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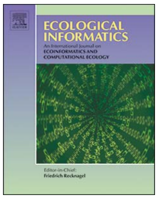

Application of open source tools for biodiversity conservation and natural resource management in East Africa

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ABSTRACT

We use forty years of animal and plant data collected in the Amboseli and Magadi ecosystems in Kajiado county, southern Kenya to demonstrate the application of open source tools to spatial analysis and the visualization of results. These highly interactive tools developed in R contain a series of commands that perform various data functions including: examining the data structure, aggregation, exploratory data analysis, vegetation biomass, greenness and grazing pressure estimations, NDVI extraction, species population estimation and spatial mapping, among other tasks. We customized the tools to suit the local community information needs and level of expertise without losing the underlying data richness or integrity. The implementation requires basic computer knowledge and can be undertaken by local community trainees using straight forward commands.

The results show that with these automated tools, long-term data in large databases can be analyzed rapidly and presented in a way that encourages community participation, ownership and uptake locally and regionally. The tools allow biodiversity scenario building and other functions such as the identification of migratory corridors, habitat utilization by animal species and general land use and resource management.

1. Introduction

The application of innovative technologies to biodiversity conservation and natural resource management is fast gaining ground in Africa, with local communities becoming actively involved (Herrick et al., 2013). Innovations such as mobile money transfers have enabled pastoralist communities to bank and transfer funds as well as use their phones to gather and share knowledge on rangelands conditions such as pasture health, disease prevalence and water availability (Herrick et al., 2013). Decisions made to move livestock in search of water, forage and best market prices are usually based on such information (Oba, 2012), now easy to upload and access on mobile platforms.

The availability of user friendly open source software and the increasing broad internet connectivity across Kenya (Macharia, 2014), sometimes powered by solar energy, provides a unique platform that enables the incorporation of scientifically based conservation strategies into traditional conservation methods practiced for millennia. While information dissemination has begun at different levels across Africa's rangelands (Reid et al., 2016), there are few examples of data collection, processing, interpretation and application at a local community level. This is partly due to a lack of user friendly analysis tools and technical knowledge among community members, which point to reduced research output at the local level.

Here we use more than forty years of animal and plant data collected in the Amboseli ecosystem, and more recently the Magadi ecosystem, in Kajiado County, southern Kenya (Fig. 1), to demonstrate the application of open source tools to biodiversity conservation and natural resource management at the community level. We show how massive long-term data collected in the two ecosystems can be rapidly analyzed and presented using a set of customized open source tools. We provide examples on how these tools support quick community decision making on grazing management and provide insights on seasonal wildlife distributions and vegetation biomass (g/m^2) shortfalls in relation to local drought conditions (Western et al., 2015b).

The highly interactive tools developed in R (R Core Team, 2016), an open source statistical computing software with spatial analysis capabilities, contain a series of commands that perform various data tasks including: examining the data structure, aggregation, exploratory data analysis, calculation of vegetation biomass (g/m^2), percentage grass greenness and grazing pressure estimations, Normalized Difference Vegetation Index (NDVI) extraction, species population estimates and distribution mapping, among other functions. The tools are customized to suit the local community data needs and level of expertise without losing the underlying data richness and integrity.

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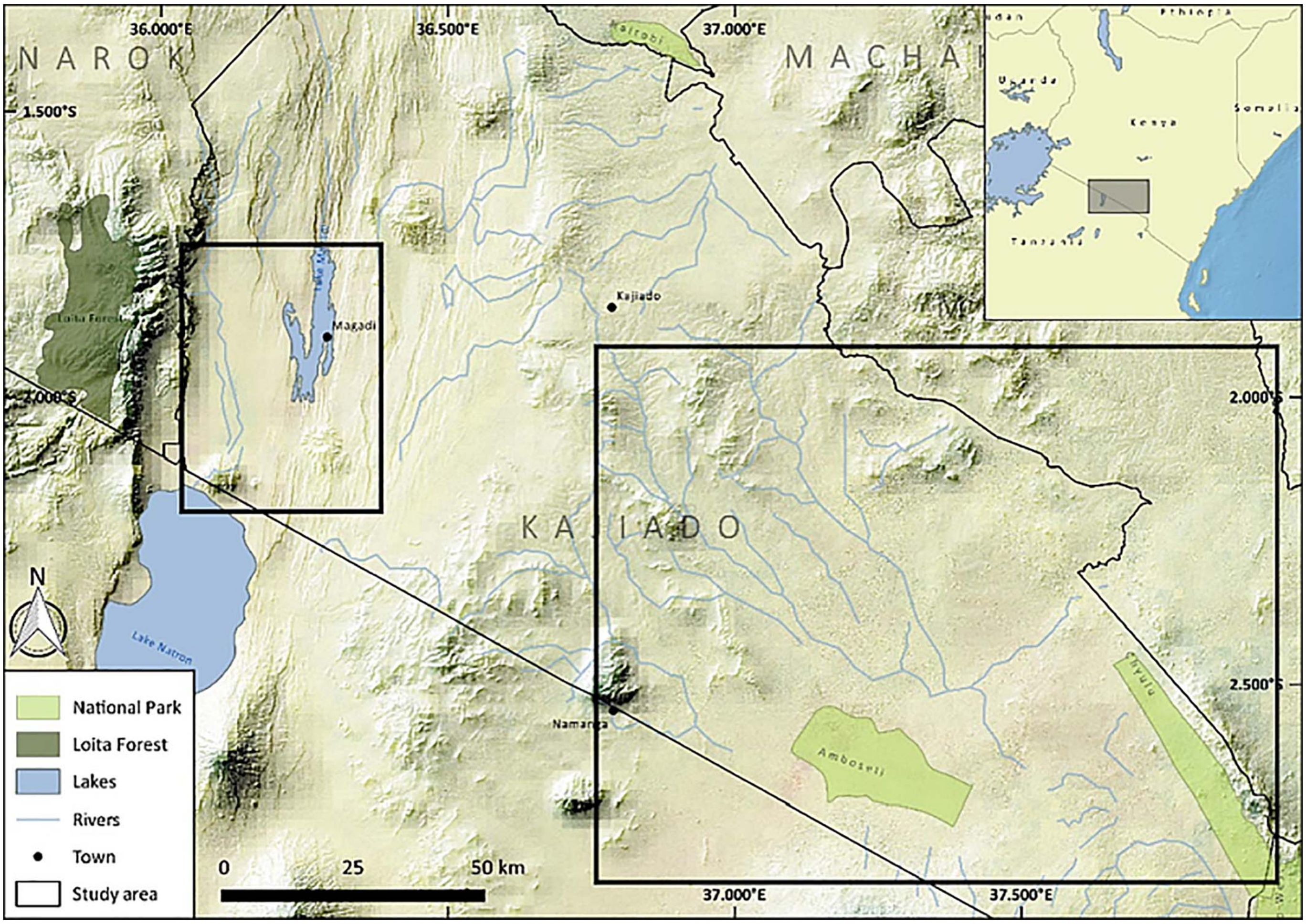

Fig. 1. The Amboseli ecosystem and the Magadi area in southern Kenya showing the Amboseli National Park and community conservation areas near lake Magadi.

The open source tools require basic computer knowledge and can be executed by local community trainees using straight forward computer commands. The digital platforms allow biodiversity scenario building, model formulation such as the identification of migratory corridors, habitat utilization by animal species, and application to county spatial planning programs (Mose and Western, 2015).

2. Study area and methods

The Amboseli and Magadi ecosystems (Fig. 1) have a combined area of 9500 km^2 and support a large population of livestock, wildlife and pastoralists (Groom and Western, 2013) freely moving over the rangelands extending into Northern Tanzania. The protected 388 km^2 Amboseli National Park is centrally located in the Amboseli ecosystem and acts as refuge for wildlife during droughts (Western and Lindsay, 1984). The pastoralist in the Magadi area have not settled permanently, in contrast to the majority of households in the Amboseli ecosystem. Recently, there has been increased spread of small scale farms from the higher elevation and rainfall areas to the north and south of the Amboseli area extending to the lowlands swamps. The mean annual rainfall in these ecosystems is 350 mm and follows a bimodal pattern with the short rains generally falling in November to December and long rains from March to May (Altmann et al., 2002). Periods of below average rainfall are common (Western et al., 2015b). Further details of the study area are provided elsewhere (Russell, 2017; Western and Maitumo, 2004). The study design and methods are based on a conceptual model (Fig. 2). Table 1 shows the data requirements and prospective user groups.

2.1. Open source tools development

The open source tools developed in R include a set of codes that extract, analyze and present graphical results for a wide range of audiences (Table 1). Both time series and spatially explicit data are analyzed on the same platform. Previously, these analyses were performed separately, with geographical information system (GIS) data processed outside the main analysis. The integrated platform speeds up and simplifies the delivery of information to conservation and natural resource decision-makers, planners and managers (Western et al., 2015a, 2015b). The tools utilize a wide range of open source packages, making the platform highly flexible and interactive. The versatility and performance of R simplifies the delivery of data to a wide range of users through the creation of a graphical user interface (GUI) using *shiny* application (Winston et al., 2016). We used *shiny's* reactive programming framework for complex calculations to prevent re-computations during interactive sessions. Shiny, through controlled data downloads, allows the data to reach a wide audience through an internet portal without the loss of data privacy.

In addition, we utilized the *markdown* package (Allaire et al., 2015) to automatically process reports in either PDF or Microsoft Word formats. The tool also displays complex multivariate datasets in the GUI and enables a variety of tasks to be performed by community members. The tasks range from NDVI extraction, animal and vegetation biomass (g/m^2) plotting, resource mapping, wildlife home-range analysis and corridor mapping.

The development of the open source monitoring system was based on the research cycle shown in Fig. 2. These tools build on long term

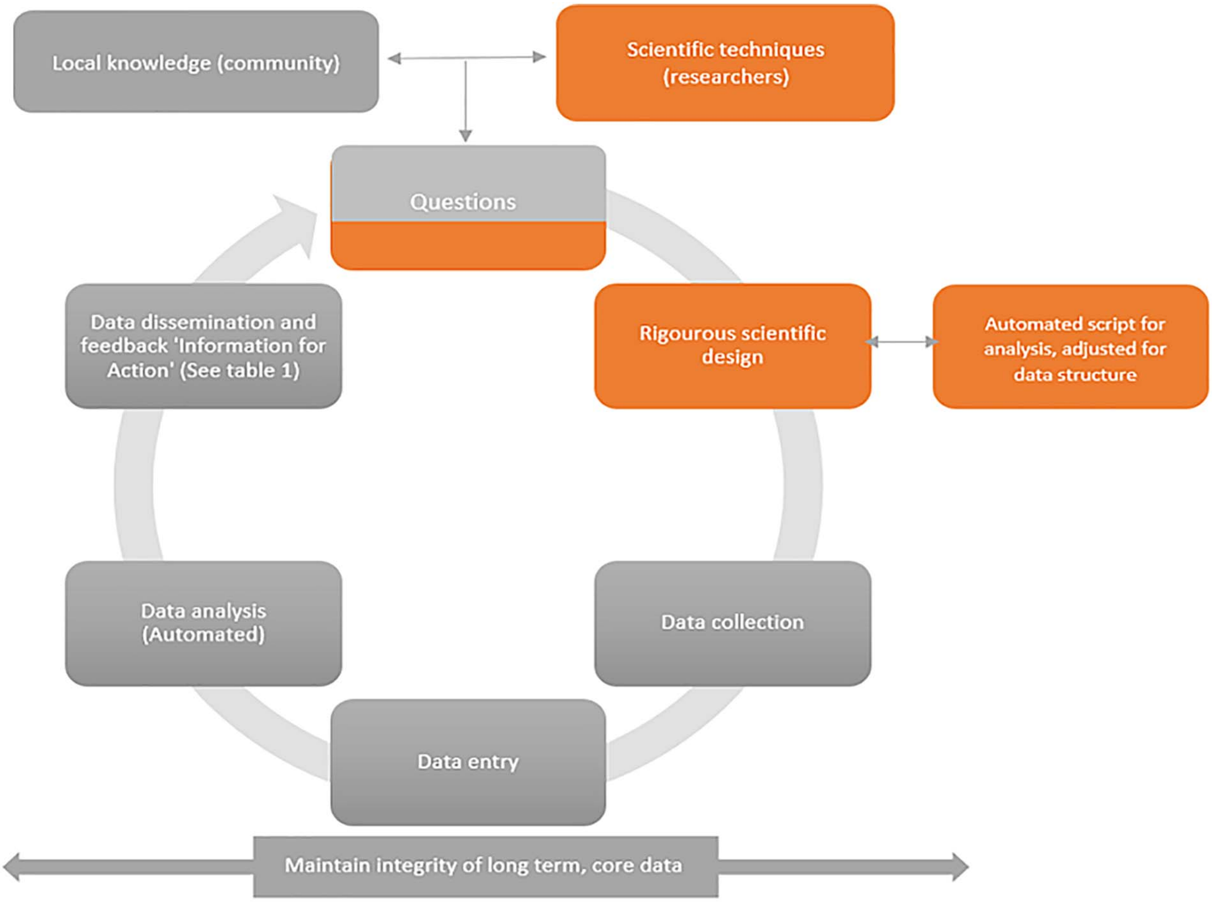

Fig. 2. A flow of information within a monitoring system (Lindenmayer and Likens, 2009), showing the community-driven monitoring in grey and the scientific input and tool support in orange. The data collection, entry and analysis originates with fieldwork or remote sensing applications. Once the data collection protocols have been designed, automated scripts process the data, without losing data privacy. Digital data entry platforms that employ mobile applications compliment the manual data entry. Data integrity is ensured by scientist and local community trainees continually working together in the resource centres (Russell, 2017; Western, 2017).

Table 1
Data needs and prospective users across the Amboseli and Magadi conservation areas in southern Kenya showing use levels that include local communities, policy shapers and scientists.

User group	Data requirements	Importance of data
Individual community members	Informal feedback through interactions with resource assessors, community meetings, and sharing of processed data.	Immediate decisions on natural resource use by individuals within a community.
Community committees (e.g. Group ranch, Grazing or Conservation)	Feedback of processed data, through formal meetings and online portals.	Seasonal and yearly decisions concerning natural resource management.
Regional decision (e.g. County governments)	Access to processed data through online portals and workshops.	Contribution to county spatial planning and regional policies.
National government	Access to processed data through online portals and workshops.	Contribution to national spatial planning, environmental impact assessments, and national policies.
Scientific community	Tidy, rigorously collected raw data.	Contribution to long-term ecological monitoring and shorter term research questions.

monitoring programs, which have been created to answer questions relevant to local community requirements, supported by scientifically rigorous methods and techniques. The automation process places emphasis on minimizing manual data processing, analysis and feedback. This allows technical and non-technical users to perform different tasks. The modules were applied to vegetation and animal data collected in the ecosystems, with an extension to satellite data analysis.

2.2. *Vegetation monitoring*

The vegetation monitoring procedures used in this study were developed by Amboseli Conservation Program, ACP (Western, 1973) and later adopted by South Rift Association of Land Owners (SORALO). The researcher-based programs integrate a community-based system founded on ‘resource assessors’ (Danielsen et al., 2010) into the long term ecosystem monitoring (Western, 2017). The resource assessors are community members who collect and disseminate information relevant to community livelihoods, conservation and development. The resource assessor team is responsible for data collection, processing and analyzing data, and for sharing and communicating the data analysis results. These teams are based at resource centres built by community groups in southern Kenya (Russell, 2017; Western, 2017).

Estimates of vegetation biomass in grams per square meter (g/m^2), relative percentage greenness and grazing pressure are measured on selected ground plots (Russell, 2017; Western et al., 2015b) on a monthly basis, using the point intercept method (Levy and Madden, 1933). For each frame, ten pins were dropped through the vegetation at an angle of 67^0 (McNaughton, 1985). Each plant hit was scored as green

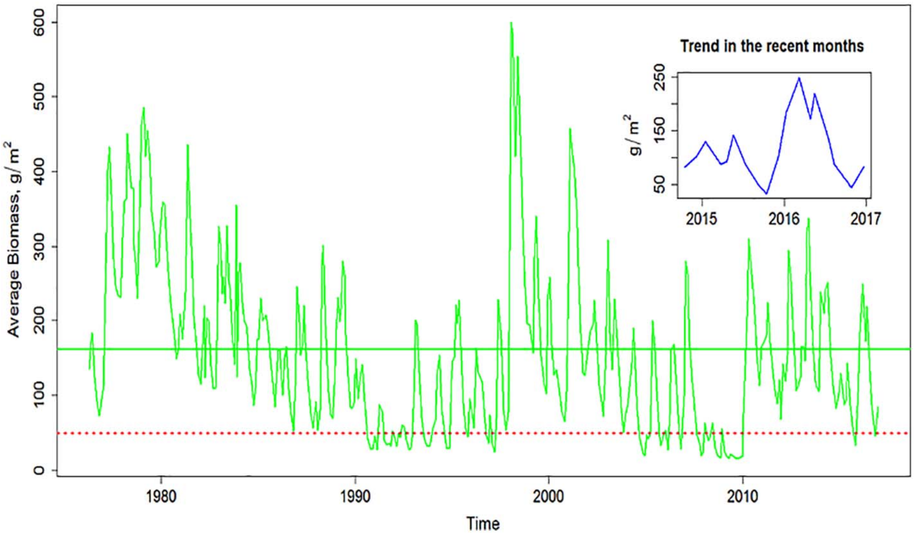

Fig. 3. Long term averages of vegetation biomass (g/m^2) in the Amboseli ecosystem from 1975 to 2016, generated by open source tools once the raw data is entered. The trends in the recent months leading into harsh conditions are shown. Biomass levels below the red dotted line indicate a drought period. The extraction of the data from a central database, aggregation and updating the graphic is automated. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

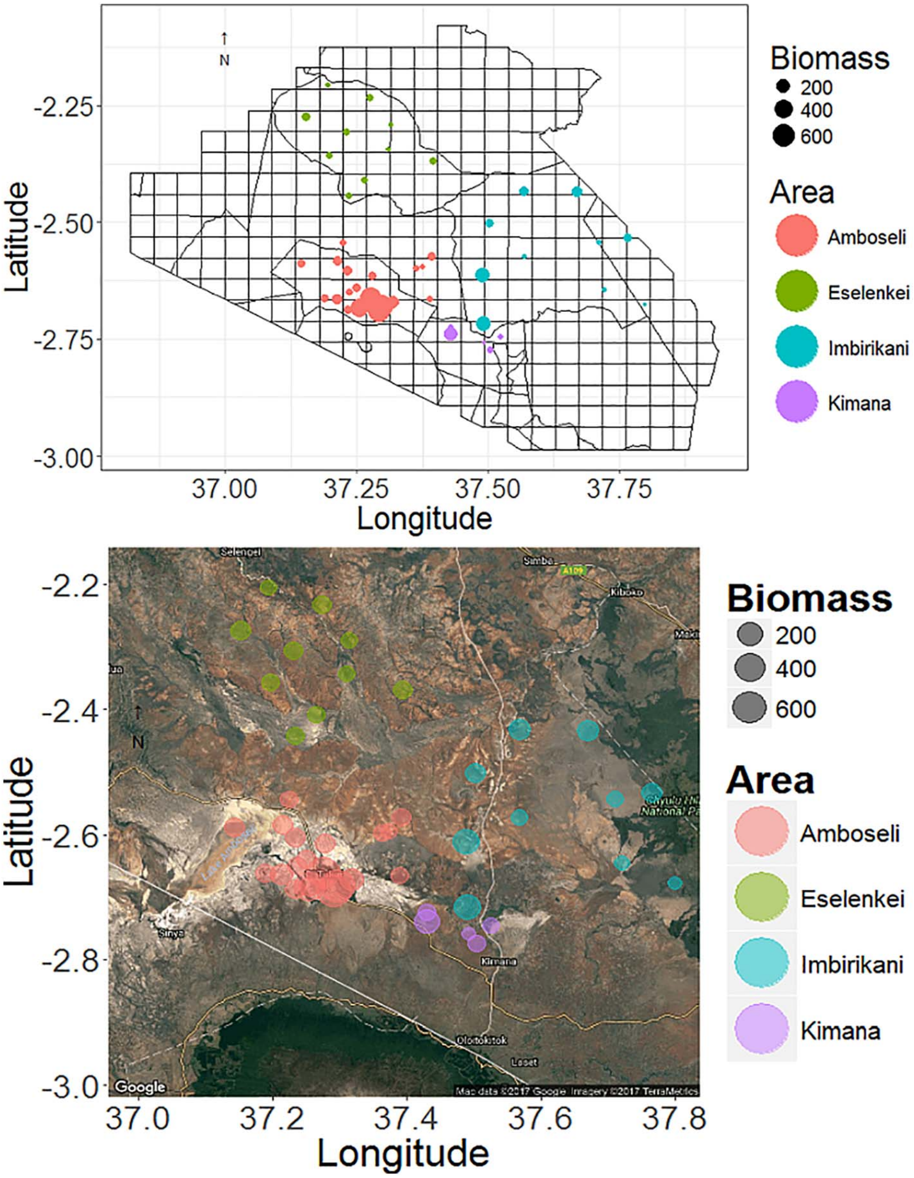

Fig. 4. Average vegetation biomass (g/m^2) mapped in four group ranches. The integrated spatial analysis tool enables the spatial display of the vegetation data both on a static map (above) and an interactive internet satellite maps (below). Different colors represent samples from each group ranch. The larger the circle the larger the biomass value. Within the shiny framework, the package leaflet allows for an interactive mapping experience, with potential to overlay other variables as required. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

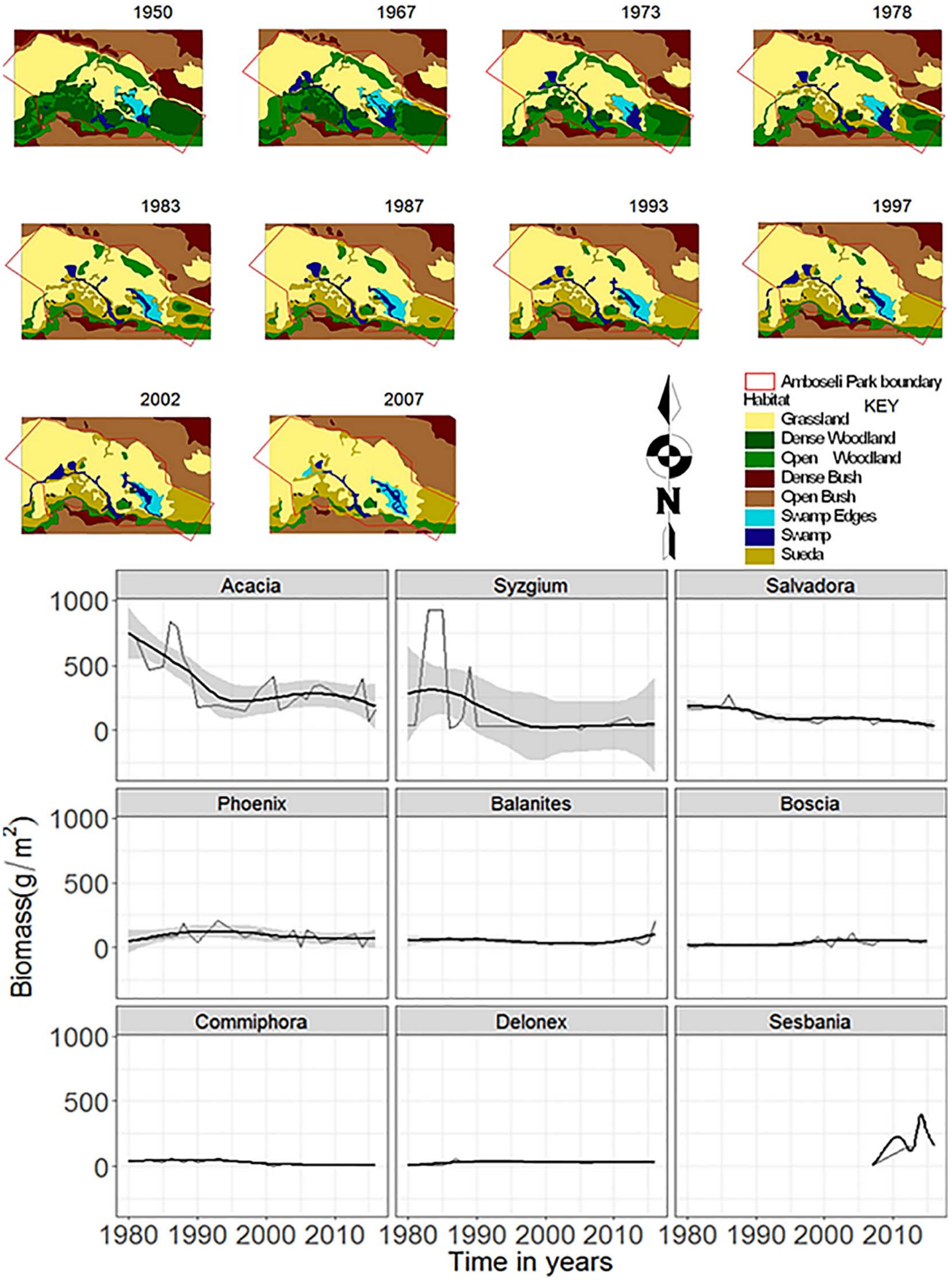

Fig. 5. Long term spatial time series display of vegetation changes in representative habitats of the Amboseli basin area, generated by the GIS module of the tool (above). Woodland cover has fallen sharply in the last five decades. An analysis of tree biomass (g/m^2) in the Amboseli ecosystem aggregated by genus (below) shows a continuous decline of the dominant *Acacia* species. The regeneration of *Sesbania* in the recent times is as a result of exclosures deterring elephants.

or brown and whether grazed or un-grazed. Total herbaceous biomass, total green, and total brown biomass was calculated using an equation derived from calibrating hits per pin against dry weight in grams per meter squared (g/m^2) (Western and Lindsay, 1984). Grazing pressure was calculated as the percentage of grazed to non-grazed hits.

The sampling is synchronized across the study area for ease of comparison. Further details of the vegetation sampling procedure have been presented in (Western, 1973; Western et al., 2015b).

2.3. Livestock and wildlife monitoring

Long term data on livestock and wildlife species has been collected regularly by ACP for the Amboseli area since 1973 (Western, 1975; Western, 2017) and by SORALO for the Magadi area since 2005 (Russell, 2017). The aerial counting method is based on a 5 by 5 km grid system in Amboseli, and a 2 by 2 km grid in Magadi. Animal population estimates for the ecosystems are made using the Jolly method 2, (Jolly, 1969). Animal species were counted spatially within a

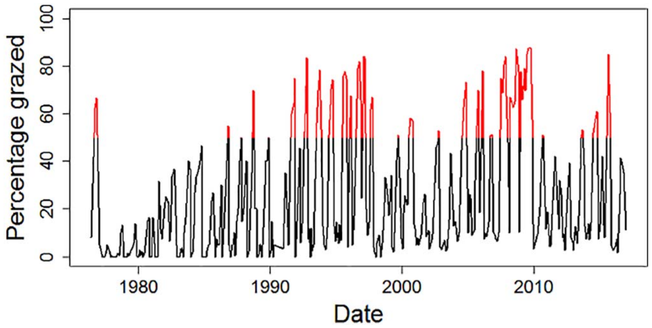

Fig. 6. The output of grazing pressure monitored in the Amboseli swamps that serve as a drought refuge for livestock and wildlife. Red indicates grazing pressure in excess of 50% offtake. The rise in peak grazing pressure is interrupted by the heavy rainfall during El-Nino period in 1998. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Universal Transverse Mercator (UTM) grid covering approximately 25 km^2 in the Amboseli ecosystem and 4 km^2 in the Magadi area. The global population estimates (PE) and the standard error (SE) for each species were calculated as $PE = N\bar{y}$ and $SE = \sqrt{\frac{N(N-n)}{n}}\ S^2$ in which $\bar{y}$ is the sample mean, S^2 sample variance, n is the sample size and N is the number of samples needed to give complete coverage of the study area. Here, N is the total number of units (grids in the entire study area), while n, represents the number of transects flown in the north–south direction for Amboseli ecosystem and east-west direction for the Magadi area. Population densities for each grid are calculated as the number of animals observed within grid, divided by the area in (km^2) of the grid. The method has been comprehensively described in many studies (Mose et al., 2013; Mose and Western, 2015; Norton-Griffiths, 1978; Western, 1973). The processed data is centrally stored in a relational database at the ACP office.

Other systematic ground-based monitoring methods that use open data kit (Hartung et al., 2010) for data collection by the resource assessors, include livestock herd follows, sampling animal body condition scores, herd structure, milk yield measurement in litres and livestock market prices.

2.4. Satellite data extraction

Rainfall and NDVI datasets were extracted from Global Precipitation Climatology Centre (Schneider et al., 2011) and Land Processing Distributed Active Archive Centre (DAAC, 2012) respectively. Plot level values were averaged to create an aggregate monthly NDVI and rainfall values for the two ecosystems.

3. Results

3.1. The application of the tool to vegetation monitoring and habitat changes

Vegetation monitoring data are processed by the open source platform once collected. The pasture biomass (g/m^2) trends and incidences of extreme conditions (below red dotted line) are shown in Fig. 3. The period preceding the 2009 drought was characterized by continuously low biomass (g/m^2). The same downward trend characterized the build up to the late 2016 and early 2017 drought conditions.

Fig. 4 shows the vegetation biomass (g/m^2) estimates in the Amboseli ecosystem processed by the spatial module of the tool. The integration of numerical and spatial data is produced on both static maps and interactive internet satellite maps. The results can be viewed online by local pastoralists, government planners and managers, conservationist and scientists.

Long term changes in habitat, vegetation biomass (g/m^2) structure, grazing pressure and agricultural spread are shown in Figs. 5, 6 and 7.

3.2. Applications to animal monitoring

The May 2016 aerial counts (Fig. 8) show the distribution of species

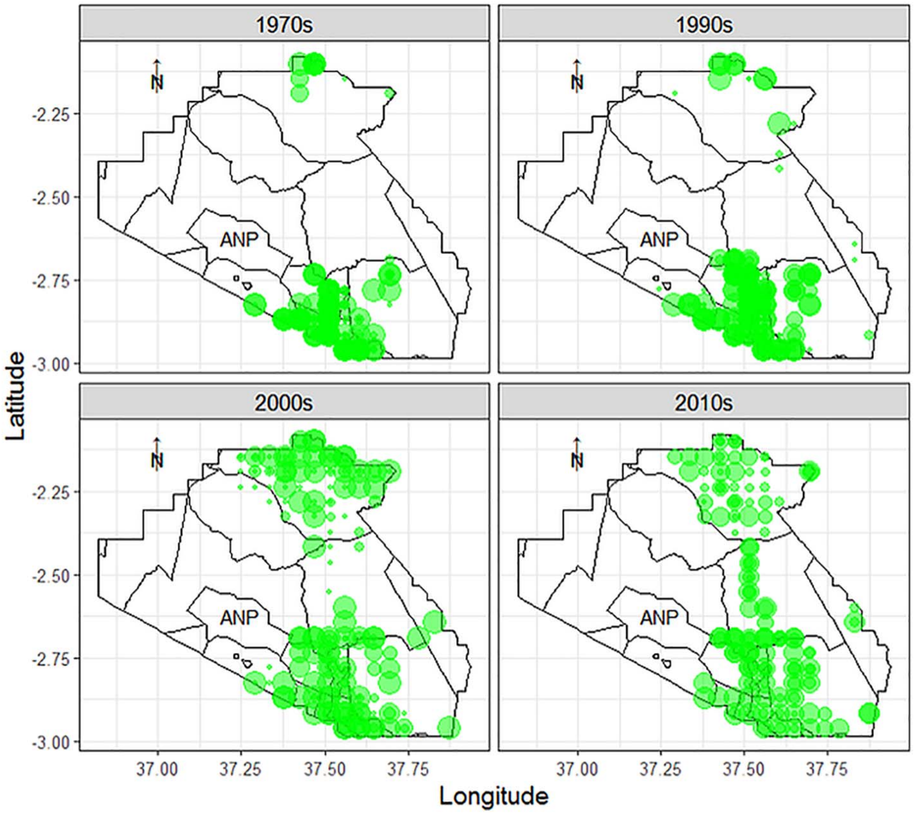

Fig. 7. Agriculture expansion is shown in green. Farms spread from the moist uplands north and south of Amboseli to the low-lying swamps, and finally along the pipeline delivering water to arable and urban areas beyond the Amboseli ecosystem. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

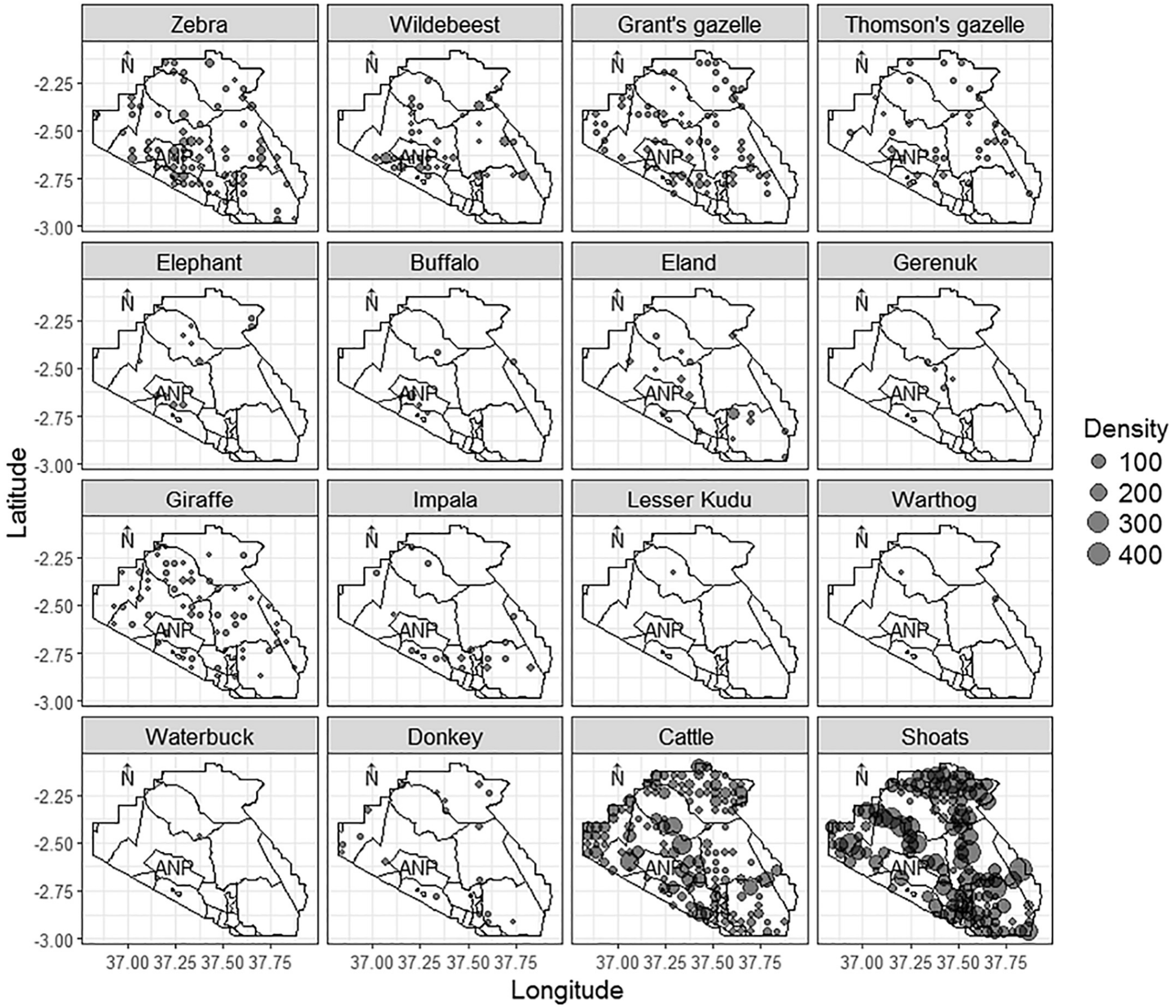

Fig. 8. Animal population density distribution in the Amboseli ecosystem for the May 2016 aerial survey conducted by ACP. The ecosystem is livestock-dominated and shows a common utilization range for both wildlife and livestock outside the protected Amboseli National Park (ANP).

Table 2
Selected species population estimates comparing the February 2010 and May 2016 aerial surveys in the Amboseli ecosystem conducted by ACP and processed by the integrated digital platform. The counts show a strong recovery from the 2009 drought.

Species	Population estimate	
	February 2010	May 2016
Zebra	3044	15,795
Wildebeest	805	8700
Grant's gazelle	2825	11,338
Thomson's gazelle	600	4350
Elephant	1098	1284
Eland	2503	3548
Gerenuk	146	196
Giraffe	2707	4296
Impala	893	2086
Donkey	1200	2015
Cattle	49,291	127,199
Sheep & goats	97,718	341,237

across the Amboseli ecosystem. Most species range widely, driven by seasonal pasture and water availability. Livestock are the most abundant and widespread species and dominate the large herbivore ecosystem. Elephant and buffalo herds are clustered inside Amboseli National Park. Aerial population estimates for selected species based on the Jolly method 2 (Jolly, 1969) are shown in Table 2. The estimates in 2016 show a strong recovery from the 2009 drought that hit the Amboseli ecosystem. (See Fig. 9.)

The rapid release of livestock body condition scores and milk production data is vital to herder decision-making and drought avoidance through movement and market sales. Milk yields and body condition showed a steep drop leading into the 2009 drought (Fig. 10) and provide a vital early-warning indicator monitored informally by individual herders, but hard for communities to assess on a wider scale.

3.3. Data visualization portal

The current interactive data portal for SORALO, viewed at http://104.236.196.1:3838/Bomaapp/ displays data on pasture conditions, climate and rainfall, water resources, and changes in settlement

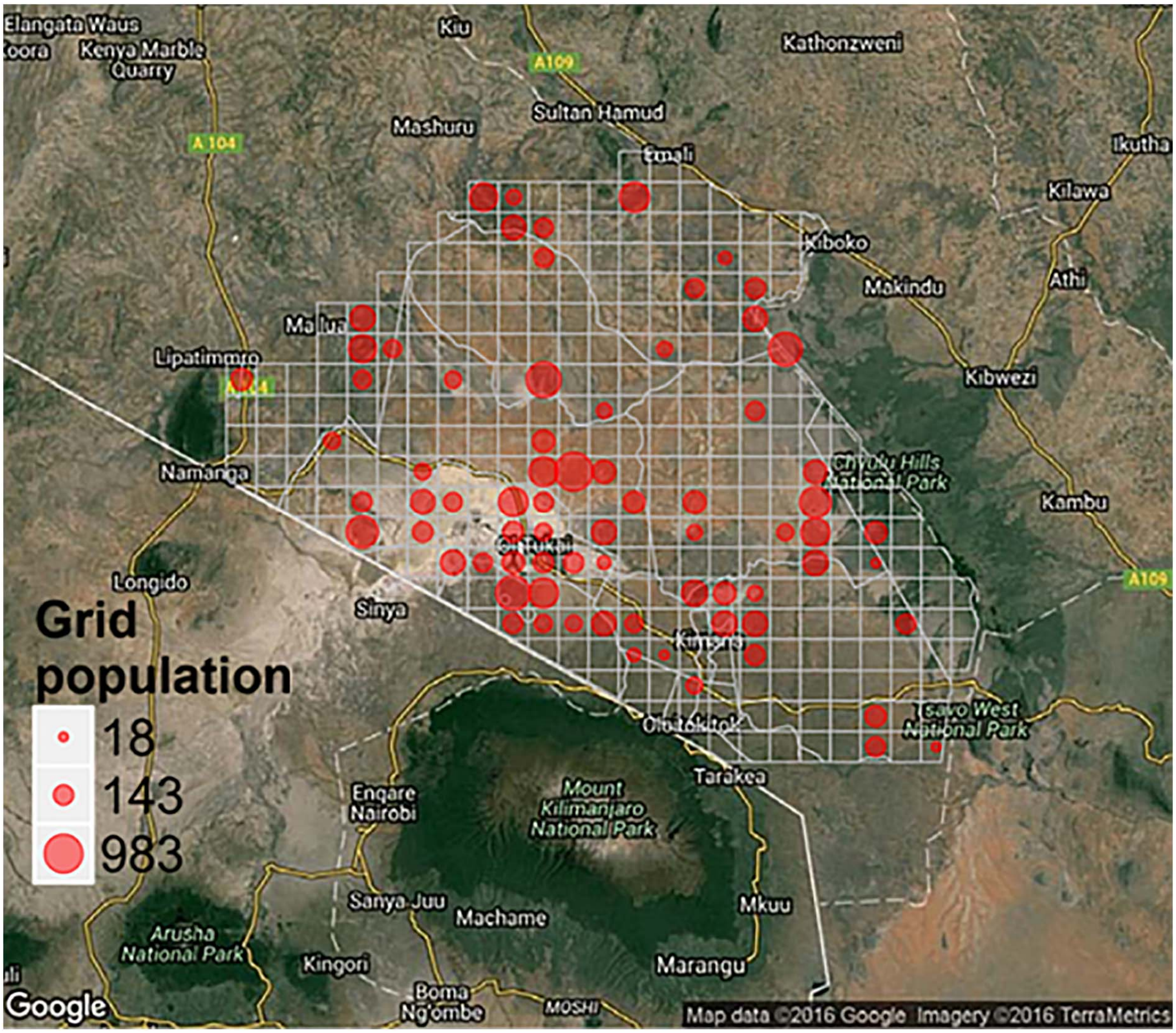

Fig. 9. Zebra population distribution in the Amboseli ecosystem in May 2016, mapped directly on satellite (Google) imagery for easy online visualization.

pattern, among other variables collected. Automatic updates are done regularly.

4. Discussion

The results of our study showing examples of outputs from a suite of open source tools that are customized for local communities' use, provide a rapid assessment of socioeconomic and ecological resources in the pastoral rangelands of East Africa. The current slow pace of delivering information and a lack of visualization tools for easy viewing and interpretation by non-technical decision-makers hinders its application to conservation planners and managers (Sarkar et al., 2006). A quick delivery of information as shown above allows for decisions from locally based monitoring to be made promptly at a local level in response to perceived threats (Constantino et al., 2012). Our examples show the application of customized tools to biodiversity conservation and to signaling of extreme droughts that are becoming more severe and frequent in many ecosystems across East Africa. Vegetation monitoring and visualization of the results show the declining vegetation biomass trends for the Amboseli ecosystem in the last few decades. The decline corresponds to an increasing grazing pressure (Fig. 6). Early warning indicators developed using the feedback system presented here are used to display the threat of heavy grazing on critical drought refuges and are signaled in red when offtake exceeds 50% (Fig. 6).

An additional advantage of the tools presented here, is the filling in of the gap created by a lack of technical capacity and scientific engagement at the lower levels (Stephenson et al., 2015) which has impeded the collection, delivery and use of data, in management decisions locally and nationally. The application of customized open source programs simplifies the complex processes and steps involved in data analysis and visualization, encouraging local and direct monitoring and use of environmental data (Raymond et al., 2010). Simple tools and standardized robust protocols avoid delays in the uptake and application of monitoring data. They also protect the raw data structure by extracting those components to be analyzed and applied to conservation planning and management while ensuring that data privacy, safety and integrity is maintained. The construction of resource centres in conjunction with landowner's associations has provided additional infrastructure necessary for local community involvement in research processes (Fig. 2) that combine scientific and traditional ecological knowledge.

These tools (http://104.236.196.1:3838/Bomaapp/ and in supporting information provided) are also easily adjustable and require minimal changes to process similar data from different ecosystems. Outputs can be presented to user groups (Table 1) through a variety of techniques that include an online data visualization portal such as the one provided above, scientific publications and community meetings in local resource centres (Russell, 2017). Below, we provide specific examples of the applications of the tools to selected datasets.

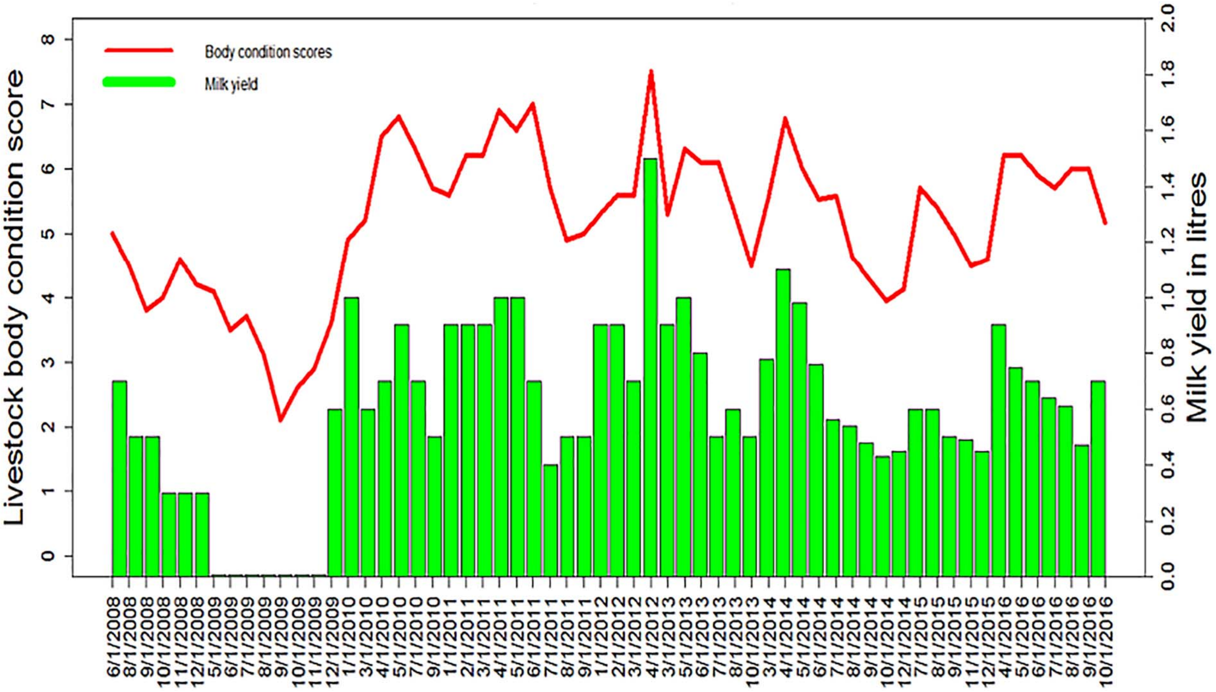

Fig. 10. Fluctuations in livestock body condition scores (red line) with milk yield (green bars) in the Amboseli ecosystem in southern Kenya. Milk yield dropped to zero during the 2009 drought, corresponding to the worst body condition scores recorded. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

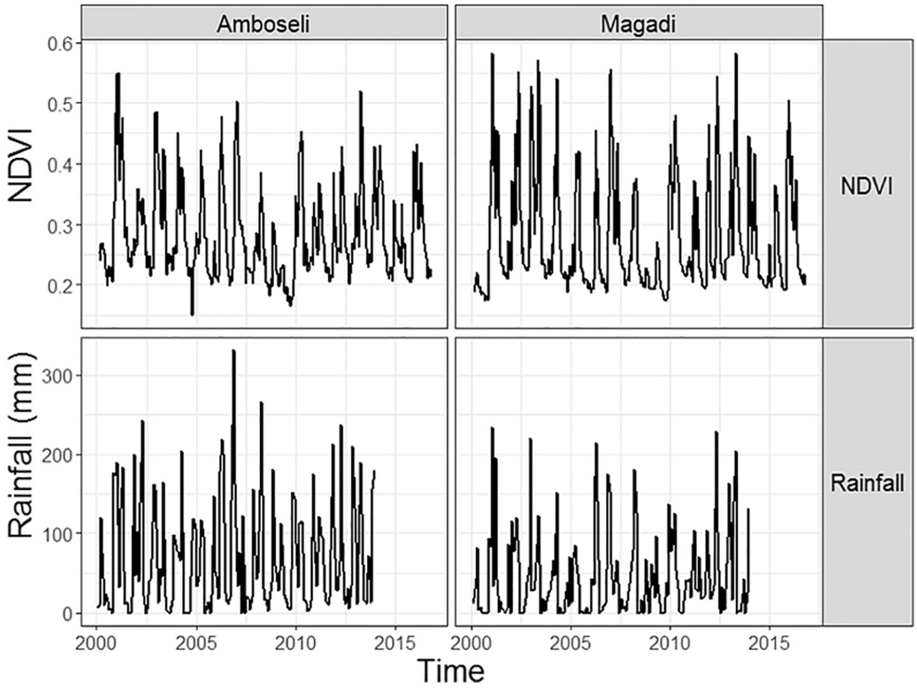

Fig. 11. Normalized Difference Vegetation Index (NDVI) and rainfall for the Amboseli and Magadi ecosystems extracted by the tool from satellite data and graphed automatically.

4.1. Habitat changes in the Amboseli National Park

Long term vegetation changes in and around the Amboseli National Park show a progressive loss of woodland vegetation and expansion of grassland and open bush (Western, 2007). The spatial time series changes presented in (Fig. 5) provide a quick analysis of the changes. Before the development of the open source tools discussed here, the GIS data processing and analysis took considerable time and skills not available to community's groups.

The availability has prompted ACP and Amboseli Ecosystem Trust to take steps to restore the loss of habitats, pasture and biodiversity in the Amboseli ecosystem (Western, 2017) by using habitat and pasture exclosures in selected degraded areas (Western and Maitumo, 2004). The restoration has seen the regrowth of tree species within the exclosures (Fig. 5) lost to elephant compression across the national park.

4.2. Aerial surveys analysis and presentation

The spread of farms (Fig. 7) in the Amboseli ecosystem after the 1990s led to the displacement of wildlife and intensified crop raiding by elephants. Mapping the spread of human activities and conflicts with wildlife provides information for land use planning and conflict resolution. Quick processing of aerial surveys is important for assessing conflict between wildlife and livestock. The 2016 aerial survey results (Fig. 8 and Table 2) show recovery from the 2009 drought (Western, 2017). The major species, including livestock, zebra, wildebeest and gazelle, show a strong recovery.

The routine analysis processed both the spatial and numeric components of the survey data simultaneously for all the species (Fig. 8) and results made available to stakeholders and partners in good time. The graphic is very effective in allowing the community groups to visualize the entire ecosystem and the species densities on a single platform and in understanding the spatial relationships between species and the environmental setting. The results of such counts and their significance are regularly posted on the ACP website (Western, 2017) for direct use and application.

4.3. Satellite and ground based vegetation monitoring

Ground monitoring has limitation that include insufficient frequency and scale to capture regional pasture abundance and conditions (Western et al., 2015b). Tools that extract complementary satellite data provide managers a wide pool of information in support of informed decision-making. Early warning proxies of rainfall and NDVI are easily downloaded and visualized for selected areas. Given the GPS coordinates, the tool processes and tailors the graphics (Fig. 11) for various interest groups ranging from senior managers to community grazing associations.

The tools presented here allow the effective combination of satellite data with ground based measures of animal body conditions, pasture production and vegetation structure through active community participation. The local engagement and direct feedback lowers the barriers to monitoring and using local and regional early warning systems across East Africa (Western et al., 2015b).

5. Conclusion

Decision support in biodiversity conservation requires an effective combination of analysis tools and expertise usually unavailable locally. The formulation of these tools calls for expanded infrastructure and understanding complex ecological process (Sarkar et al., 2006). Once developed, the applications are straight forward. The work presented here and applied to conservation and development planning in the Amboseli and Magadi ecosystems has encouraged other institutions, including the Northern Tanzania Rangeland Initiative, to standardize monitoring, sampling and data entry and analytical techniques, as well as collaboration in developing and applying the techniques. Use of the open source decision tools has seen previously unanalyzed historical data sets in many institutions in the region processed and results made available to communities and natural resource managers for planning purposes. We intend to develop customized mobile applications of these tool, aimed at linking social media feeds and one-stop software programs for assessing spatial trends, drought early-warning systems and ecosystem health.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoinf.2017.09.006.

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