatic and hydrological processes at scales relevant for water resources management and climate change impact projections. Climate and land use change are two key factors affecting ET (Li et al., 2017; Vörösmarty et al., 2000). While much emphasis has been placed on potential impacts of climate change, impacts of land use change may outweigh or enhance the impacts of climate change (Divino et al., 2015; Scanlon et al., 2007; Vörösmarty et al., 2000; Zou et al., 2017). This is because vegetation exerts strong controls on key hydrological variables including ET, deep drainage and runoff. Significant land alterations affect water resources by altering the partitioning of precipitation (Calder, 1998; Nosetto et al., 2012).

Reduced evapotranspiration following land clearance has been shown to modify the water budget partitioning by increasing aquifer recharge and surface runoff (Leblanc et al., 2008; Scanlon et al., 2007). However, these increases in recharge and surface runoff can be offset by increased withdrawals for irrigation (Falkenmark and Lannerstad, 2005). Moreover, the contribution of climate and land use change to changes in water resources for different geographic regions is still unclear (Feng et al., 2016; Li et al., 2017). Discriminating these human-induced perturbations from natural factors is expected to increase in importance as anthropogenic transformations of the earth surface intensify (Gerten, 2013; Mao et al., 2015; Seneviratne et al., 2010). This continues to be a challenge particularly because as the basin scale increases so are the increased mixed effects making it difficult to discriminate the influence of LUCC from those of climate (Odongo et al., 2014; van Dijk et al., 2012).

In water-stressed environments, land use conversions oftentimes lead to increased competition for already scarce water (Feng et al., 2016). Present understanding of the effect of these competing demands is still limited (Menz et al., 2013). Specifically, debate on whether the LUCC has determined ET trends or whether the effect of LUCC on ET can be offset by the effect of climate change on ET remains unresolved (Li et al., 2017). For example, East African catchment experiments of the late 1950s and 1960s concluded that there were no significant changes of ET and runoff after land use conversions (Blackie, 1972; Blackie and Robinson, 2007; Dagg and Blackie, 1965). Similar observations in resilience of ET following significant land use and climate changes in a humid temperate catchment in southwest Michigan, United States have also been reported (Hamilton et al., 2018). However studies in the Sahel and Australia where native forests have been cleared for agriculture have observed significant increases in groundwater recharge due to reduced ET rates and modifications of the soil properties leading to increased infiltration capacity (Jackson et al., 2005; Leblanc et al., 2008;

Schofield, 1992; Taylor et al., 2002) whereas agricultural expansion in the Upper Blue Nile basin in Ethiopia has led to increased surface runoff and reduced ground water recharge (Woldesenbet et al., 2017). The opposite conversion of grassland areas to forests usually lead to increased evaporative water fluxes and reduced water yields (Farley et al., 2005; Nosetto et al., 2005; Scanlon et al., 2007).

While land use transitions between forests and grasslands have shown the greatest impact on the water balance (Farley et al., 2005; Nosetto et al., 2005), transitions between structurally more similar vegetation types, such as croplands from grasslands, have received much less attention, although their hydrological impacts could also be large (Nosetto et al., 2012). The opposite case of converting croplands to grassland has however, been undertaken in China following the grain for green programme initiated in 1999 to recover degraded ecosystems (Feng et al., 2016; Li et al., 2016; Qiu et al., 2011a; Qiu et al., 2011b). The results of this programme have shown evidence of increased ET primarily driven by the vegetation greening (Feng et al., 2016; Jin et al., 2017; Li et al., 2016). Other studies have reported evaporative water losses due to land use change in Africa (e.g. Farah and Bastiaanssen, 2001; Karimi et al., 2015; Kiptala et al., 2013; Kongo et al., 2011). Specifically, quantifying the hydrological impacts of land use conversions from grassland to croplands and reverse abandonment of croplands back to grasslands are largely understudied even though the impacts could be large especially in catchments where grasslands have been the dominant vegetation and observed to decline at the expense of croplands.

In this study we hypothesize that the effect of land use transitions outweighs that of climate on ET. We test this hypothesis by analysing conversions from grassland and croplands and abandonment of croplands to grasslands. Therefore, the objective of this study was to quantify individual contributions of climate and LUCC on ET and identify the main factors that influence ET. The study aims at filling the knowledge gap in understanding the role of LUCC and climate on the ET of Lake Naivasha basin such that water policy directives by land and water managers maybe targeted cautiously when promoting land use changes for purposes of mitigating likely effects of climate on basin water balance.

Method

Study area

The Lake Naivasha basin is situated in the Kenyan Rift Valley at a latitude of 0º 09′ to 0º 55′S and a longitude of 36º 09′ to 36º 24′E covering an area that is approximately 3500 km^2 (Figure 1). The maximum altitude is about 3990 m above mean sea level (a.m.s.l.) on the eastern side of the Aberdare Mountains and the minimum altitude is about 1980 m a.m.s.l. near the lake. The lake does experience periodic wet and dry cycles. Extended dry periods over time and increased abstractions have led to periods of water scarcity in the basin. The lake is a RAMSAR wetland (Ramsar, 1996) despite supporting important economic activities including fishing, agriculture, horticultural flower industries, power generation, domestic water supply and tourism (Becht and Nyaoro, 2005). The catchment population has more than doubled from ~250,000 persons in 1980 to over 600,000 persons in 2009 (KNBS, 2009). The increased population in the basin and the socio-economic developments have been linked to the land use and land cover changes and consequently impacted the eco-hydrological processes in the basin (Odongo et al., 2014). The population increase in the basin was found to correlate strongly with increases in cropland, woodland, grassland and built-up (Odongo et al., 2014). While paved surfaces and built-up areas have been known to have a large potential effect on the hydrology of basins, the present study focused on the land cover conversions among woody savanna, grassland and cropland. Specifically the population pressure on land for settlements and farming has resulted in conversions of previously dominated grassland and woody savanna areas into cropland. These grasslands and woody savannas are part of transitional lands that are usually cultivated for crops in some years and later abandoned for other grassland areas (Odongo et al., 2014). The impact of these conversions on ET relative to climate is largely unknown. Whereas long-term human influences on streamflow and lake levels have been studied in the basin (Becht and Harper, 2002; Odongo et al., 2014; Odongo et al., 2015; van Oel et al., 2013), the evaporative losses of different land use and land cover classes, their trends and climatic drivers are largely unknown. This study focuses on these land use alterations in the upper part of the basin that is most hydrological active where the three rivers contribute up to 90% of the inflows into the lake.

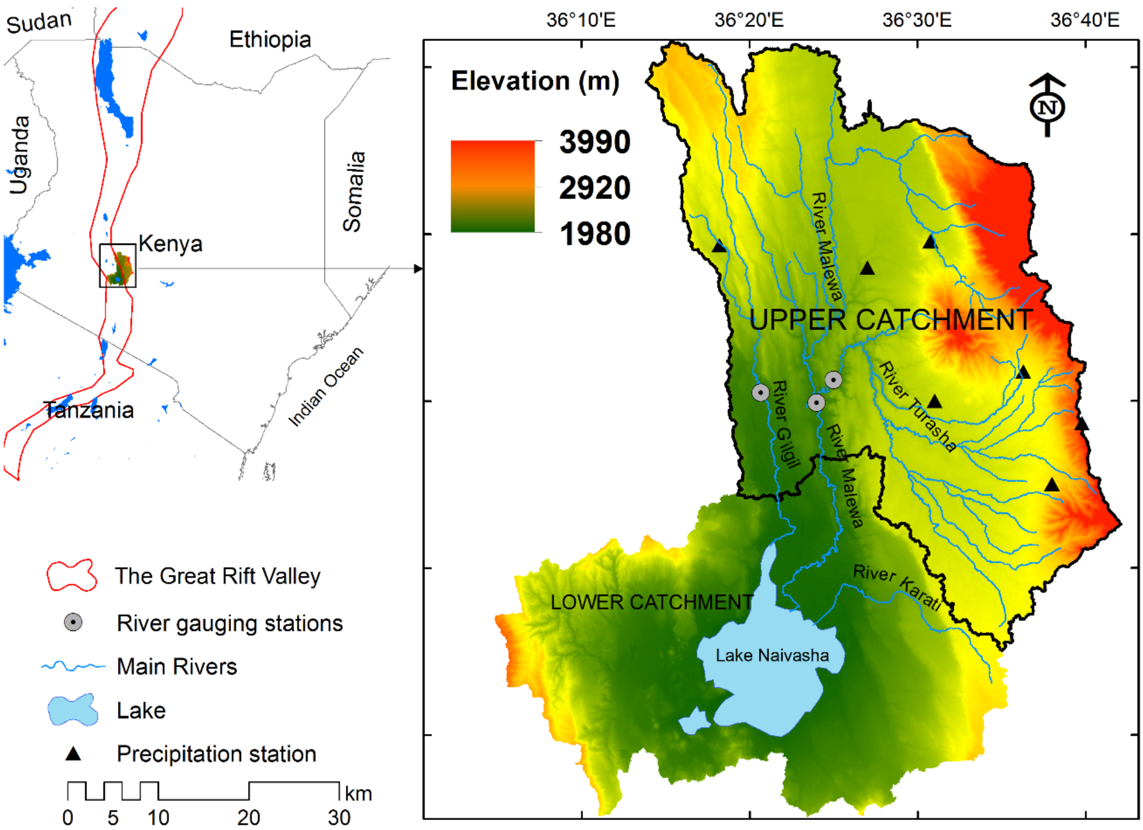

Figure 1: Lake Naivasha Basin and its main rivers in the upper catchment and the lake in the lower catchment

Methods and Data

Remote sensing products and meteorological data

The SEBS algorithm (Su, 2002) was used to estimate ET. The model description, implementation, inputs and validation of the model outputs are described in Odongo (2016). The SEBS model is a Soil-Vegetation-Atmosphere Transfer (SVAT) scheme that couples the dynamics of both climate and land surface interaction to simulate the energy fluxes with evapotranspiration from the land surface being one of the key variables. In summary, the main meteorological variables used in the SEBS calculations were air temperature, dew temperature, surface pressure, sea level pressure, radiation components, and wind speed were obtained from ECMWF website (http://data-portal.ecmwf.int/) at a temporal resolution of 3h and spatial resolution of 0.125°× 0.125°. The ECMWF provided meteorological input data for the basin because available and comparable ground observations data covering the basin at relevant resolution is not available. The study area is within the Equatorial tropical latitude and variability of meteorological data such as temperature, air pressure and humidity would not vary significantly at 12.5 km spatial scale resolution. This resolution was much finer compared to for example the resolution of meteorological reanalysis data set from NASA's Global Modeling and Assimilation Office (GMAO, 1.00°×1.25°) used in MOD16 ET (Mu et al., 2011). The land surface variables (emissivity, land surface temperature, albedo, normalized difference vegetation index (NDVI), and Leaf Area Index (LAI) used in SEBS were obtained from the MODIS website (http://modis-land.gsfc.nasa.gov/). The remote sensing products and meteorological data used are summarized in Table 1.

Being a data sparse environment we opted for MODIS and ECMWF datasets to run the model because (1) High temporal resolution and long-term existence of these data sets that allowed for testing our hypothesis (2) MODIS is the only remote sensing product that provides annual land use and cover maps for monitoring environmental change and (3) Use of these datasets to estimate ET over East Africa and entire Africa (Sun et al., 2011; Sun et al., 2012), a data sparse region, has also been shown using flux tower measurements to provide promising results.

Table 1: Summary of remote sensing and meteorological data used in the study

Input data	Source	Spatial resolution	Temporal resolution	Coverage
Land surface temperature	MODIS (MOD11A1)	1000 m	Daily	2003-2013
Emissivity	MODIS (MOD11A1)	1000 m	Daily	2003-2013
Albedo	MODIS (MCD43B3)	500 m	16 day	2003-2013
NDVI	MODIS (MOD13A2)	500 m	16 day	2003-2013
Leaf area index	MODIS (MCD15A2)	1000 m	8 day	2003-2013
Land use/cover	MODIS (MOD12Q1)	500 m	Annual	2003-2013
Shortwave down-welling radiation	ECMWF	~12.5 km	3 hourly	2003-2013
Longwave down-welling radiation	ECMWF	~12.5 km	3 hourly	2003-2013
Air temperature	ECMWF	~12.5 km	3 hourly	2003-2013
Surface pressure	ECMWF	~12.5 km	3 hourly	2003-2013
Dew point temperature	ECMWF	~12.5 km	3 hourly	2003-2013
Wind	ECMWF	~12.5 km	3 hourly	2003-2013

The SEBS model was simulated on a daily time step. The model simulation results had missing days since it is difficult to retrieve a dataset from remote sensing without gaps due to the temporal resolution, cloud coverage, sensor failures and unreliable data flagged by the quality control of MODIS on the surface variables such as land surface temperature and emissivity. To overcome this, we employ the approach of Gokmen et al. (2013) and Jin et al. (2013) where the sum of available daily ET estimates is divided by the number of days with available ET to be representative of the daily monthly average ET. Later this is multiplied by the total number of days for each month to get the monthly total ET and the summation of the monthly ET yields estimates of annual ET.

Assessment of ET, land use and climatic change

Land use classes of the basin generated from MOD12Q1 based on the International Geosphere-Biosphere Programme classification (IGBP) (Loveland and Belward, 1997) were used to develop annual land use transition matrix among the dominant land use classes in the basin from 2003 to 2012. The dominant land uses identified were grassland, woody savanna and cropland natural vegetation mosaic. In this paper, the cropland natural vegetation mosaic is referred as "cropland" and is different from the IGBP actual land use class labelled as cropland which was less dominant and covered about ~3.5-12% of the entire basin area over the study period. The ET from the dominant land use, newly converted and unconverted classes were then extracted using zonal analysis for each year. Following the approach by Li et al. (2017) we assumed that if both climate and land use do not change over time, then ET in the region would remain constant on the long term. Also, if climate conditions in the basin were to remain the same despite changes in land uses, the trend and effect of climate change on ET would be the same among the land use types. This way it is possible to monitor and evaluate ET changes for surfaces that did not undergo changes year to year versus those that underwent changes. For example, the effect of climate on ET if a surface changed from grassland to cropland compared to a surface that is grassland and unchanged between two periods, can be estimated by the difference in ET between the two periods for the two cases while the effect of land use change can be estimated by the difference in ET between the unchanged surface and the changed surface for each respective year. We employ this method in evaluating the ET responses among the key dominant land uses in the upper Lake Naivasha basin namely grassland, cropland and woody savanna. Impact of ET due to reverse changes from cropland to either grasslands or woody savanna (abandonments) were also estimated and compared with ET of unchanged surfaces to determine recovery of ET. To evaluate the impact of land use changes on ET we examined and compared annual change of ET between unchanged land use of type *j* and annual change in ET between converted land use of type *j* to type *k*. The equations below summarize the computation of the land use change (Equation 1) and climate (Equation 2) impact on ET as explained above and used in this study.

$$\Delta ET_{t_i}^{lucc} = ET_{t_i}^{u} - ET_{t_i}^{c} \qquad \text{Equation (1)}$$

where $\Delta ET_{t_i}^{lucc}$ is change in ET due to land use change for the current year t_i, $ET_{t_i}^{u}$ and $ET_{t_i}^{c}$ are the ET from unchanged land use of type *j* and changed land use from type *j* to type *k* respectively.

$$\Delta ET_{t_i}^{climate} = ET_{t_i}^{lulc} - ET_{t_{i-1}}^{lulc} \qquad \text{Equation (2)}$$

where $\Delta ET_{t_i}^{climate}$ is the change in ET due to climate change in the current year t_i compared to the previous year t_{i-1}, $ET_{t_i}^{lulc}$ and $ET_{t_{i-1}}^{lulc}$ are the ET for similar land use type for the current year t_i and previous year t_{i-1} respectively. Then, the partial correlation was used to examine the impacts of climate variables (Precipitation, Surface-air temperature difference, actual vapour pressure and net radiation) and NDVI on ET trends.

Results

Land use and cover transitions

Trends in land use and cover changes in upper Naivasha basin are shown in Figure 2. The MODIS retrieved land use/cover showed that the upper Lake Naivasha basin has undergone significant land use/cover conversions from 2003 to 2012 (Figure 3) especially between grasslands, woody savannas and cropland (Table 2 and Table 3). Between this period, much of the grasslands have been on decline from ~53% to ~15% while woody savannas and cropland have been on the increase from ~18% to ~32% and ~16% to ~32% respectively. Evergreen forest and shrublands declined from ~6.4% to ~6% and 1.7% to 0.3% respectively. The cropland, however, represent the lands that were previously predominantly grassland since the population in this part of the basin practices crop rotations and in some years the land is abandoned and left fallow besides being used for grazing. These land use conversions have been shown to alter the water balance in the basin (Odongo et al., 2014).

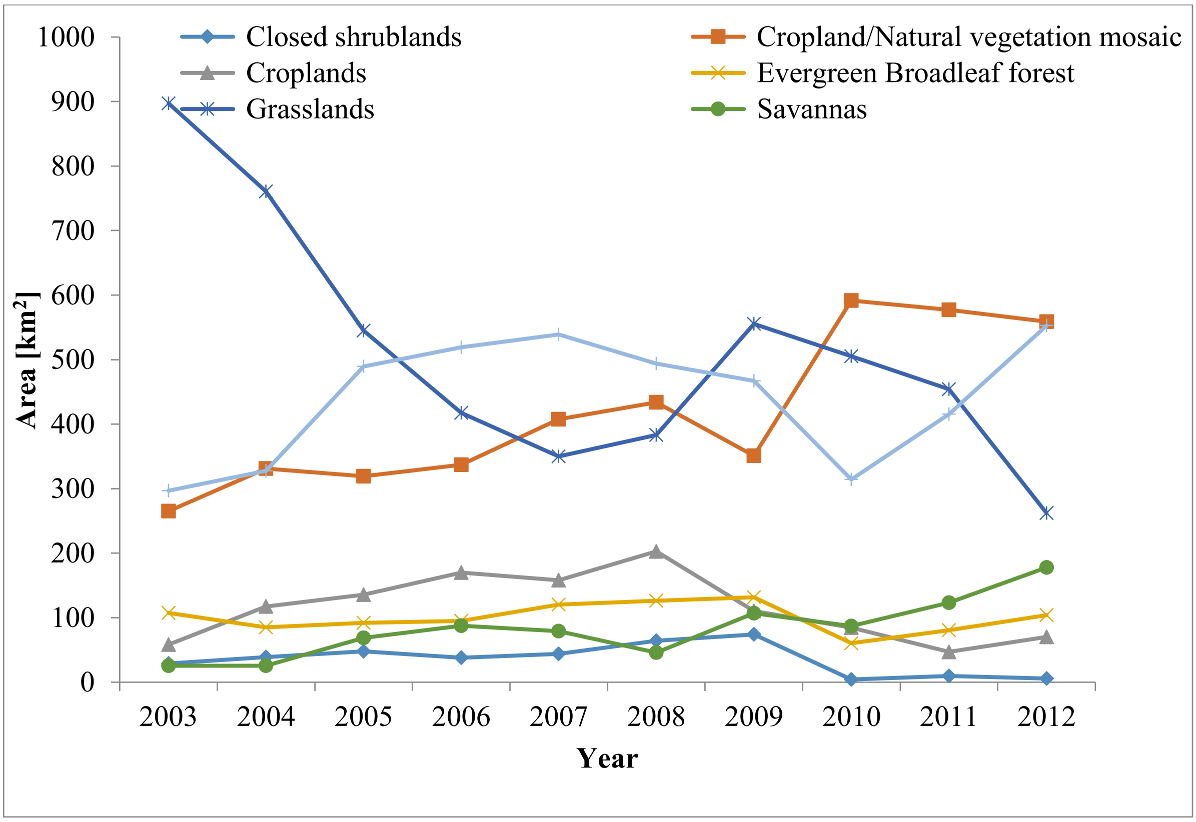

Figure 2: Land use/cover changes in the upper Lake Naivasha basin from 2003 to 2012

Woody savannas and cropland/natural vegetation mosaic accounted for most of the land use transitions to grasslands with both accounting for at least 50% in most years (Figure 4). Land use conversions to cropland from other land uses were also dominated by those from woody savannas and grasslands accounting for at least 50% in most years (Figure 5).

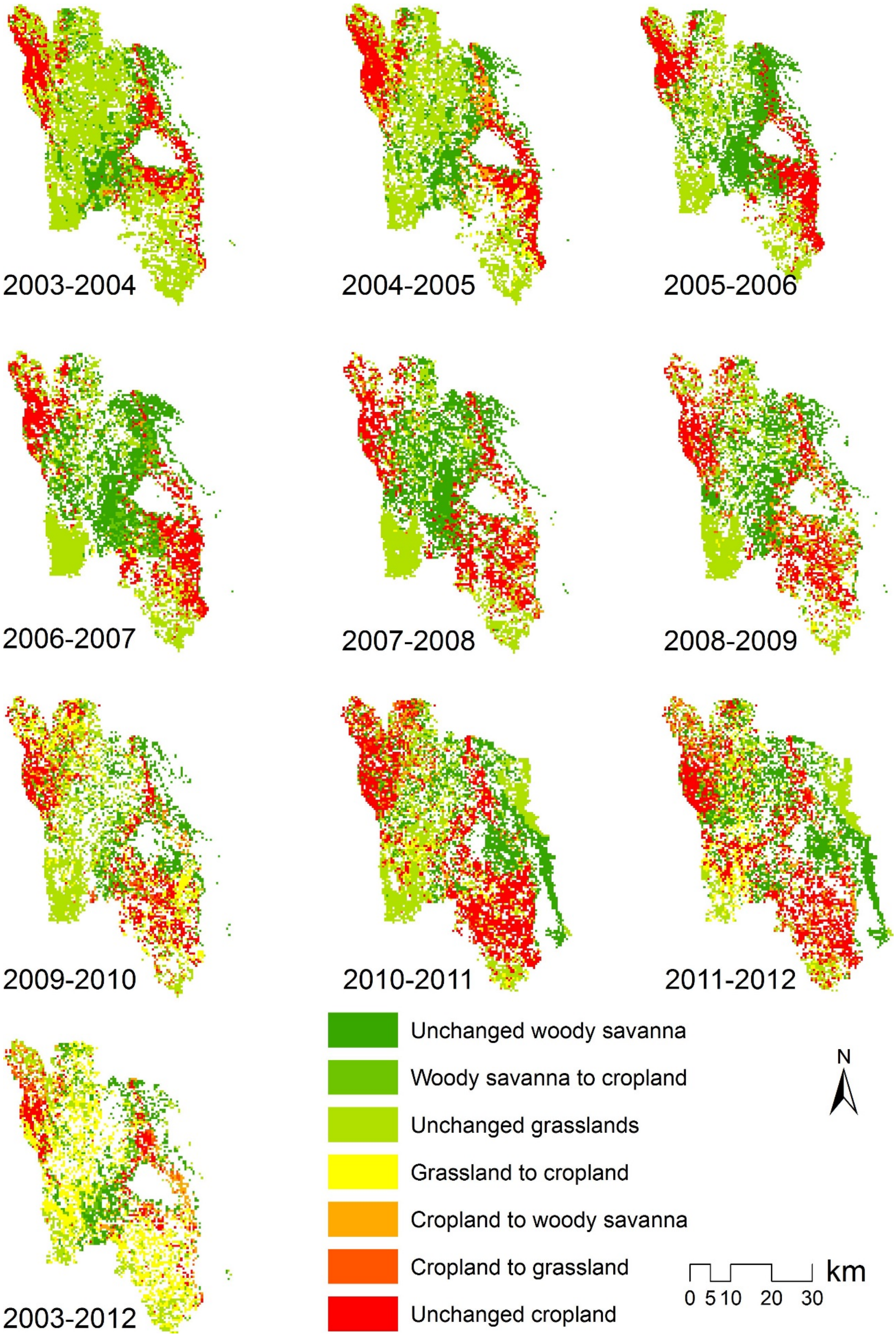

Figure 3: Spatial patterns of inter-annual land use transitions in the upper Lake Naivasha basin. Blank areas are unclassified.

Table 2: Annual land use transitions to grasslands in Lake Naivasha between 2003 to 2012 (Areas are in km^2)

Transition Year	Forest to grassland	Shrubland to grassland	Woody savannas to grasslands	Savannas to grassland	Cropland to grassland	Cropland/Natural Vegetation to grassland	Total area
2004	3.68	0.22	26.85	8.01	14.29	22.73	75.78
2005	0.00	0.43	24.25	5.63	9.31	15.81	55.43
2006	1.08	1.95	25.12	16.02	26.20	12.34	82.71
2007	1.52	0.87	21.87	8.01	21.22	23.82	77.30
2008	4.11	0.87	46.77	19.49	14.72	39.19	125.15
2009	4.76	0.22	133.16	9.74	54.13	73.40	275.42
2010	1.73	66.69	125.37	45.90	24.68	53.05	317.42
2011	1.73	0.87	37.03	16.67	21.22	60.19	137.71
2012	4.55	5.20	35.73	8.44	5.85	55.43	115.19

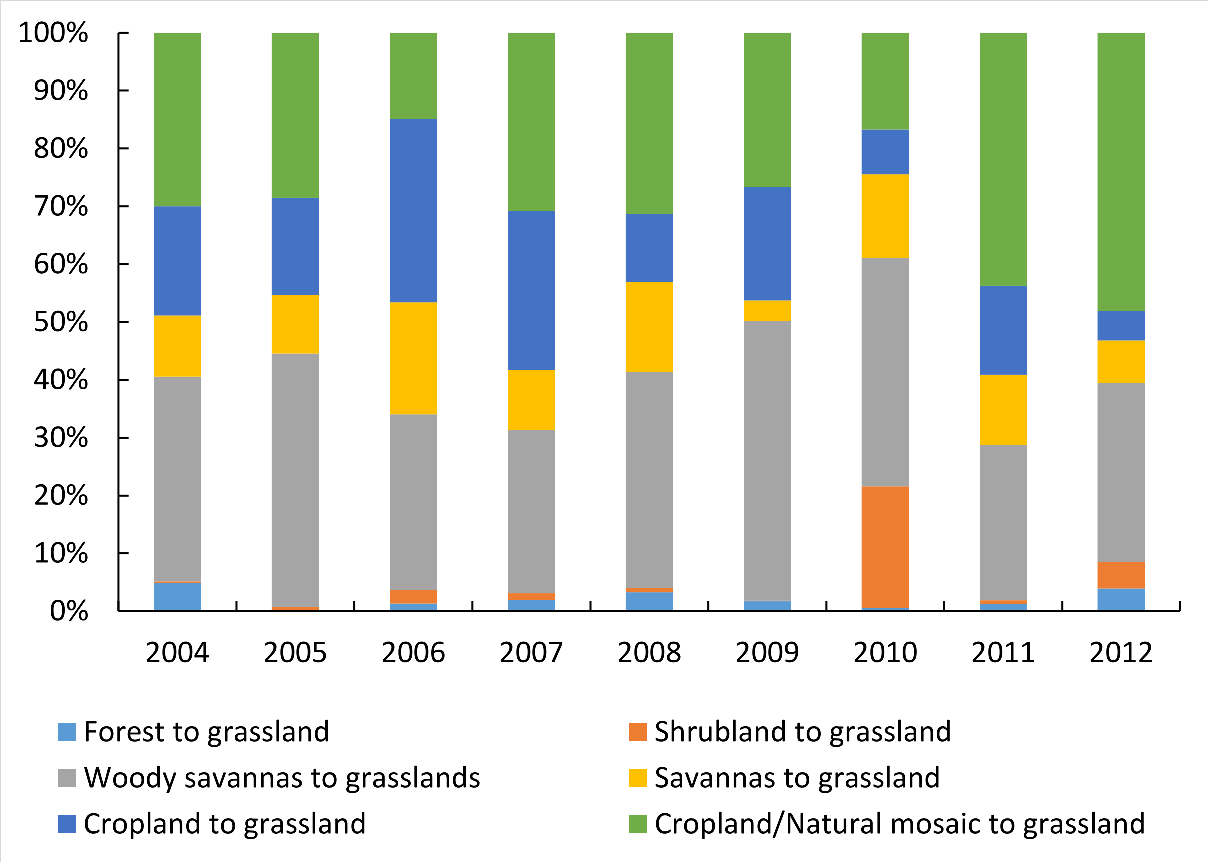

Figure 4: Percentage annual land use transitions to grasslands in Lake Naivasha between 2003 to 2012. Transitions from Woody savannas and Cropland/Natural vegetation mosaic were the most dominant transitions accounted for over 50% of all land use transitions to grasslands in most of the years

Table 3: Annual land use transitions to cropland natural vegetation mosaic (CNVM) in Lake Naivasha between 2003 to 2012 (Areas are in km^2)

Transition Year	Forest to CNVM	Shrubland to CNVM	Woody savannas to CNVM	Savannas to CNVM	Grassland to CNVM	Cropland to CNVM	Grand Total
2004	14.07	0.00	30.31	3.46	60.63	12.13	120.60
2005	0.87	0.22	13.21	4.11	61.71	10.18	90.29
2006	1.30	0.00	29.45	4.33	27.50	23.38	85.96
2007	0.87	0.00	81.41	4.98	40.27	29.01	156.55
2008	3.90	0.00	73.83	8.01	23.60	28.58	137.92
2009	1.08	0.22	21.44	2.60	25.98	48.28	99.60
2010	8.23	0.65	115.19	36.16	168.45	59.54	388.22
2011	2.60	0.87	23.17	14.94	85.74	27.28	154.60
2012	2.81	1.08	52.61	25.55	119.30	7.15	208.51

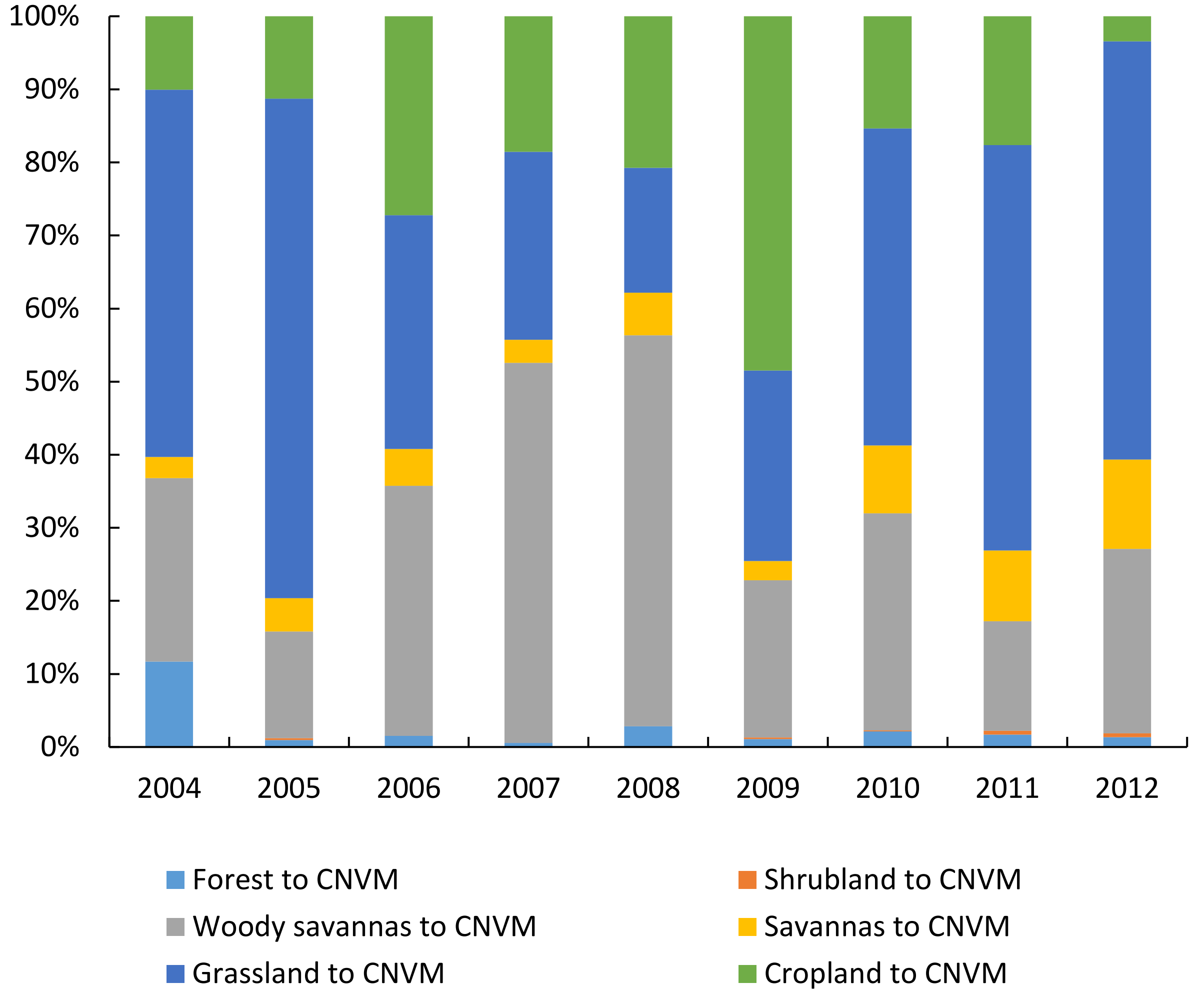

Figure 5: Percentage annual land use transitions to cropland natural vegetation mosaic (CNVM) in Lake Naivasha between 2003 to 2012. Transitions from Woody savannas and grassland were the most dominant transitions accounting for over 50% of land use transitions to CNVM in most of the years

Impacts of land cover transitions on ET

The results indicate that although forest and shrublands covered a small part of the basin, they had the highest annual evapotranspiration compared to the other land uses/cover types. Grasslands and savannas evaporated the least (Figure 6). However, the volume of total water released was less for shrublands (~0.26–5.24 %) and forests (~3.96–8.92%) because they covered much smaller areas compared to cropland/natural vegetation, grasslands and woody savannas that released ~16.43–25.91%, ~15.48–51.63%, ~17.70–32.09% respectively over the study period. Over the 10-year period, averaged ET for the respective land uses/covers suggested that grasslands, woody savannas and cropland accounted for 28.7%, 25.9% and 25% respectively of the total evaporated water in the basin with shrublands, savannas and evergreen forest contributing the least at 2.3%, 4.7% and 6.6% respectively. Basin wide annual ET estimates accounted for at least 55-86% of the total annual precipitation in the basin and 76-89% of potential evapotranspiration (Table 4).

Table 4: Percentage partitioning of annual precipitation into evapotranspiration

Year	P (mm)	ET (mm)	ET/P (%)	PET (mm)	ET/PET (%)
2003	1074	724	67	798	89
2004	893	710	79	810	88
2005	843	722	86	770	89
2006	1095	655	60	743	81
2007	948	621	65	752	77
2008	873	617	71	749	76
2009	735	614	84	751	76
2010	1171	654	56	744	81
2011	1144	643	56	753	79
2012	1190	651	55	811	80

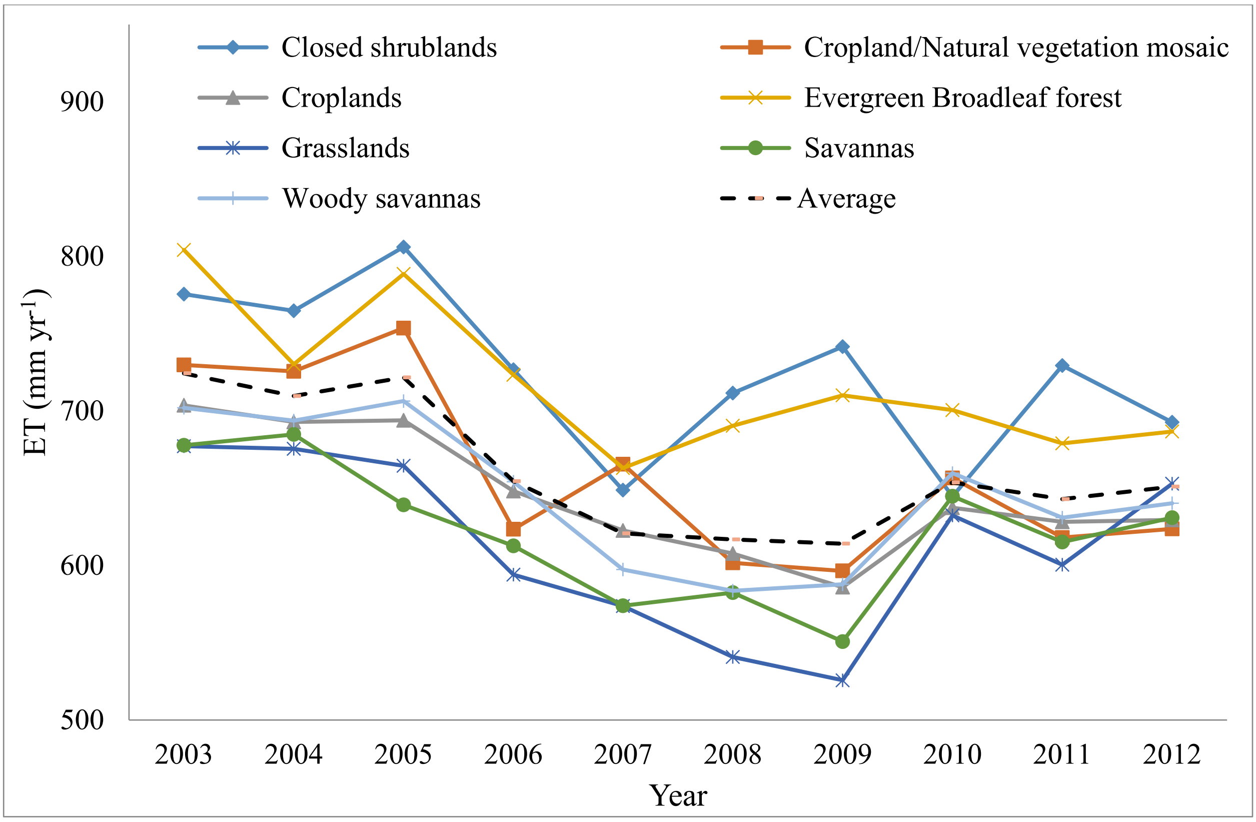

Figure 6: Annual trends in evapotranspiration of different land use/cover in upper Lake Naivasha basin

Grassland and woody savannas areas that did not undergo transition to other land use forms had significantly lower ET compared to cropland areas that did not also undergo transition (Figure 7). Conversion of cropland back to grasslands (abandonments) led to reduced ET that was lower than ET from unchanged cropland areas (Figure 7a). However, the ET from the abandonment was much higher than ET from unchanged similar surfaces. This observation was similar for changes between woody savannas and cropland from 2004 to 2008, however, after 2008 ET from the converted cropland areas became larger than unconverted woody savanna areas (Figure 7b). The annual difference in ET due to land use conversions from grassland to cropland was predominantly larger than from grassland and cropland surfaces that did not undergo conversions for most of the years except for year 2006, 2010 and 2011 (Figure 8). Similarly, annual difference in ET due to conversions from woody savanna to cropland was equally high in most of the years with the exemption of years 2006, 2007, 2008, 2010 and 2011 (Figure 9). Since the dominant land use transitions were those from grassland and woody savannas to cropland, the annual ET contribution by volume from these land use transitions released more ET than abandonments of cropland to grasslands and woody savannas (Table 5).

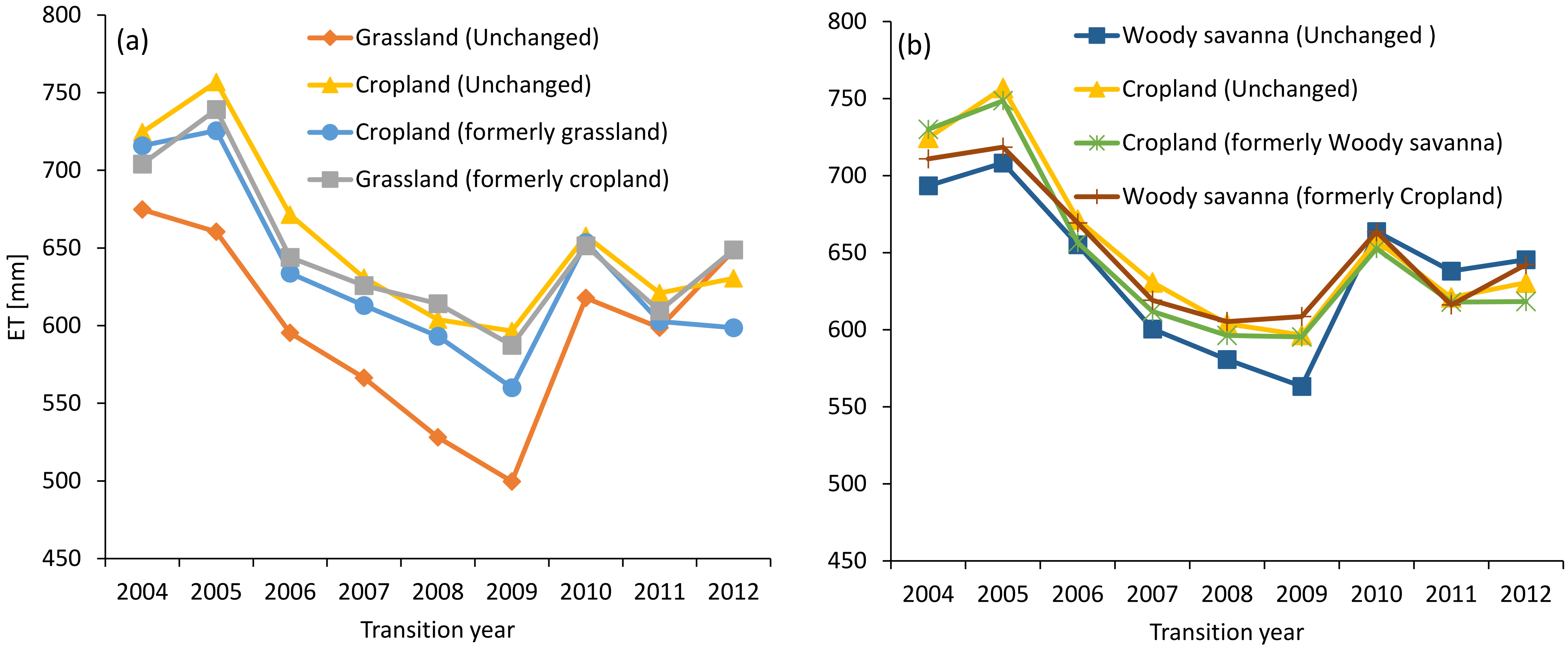

Figure 7: ET trends for (a) cropland and grassland areas (b) cropland and woody savannas that remained unchanged and those that experienced land use transitions

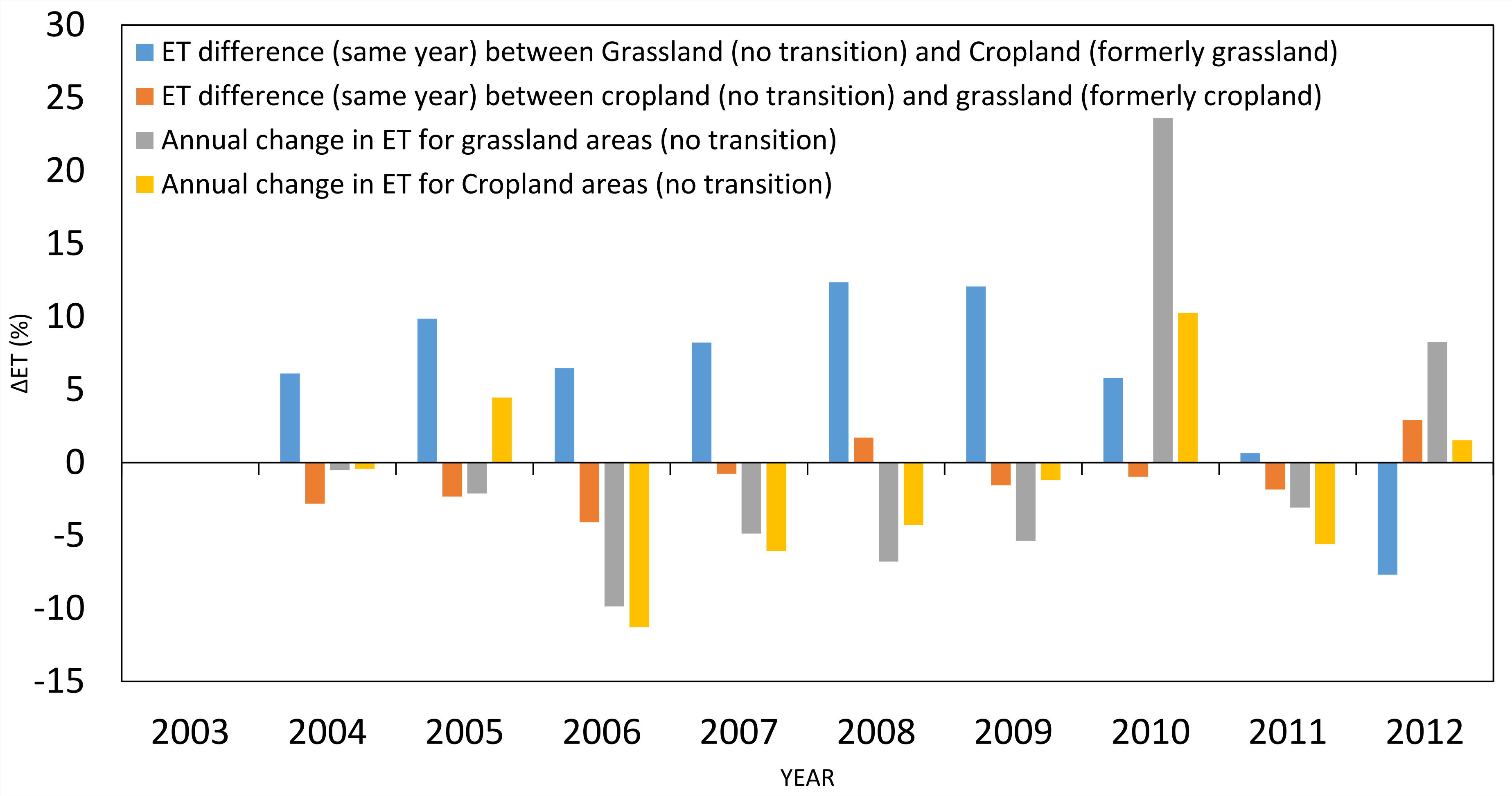

Figure 8: Annual percentage change in ET for areas with and without land use transitions. ET due to land use transition from grassland to cropland is the difference in ET of unchanged grassland areas and ET from previous grassland areas that have been converted to croplands.

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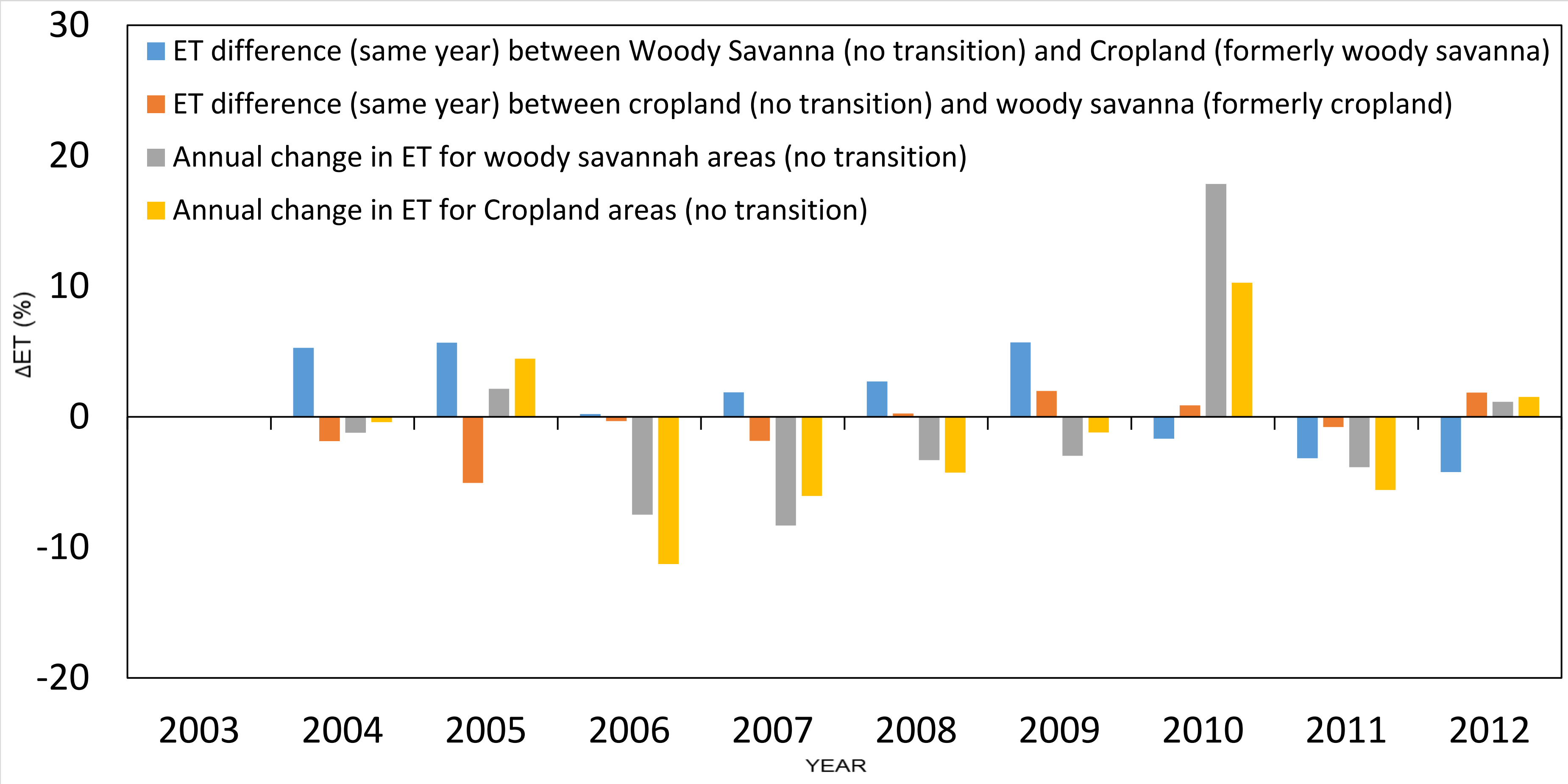

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337 Figure 9: Annual percentage change in ET areas with and without land use transitions. ET due to land use transition from woody savannah
338 to cropland is the difference in ET of unchanged woody savannah areas and ET from previous wood savannah areas that have been
339 converted to croplands.

Table 5: Annual volume of ET contribution from land use transition and non-transition areas. The numbers in parenthesis indicate the percentage ET contribution of replaced land use to the total volume released by the same land use. The last two columns represent the combined contribution of converting grassland and woody savannah to CNVM as well abandonment from CNVM to both grassland and woody savanna

	$\times 10^6$ (m^3y^{-1})							Combined contribution (%)	
Transition Year	Grassland to CNVM	CNVM to grassland	Unchanged grassland	CNVM unchanged	Unchanged woody savannah	woody savannah to CNVM	CNVM to woody savannah	Grassland and Woody savannah to CNVM	CNVM to grassland and woody savannah
2004	43.41 (*22*)	16.01 (*3*)	476.11	158.28	164.09	22.13 (*12*)	14.47 (*8*)	29.28	4.54
2005	44.78 (*20*)	11.68 (*3*)	332.90	176.81	187.70	9.89 (*5*)	53.52 (*22*)	23.62	11.13
2006	17.43 (*9*)	7.95 (*4*)	209.09	178.82	265.54	19.34 (*10*)	13.19 (*5*)	17.05	4.26
2007	24.68 (*13*)	14.91 (*8*)	163.35	167.44	248.74	49.81 (*23*)	19.57 (*7*)	30.79	7.72
2008	14.00 (*7*)	24.07 (*14*)	144.51	183.15	227.19	44.03 (*19*)	19.00 (*8*)	24.06	10.38
2009	14.55 (*9*)	43.11 (*23*)	149.20	152.30	179.41	12.76 (*8*)	42.16 (*19*)	15.21	20.60
2010	110.10 (*43*)	34.56 (*18*)	156.23	145.29	113.25	75.17 (*34*)	25.29 (*18*)	56.05	18.17
2011	51.67 (*16*)	36.69 (*14*)	216.76	269.74	202.00	14.31 (*5*)	36.42 (*15*)	19.66	14.86
2012	71.41 (*24*)	35.97 (*24*)	116.81	228.52	230.47	32.53 (*13*)	52.01 (*18*)	31.26	20.21

Climatic factors controlling Evapotranspiration

The decline in ET over the study period could generally be explained by a combination of factors: reduced moisture supply through precipitation, reduced net radiation and increased actual vapour pressure combined with decrease in the difference between air and surface temperature (Figure 10).

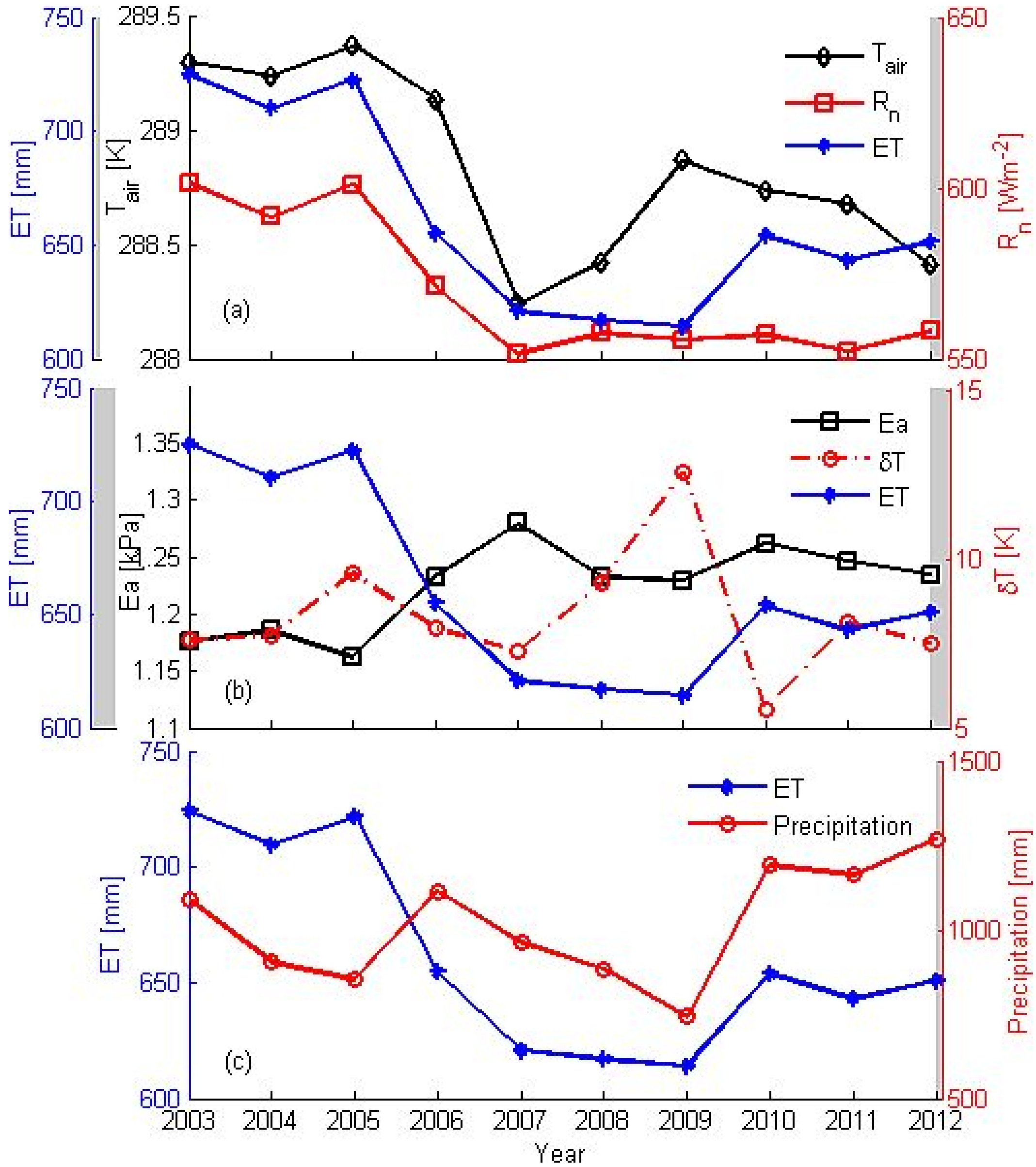


Figure 10: Annual trend of ET alongside (a) R_n and air temperature (b) difference between air temperature and surface temperature (δT) and actual vapour pressure (Ea) (c) ET and precipitation between 2003 and 2012

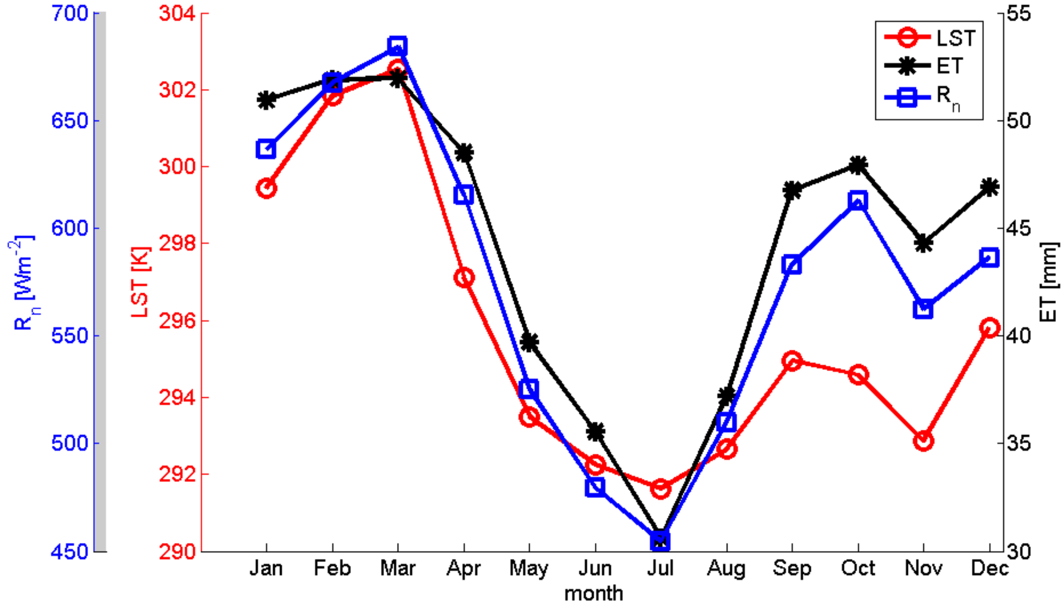
Precipitation, net radiation and NDVI influenced ET more significantly during wet season while actual vapour pressure was dominant during the dry season (Table 6).

Table 6: Partial correlation coefficients between precipitation (P), surface-air temperature difference (δT), actual vapour pressure (E_a), net radiation (R_n) and NDVI.

ET	P	δT	E_a	R_n	NDVI
Annual	0.14	-0.14	-0.15*	0.78**	0.09
Wet season	0.28*	0.12	-0.18	0.65**	0.27*
Dry season	0.26	-0.31	-0.37*	0.34*	-0.08

* indicates significance value at $p=0.1$ and ** indicates $p=0.05$

On a monthly basis, ET was observed to be highest in the driest months (~ 47–64 mm) of January through to March before starting a decline in the wettest months and reaching minimum values ~32 mm in July for most of the land use/cover (Figure 11). After July, ET starts to increase again reaching ~ 45–55 mm in October before taking a small decline in November which coincides with the peak of the short rainy period of October, November and December. Modelled ET appeared to decline with decreasing precipitation during the months of May through to August coinciding with decreasing LST over the same period. This suggested that even though there was plenty of moisture following the rains in May, a lack of sufficient energy ensured ET rates were low between May and August. Later, in the months between July and March following increased net radiation, ET appeared to increase. ET scaled well with monthly temperature difference between LST and air temperature (δT) and net radiation indicating a significant control of these variables in determining ET in this part of the basin (Figure 12).



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377 Figure 11: Monthly averaged trends of LST, ET and net radiation

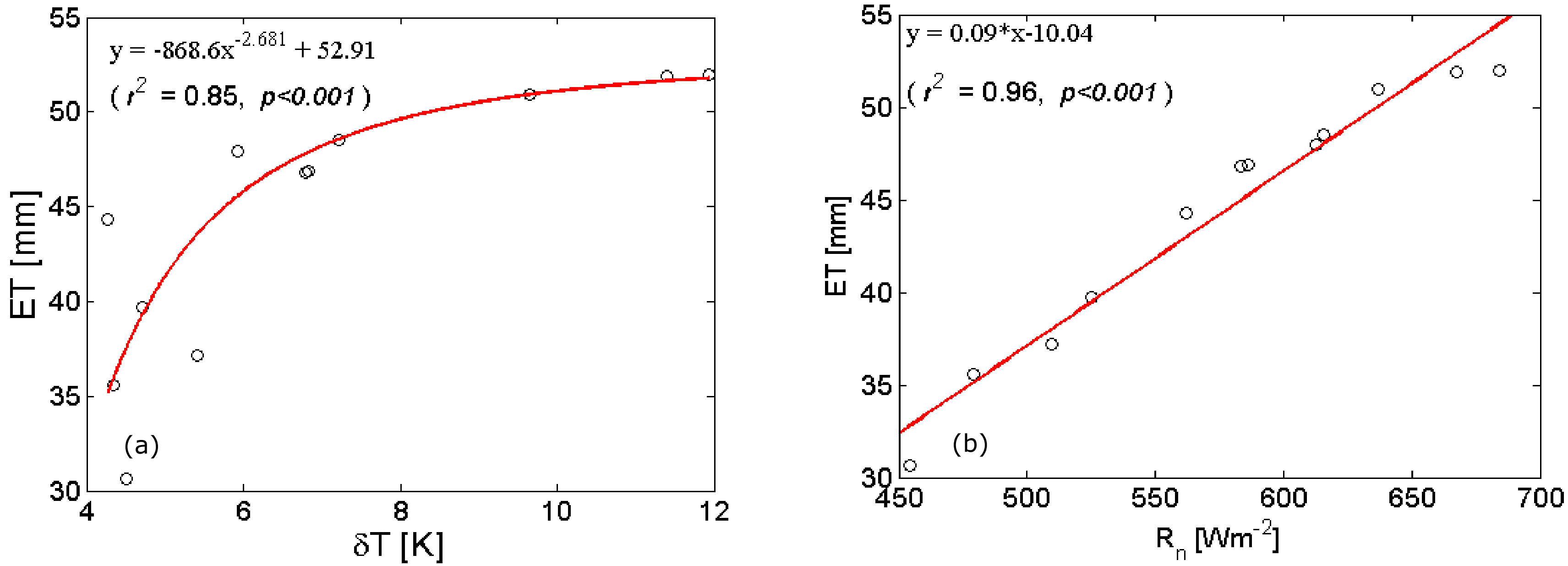

Figure 12: Relationship between 10-year monthly averages of (a) δT and ET and (b) net radiation and ET.

Discussion

Influence of climatic factors on evapotranspiration

The findings showed that annual evapotranspiration in the basin declined by about 10% in the 10-year period studied. This decline was due to interannual precipitation decline, most pronounced decline between years 2003 to 2006 and 2006 to 2009 (Odongo, 2016), in combination with reduced net radiation over the period studied but also reduced difference between air and surface temperature were observed (Figure 10 and Table 6). Reduced net radiation (i.e. dimming) is usually associated to increased amounts of cloudiness and aerosols in the atmosphere (Liepert, 2002; Roderick et al., 2009; Stanhill and Cohen, 2001) but also increased surface albedo and land surface temperature due to extensive land use changes could also contribute the decline. For the study area, evidence of increased amounts of cloudiness and aerosols have been previously reported over the study period (Odongo, 2016).

Overall, these factors accounted for at least 90% of the observed decline in the evapotranspiration. This finding compares favourably to other studies in Africa (e.g. Jung et al., 2010; Marshall et al., 2012) that have reported reduced moisture in Southern Hemisphere, particularly in Africa and Australia, from 1998 to 2008 that has been attributed to the recently observed decline in global ET. In particular, the East African region has experienced decreased evapotranspiration due to substantial drying during the growing season (i.e. June, July and August) (Marshall et al., 2012). However, after the 2009 drought in Lake Naivasha basin, the moisture conditions improved. This was accompanied also by improved radiation that led to a reversal in the evapotranspiration trend with an increase towards 2012.

Understanding the key factors determining the evaporative demand and associated hydrological processes is crucial because the rate and direction of change of terrestrial water and energy balance has significant consequences for the growth and survival of plants (Hoffman et al., 2011). However, the effect of declining evapotranspiration especially in water limited environments such as the Lake Naivasha basin where changing evaporative demand and moisture supply through precipitation have a strong influence on terrestrial water balance is not straightforward. Historical evaporative demand in Lake Naivasha as measured using the pan evaporation method has been reported to be on the decline over the past 50 years (Odongo, 2016). These declining trends in pan data have also been observed in many parts of the world such as USA (Hobbins et al., 2004), Australia (Roderick and Farquhar, 2004), China (Zhang et al., 2007), India (Jaswal et al., 2008) and South Africa (Hoffman et al., 2011) and have been attributed to declines in radiation and wind speed (Roderick et al., 2009). However, pan evaporation between the year 2000 to 2010 in Naivasha was on the rise, indicating an increasing atmospheric demand and opposite in trend to that of the modelled evapotranspiration (Odongo, 2016). While increasing air and land surface temperatures on the one hand are expected to accelerate evaporation and the effect of declining wind speed and evaporation on the other hand is expected to lessen the effect of increasing temperatures on soil and plant water balance. Under conditions of non-limiting moisture supply it would have been expected that increasing atmospheric demand was matched with increasing evapotranspiration. However, sustained reduction in rainfall over the period ensured there was low moisture supply that suppressed evapotranspiration over this period. This is in agreement with findings of Jung et al. (2010) that evapotranspiration is more limited by moisture supply in the Southern Hemisphere than by changes in atmospheric demand.

Impacts of Land use transitions of ET

This paper characterizes changes in ET on a catchment level in a sub-Saharan Africa river basin using remote sensing and surface reanalysis data. A previous study hypothesized that effects of land use changes on the hydrology of the basin were insignificant in the short-term and only discernible in the long-term (Odongo, 2016). In this study we demonstrate how to quantify these changes at the annual scale using remote sensing. We explore the use of high temporal resolution analysis on an annual scale to investigate the impact of land use conversions on ET changes among key dominant land uses in Lake Naivasha basin.

Overall, the findings show that evapotranspiration accounted for between 55% to 86% of the annual precipitation in the basin. Grasslands, woody savanna and cropland/vegetation mosaic being the dominant land use/covers accounted for up to ~80% of the total ET in the basin. Conversions among these land uses are most important because they cover most of the basin area and therefore alterations associated with these land uses determine the amount of evapotranspiration and subsequently have implications on the hydrological partitioning of water supply to the lake and groundwater recharge. Specifically, ET changes from grasslands to cropland were more pronounced than the reverse changes (abandonment) compared to ET changes from woody savannas to cropland. Conversion of cropland to forest and grassland program of China in late 1990s also showed that recently restored grassland areas exhibited lower water use than earlier restored sites (Qiu et al., 2011a; Tian et al., 2016). Mingliang et al. (2008) also observed that cropland transitions increased evapotranspiration while abandonment decreased evapotranspiration. A possible explanation for this was that restored grasslands were dominated mainly by annual herbs that are least resistant to drought compared to the older established perennial grasses that are more strategic in conserving water. Species composition is known to shift progressively in time after abandonment and may alter the exchange of water and matter between the vegetation and the atmosphere (Rosset et al., 2001). The abandonment of agricultural land is also known to improve water retention and soil recovery along with nutrient cycling, and increase biodiversity (Benayas et al., 2007). However, changes of other land use forms have been shown to significantly degrade soil hydraulic properties and subsequently lower evapotranspiration e.g. conversion of cerrado vegetation to pasture (Nóbrega et al., 2017). Similar patterns in ET were also evident in the changes between woody savannas to cropland although the magnitudes of these change were less. Overall these findings imply that recently cultivated agricultural lands could increase local water demands, while abandonment of the farms could decrease the water loss and eventually increase the water availability. Also, recovery of soil following abandonment might be impeding ET since parts of the catchment are being continuously transformed with no ample time given for soil recovery.

One key finding of these land use alterations is that conversions of grasslands areas to cropland had a greater effect than climatic influence during periods of low rainfall. Climate dominance only becomes apparent when rainfall increased for years 2006, 2010 and 2012. However, this distinction was not so apparent in the conversion of woody savannas to cropland where climatic influences tended to be dominant for most of the years. This is possibly due to the closeness in structural similarity of the two vegetation types. These findings suggest that certain land use conversions may dominate climatic influences and therefore would alter hydrologic conditions more than climate if those conversions would be intensified at a larger scale. For the case of Lake Naivasha agricultural land area has been on the increase even though the overall ET trend has been on the decline. This finding was similar to studies in Sahel that have also experienced significant declines in ET even though agricultural land use area has been expanding (Marshall et al., 2012). While land expansion of cropland from grasslands and woody savannas has seen annual increases in ET between these conversions, the overall 10 year trend studied has been a decline in ET mainly driven by the interannual precipitation decline in combination with reduced net radiation over the period studied but also reduced difference between air and surface temperature were observed.

Conclusion

This study presented use of remote sensing and climate reanalysis data to estimate evapotranspiration and changes among key vegetation covers in Lake Naivasha Basin in Kenya. The method presented offers a basis for estimating the hydrological consequences of land use and cover conversions as well as climatic change at catchment scale. Specifically, the approach was able to quantify the trend in evapotranspiration among the land uses and its response to both the land use changes and climate. The findings showed that annual evapotranspiration in the basin declined by about 10% between 2003 and 2012 mainly due to sustained decline in precipitation combined with reduced net radiation as well as reduced difference between air and surface temperature. Land use conversions among the dominant vegetation covers of grasslands, woody savanna and cropland/vegetation mosaic accounted for up to ~80% of the total ET in the basin. Moreover, annual land use conversions from grasslands to croplands showed a greater influence than climate. However, conversions from woody savannas to croplands were not as apparent compared to those of grasslands to croplands suggesting that certain land use conversions may dominate climatic influences and consequently alter water balance more than climate if those conversions were to be intensified at a larger scale. These findings implied that newly cultivated cropland could substantially increase local water demands, while the reverse conversion (abandonment of cropland) could reduce the water loss and eventually increase the water availability. The analysis presented showed the hydrological effects of different land use and land cover change trajectories and provided valuable insights that will aid catchment managers anticipate likely impacts, minimize uncertainties and provide a solid base for sustainable land use planning.

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