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2020 Progress Report

Pilot Application of GeOC4SLiM to Identify Potential Areas for Outscaling Community-based Breeding Programs (CBBP) for Small Ruminants in Ethiopia and Kenya

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1 Introduction

Sustainable Livestock Management (SLiM) are required to interrelated UN Sustainable Development Goals (SDGs) on poverty alleviation, achieved food security, improved nutrition, promoted sustainable agriculture and land degradation neutrality (Godfray *et al.*, 2010; Eisler *et al.*, 2014). SLiM options are fitted to the social, economic and ecological contexts (Eisler *et al.*, 2014). The high contextual diversity of drylands in particular prevents the design and application of "uniform blanket" policies to promote SLiM over large scales where significant impacts are expected. The Geoinformatics Options by Context for promoting Sustainable Livestock Management options (GeOC4SLiM) has designed to provide stakeholders/projects and programmes with standardized description of SLiM options, and plausible extrapolation domains for supporting outscaling of SLiM options (Le and Rischkowsky, 2018). In specific, the tool is expected to improve targeting of SLiM-related projects/programs in coping with given limited resources and inherent diversity of socio-ecological context, such as:

(1) Targeting options in context: given a defined socio-ecological context, tool users can know about *what* promising SLiM options from current large shares of SLiM data or knowledge, or,

(2) Targeting context given option, i.e. relevant extrapolation/recommendation domain: given a set of promising SLiM options identified in a limited number of project sites, tool users can know *where* efforts should be focused by managing or coping with *what potential drivers*. The visualization of relevant extrapolation/recommendation domain would support the outscaling of site-specific successful SLiM options.

In many developing countries, community-based breeding programs (CBBPs) for small ruminants have been suggested as alternatives to centralized/government-controlled and/or commercial breeding schemes (Haile et al., 2011; Haile et al., 2019). CBBP takes into account farmers' needs, views, decisions, and active participation, from inception through to implementation, and their success is based upon proper consideration of farmers' breeding objectives, infrastructure, participation, and ownership. CBBP overcomes the limitations of state-based, centralized breeding schemes that are often failed to sustainably provide the desired genetic improvements with proper participation of end-users in the process, as well as the shortcomings of commercial breeding services that often cause genetic erosion of indigenous animal populations and breeds (Haile *et al.*, 2011; Haile *et al.*, 2013; Haile *et al.*, 2019). CBBPs for small ruminants have been implemented in ICARDA research sites and communities in Ethiopia since 2009. Substantial genetic gains and socio-economic benefits of site/community-specific CBBPs for sheep were evaluated by Mueller et al. (2019), Haile *et al.* (2020), and Gutu *et al.* (2015). Genetic gains and productivity improvements of goats in CBBP sites/communities were assessed by Jembere *et al.* (2020), Rekik et al. (2019) and Jembere (2016).

This report presents pilot/demonstrative applications of the GeOC4SLiM for support prospective stakeholders in Ethiopia and Kenya to (1) define CBBPs for small ruminants by context and (2) map the areas of socio-ecological contextual similarity (as integrated extrapolation/recommendation domains) for support scaling.

2 Methods and data

2.1 GeOC4SLiM approach and tool

The concept underlying the GeOC4SLiM tool is the system-based options by context (OxC) framework as illustrate in Figure 1 (Le *et al.*, 2017). The OxC framework is a systems-based clarification of the relationship between context (including drivers) and management options as the basis for data integration, selection of objective-oriented indicators and analysis/assessment of the diversity of land use systems and related contexts over space (Figure 1). The framework draws on insights of current frameworks for social-ecological systems in transitions (Ashley and Carney, 1999; Reynolds et al., 2007; Pahl-Wostl et al., 2010; Scholz et al., 2011), but is kept simpler for operational implementation.

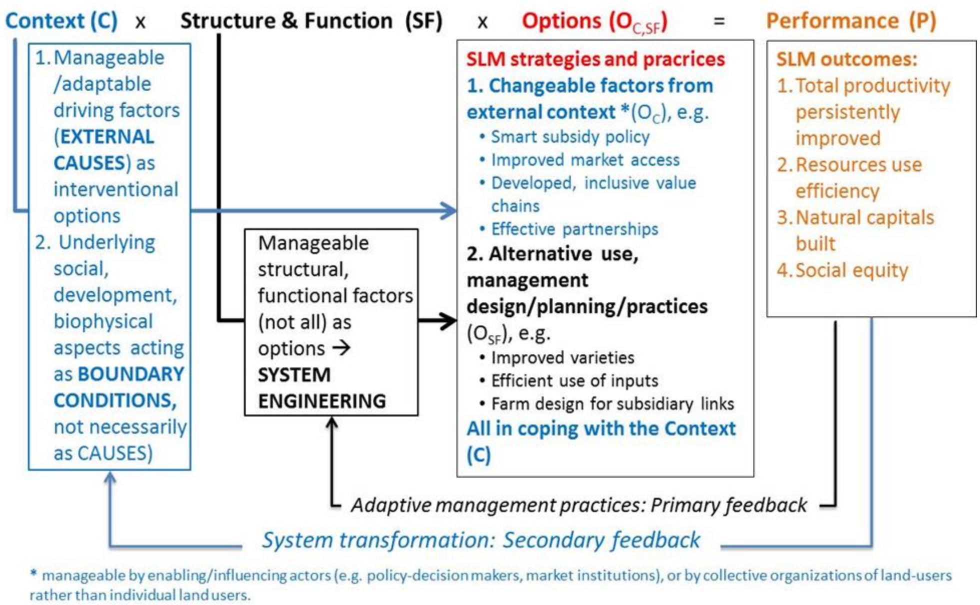

Figure 1: Relationship between SLM management options, structure and function of land use systems and context with a system-in-transition thinking. Sources: Le et al. (2017).

As a web-based integrative tool, GeOC4SLiM has two interrelated domains (sub-tools) (Figure 2): (1) The web-based geographic information system (called WebGIS domain/sub-tool) (https://mel.cgiar.org/geoc/webgis[1]). This domain includes a web-based GIS interface with key functions (filtering/querying, zonal statistics, spatial similarity analysis), and GIS database of drivers and performance/impact indicators of SLiM and/or SLM. (2) The Sustainable Livestock Management component (called SLiM domain/sub-tool) (https://mel.cgiar.org/geoc/slim[2]). The SLiM domain/sub-tool includes the web-based form for importing standardized and completed SLiM options by context, and the SLiM database. The two components are matched and synchronized (Figure 2).

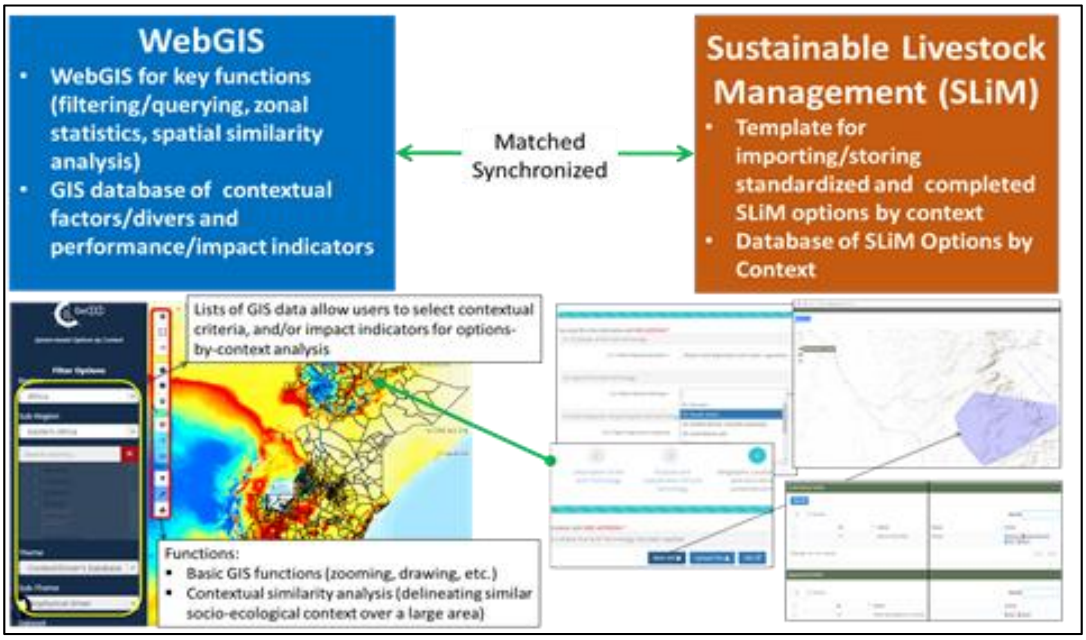

Figure 2. GeOC4SLiM tool integrates standardized system characterizing SLiM with user-friendly WebGIS

2.2 GIS-based variables and fCSET

GIS-based variables

There are 26 variables in the format of GIS raster that were embedded in the WebGIS domain/sub-tool. The categories of these GIS variables are shown in Figure 3. The brief definitions and data sources of the variables are shown in Tables S1 and S2 (see Supporting Information). GIS data are collected and resampled (up- or down-scaled to 1 km resolution) from different sources (such as USGS, FAO-IIASA, UNEP, IUCN, CIESIN-CIAT, CGIAR-CSI). Important data such as inter-annual trends of rainfall, social-ecological contextual types are driven from the analyses of CRP-Dryland Systems data on integrated systems work. Agricultural resource poverty, proximities to roads, towns and water bodies were calculated by ICARDA Geoinformatics Unit (http://geoagro.icarda.org/en/).

[1] When this link is not working it means that the domain is being under maintenance/improvement, and the temporary alternative link is https://mel.cgiar.org/slm/visualization
[2] When this link is not working it means that the domain is being under maintenance/improvement, and the temporary alternative link is http://dev.scio.services/slim

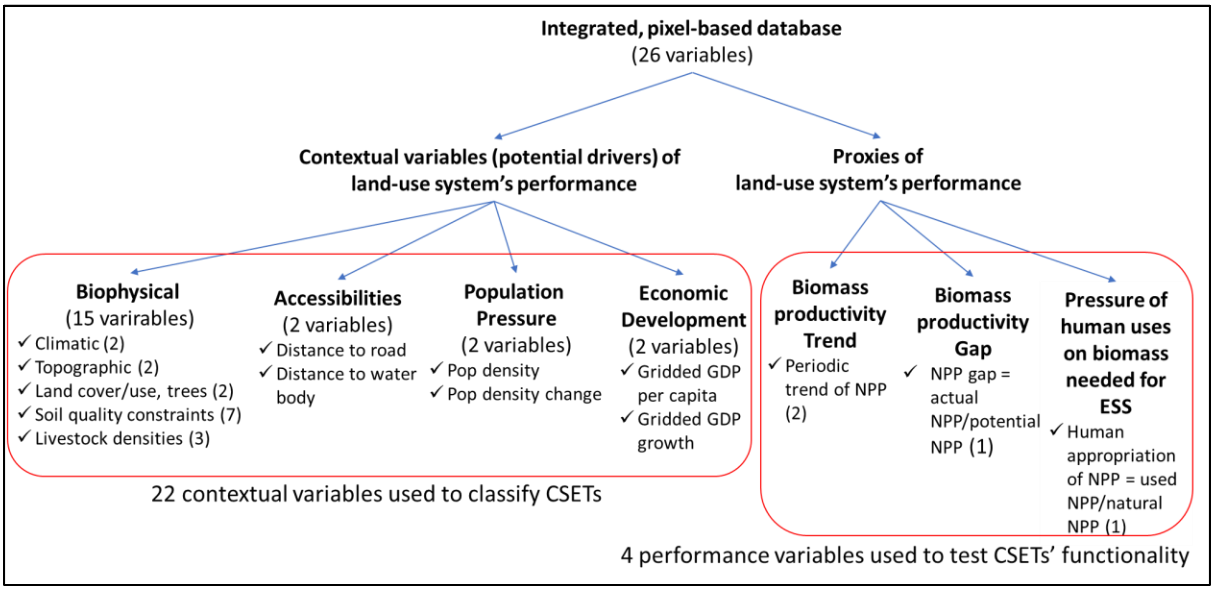

Figure 3. Categories of GIS-based variables

Functional context socio-ecological types (fCSET)

High contextual diversity over large-scale land resources makes (1) "uniform blanket" policies promoting SLiM less effective and (2) the synthesis and upscaling of site-based successful lessons on SLiM difficult. To overcome the challenge, GeOC4SLiM tool provides users with tested spatial extrapolation/recommendation domains based on functional typologies of socio-ecological context. Functional context socio-ecological types (fCSET) were identified by two subsequent steps (Figure 4):

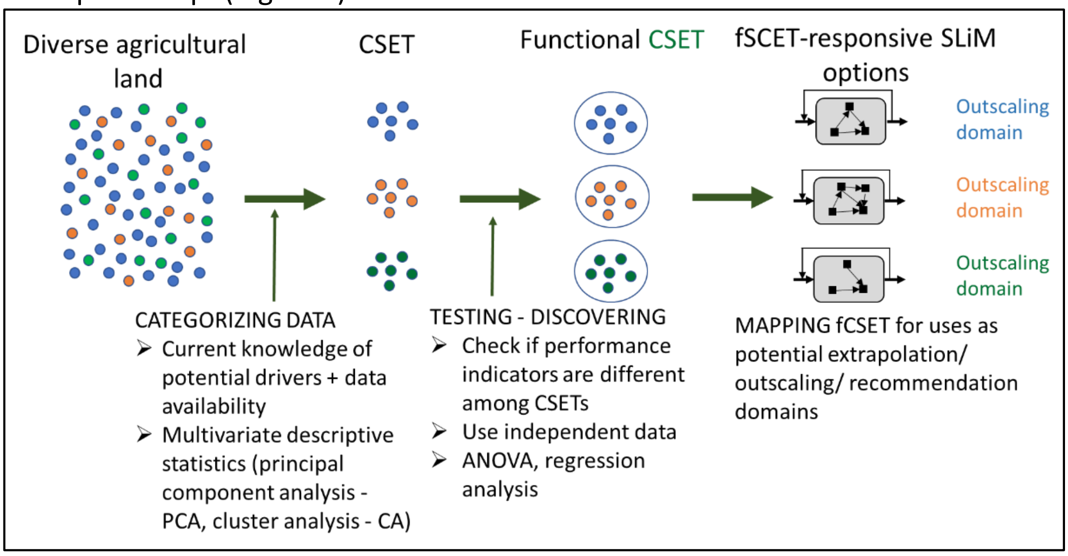

Figure 4. Subsequent steps for analysing and mapping fCSET as integrated extrapolation/recommendation domains

(1) Grouping common biophysical, economic and social drivers of SLiM adoption/performance and change into distinct context types. The socio-ecological drivers selected for analysis were based on a literature review. For each broad land cover class, the context socio-ecological types (CSETs) were defined using sequential spatial multi-variate statistics (principal component analysis - PCA then cluster analysis - CA).

(2) Testing if the defined CSET can shape the performance of SLiM in term of basic indicators of land degradation or improvement. The differences in NPP trend, human appropriation of NPP (HANPP) and NPP gap (difference between potential and actual NPP of the land) among pixels of different CSETs were evaluated by unbalanced ANOVA. If the ANOVAs are statistically significant, the CSETs become functional CSET (i.e. fCSET). The indicating aspects of the indicators are summarized in Table S2.

Significant uses of the fCSET data: The results can be used by SLiM-related projects/programs and citizen scientists/planners to improve their targeting. For example given limited resource and aims, we can know approximately, where efforts should be focused by managing or coping with what drivers. The fCSETs can also be used as extrapolation domains: given SLiM outcomes in a number of specific sites, we can identify where similar SLiM options have a potential of success based on contextual similarity.

Spatial analysis for defining fCSET in major land cover classes in Ethiopia and Kenya was done separately, i.e. outside of GeOC4SLiM (Le and Rischkowsky, in prep). The spatial input and output variables of this work were uploaded to the WebGIS sub-tool of GeOC4SLiM for the tool uses.

2.2 Geo-referenced and standardized characterization of site-specific CBBP options

We considered 14 implementation sites of CBBPs for sheep and goats in Ethiopia (Table 1) (Le, 2020). The data of socio-ecological conditions, CBBP practices performances in the format of Online Template for Sustainable Livestock Management Option-by-Context (SLiM OxC) (https://mel.cgiar.org/geoc/slim[4]) (Le and Rischkowsky, 2019). Each SLiM OxC data has six main parts: (1) data generators and sources (2) description of the implemented SLiM option, (3) perceived purposes and SLiM type, (4) geographic location and geo-referenced socio-ecological context, (5) specification of inputs and costs, (6) adoption and impacts. The filling of information fields are based on either the provided answer choices (drop-down menus provided), or texts with structured instruction. Besides optional information fields, there are compulsory fields that form a minimal description of the SLiM data. Because the SLiM data are compiled using different available information sources that are very much varying in reported categories and variables, spatial clarities and times, the data are presented by version-to-version over time. The version-to-version approach offers chances to improve data quality and comprehensiveness upon new reference sources considered and additional peer-reviews offered, meanwhile encourage usages of the current version with informed limitations.

[3] When this link is not working it means that the domain is being under maintenance/improvement, and the temporary alternative link is http://dev.scio.services/slim

[4] When this link is not working it means that the domain is being under maintenance/improvement, and the temporary alternative link is http://dev.scio.services/slim

Table 1. Considered sites (14) of CBBP for sheep and goats in Ethiopia

CBBP site	*Animal*	*District*	*Zone/Province*	*Region*	*References*
Addis-Mender	Goats	Sekota	Wag Hemira	Amhara	Rekik *et el.* (2019)
Azoliku	Goats	Sekota	Wag Hemira	Amhara	Rekik *et el.* (2019)
Arfaide	Goats	Konso	Konso Special Wodera	SNNP	Rekik *et el.* (2019)
Baide	Goats	Konso	Konso Special Wodera	SNNP	Rekik *et el.* (2019)
Bilagu	Goats	Sekota	Wag Hemira	Amhara	Rekik *et el.* (2019)
Blaku	Goats	Zikuala	Wag Hemira	Amhara	(Jembere, 2016; Jembere *et al.*, 2020)
Bonta	Sheep	Amibara	Zone 3	Afar	(Haile *et al.*, 2013; Haile *et al.*, 2020)
Dingur	Goats	Enderta	Southern Tigray	Tigray	(Jembere, 2016; Jembere *et al.*, 2020)
Masoya	Goats	Konso	Konso Special Wodera	SNNP	Rekik *et el.* (2019)
Mehal-Meda	Sheep	Gera Midima Keya Gabriel	North Shewa	Amhara	(Haile *et al.*, 2013; Haile *et al.*, 2020)
Molale	Sheep	Mama Midima Lalo	North Shewa	Amhara	(Besufkad, 2019)
Tabela-Kuchale	Goats	Konso	Konso Special Wodera	SNNP	Rekik *et el.* (2019)
Saziba	Goats	Sekota	Wag Hemira	Amhara	Rekik *et el.* (2019)
Workadivno	Goats	Sekota	Wag Hemira	Amhara	Rekik *et el.* (2019)

2.4 Two types of use cases for targeting in promoting CBBPs of small ruminants

As a pilot implementation of the GeOC4SLiM tool, in this presented report we demonstrate two typical uses cases and concrete results.

Use Case 1 (UC1): Searching CBBP sites and related standardized-integrated data given considered socio-ecological contexts

Concrete questions the tool is meant to help answer:

Q1-UC1: In the rainfed Ethiopian cropland, how many functional context socio-ecological types (fCSET) can be found for using as extrapolation/recommendation domains?

Q2-UC1: In the rainfed Ethiopian cropland, how many CBBP sites (upon on available data encoded in GeOC4SLiM) can be found? How were these CBBP sites distributed over the contextual/extrapolation/recommendation domains?

Use case 2 (UC2): Mapping integrated extrapolation/recommendation domains for context-specific CBBPs

Concrete question the tool is meant to help answer:

Q1-UC2: Given O good performed CBBPs found in C contextual types of Ethiopian rain-fed cropland, where are the areas in Ethiopia and Kenya having a potential of successful implementations of these CBBPs?

3 Results

3.1 Searching CBBP sites versus context

Functional context socio-ecological types (fCSET) in the rainfed Ethiopian cropping land

The searching for fCSETs within rain-fed cropland in Ethiopia found 6 categories with full characterization as shown in Table 2. These contextual types are functional regarding land productivity performance, as the key indicators of land degradation/improvement (being independent from the contextual variables used) are significantly different among the types (see Figure 1S) (Le and Rischkowsky, in prep).

Table 2. Mean values of contextual variables for 6 fCSETs found in the Ethiopian rainfed cropland

Contextual aspect	*Contextual variables*[a]	*fCSET in rainfed cropland*					
		RFC1 (65,863 km2)	*RFC2 (53,568 km2)*	*RFC3 (44,468 km2)*	*RFC4 (43,634 km2)*	*RFC5 (18,182 km2)*	*RFC6 (1,959 km2)*
Climate	Mean annual precipitation (mm/yr)	1097	1164	832	673	1449	1031
	Humidity index	0.71	0.85	0.50	0.37	0.87	0.65
Topography	Elevation (m a.s.l)	1972	2618	1407	481	1507	2205
	Surface slope (degree)	3.6	3.7	2.9	0.8	1.9	2.0
Soil condition	Constraint on soil nutrient availability	1	1	1	2	2	1
	Constraint on soil nutrient retention	1	1	1	1	2	1
	Constraint on soil root condition	2	2	2	1	1	1
	Constraint on soil oxygen condition	1	1	1	1	1	2
	Constraint on salt condition	1	1	1	1	1	1
	Constraint on soil toxicity	1	1	1	1	1	1
	Constraint soil work condition	3	3	2	2	2	3
Trees	Tree density or coverage (%)	16	16	11	6	27	7
Livestock	Sheep density (head/km2)	28	77	13	7	20	43
	Goat density (head/km2)	20	16	29	25	18	13
	Catle density (head/km2)	95	123	46	19	91	102
Physical access to market	Distance to the nearest road (m)	40	32	44	67	20	6
	Distance to the nearest town (m)	75	91	82	143	52	18
Demography	Population density (person/km2)	209	206	127	43	402	1111
	Population change (Δperson/km2/15 years)	92	97	49	21	135	928
Economic status	Gridded GDP per capia ($USD/person/yr/15°x15°)	12	11	14	16	23	15
	Annual growth of GDP per capita (Δ%/yr)	0.23	0.17	0.34	0.44	0.40	0.21

[a] related data sources are listed in Table S1

From Table 2, the fCSET were qualitatively levelled for the contextual factor aspects that reflect the contextual typologies:

RFC1: Rainfed cropland - Humid - High elevation - Good soil - Scattered trees - Medium livestock - Remote - Less populated- Very poor

RFC2: Rainfed cropland - Humid - High elevation - Good soil - Scattered trees - High livestock - Remote - Less populated - Very poor

RFC3: Rainfed cropland - Semi-arid - Medium elevation - Good soil - Scattered trees - Low livestock - Remote - Less populated - Very poor

RFC4: Rainfed cropland - Semi-arid - Low elevation - Medium soil - Sparse trees - Low livestock - Very remote - Sparse population - Very poor

RFC5: Rainfed cropland - Humid - Medium elevation - Medium soil - With trees - Medium livestock - Fairly remote - Populated – Poor

RFC6: Rainfed cropland - Dry sub-humid - High elevation - Good soil - Sparse tree - Medium livestock - Near towns - Highly populated - Very poor

Searched CBBP sites *versus* fCSETs (extrapolation/recommendation domains) in Ethiopian rain-fed cropland

Of 14 Ethiopian CBBP sites encoded in GeOC4SLiM, there are 14 sites located on rain-fed cropland. These 14 sites are distributed in 4 fCSET (extrapolation/recommendation domains) as shown in Table 3. The distribution of concrete CBBP sites (with labelling tags) in domains RFC1, RFC2, RFC3 and RFC4 are shown in Figures 5, 6, 7 and 8, respectively.

Table 3. CBBP sites searched within each fCSET (extrapolation/recommendation domains) in Ethiopian rain-fed cropland

fCSET	*CBBP site*	*District*	*Region*	*Targeted animal*
RFC1	Alikozu	Sekota	Amhara	Goats
	Baide	Konso	SNNP	Goats
	Bilagu	Sekota	Amhara	Goats
	Dingur	Enderta	Tigray	Goats
RFC2	Arfaide	Konso	SNNP	Goats
	Mehal-Meda	Gera Midima Keya Gabriel	Amhara	Sheep
	Molale	Mama Midima Lalo	Amhara	Sheep
RFC3	Blaku	Zikuala	Amhara	Goats
	Masoya	Konso	SNNP	Goats
	Saziba	Sekota	Amhara	Goats
	Workadivno	Sekota	Amhara	Goats
RFC4	Bonta	Amibara	Afar	Sheep

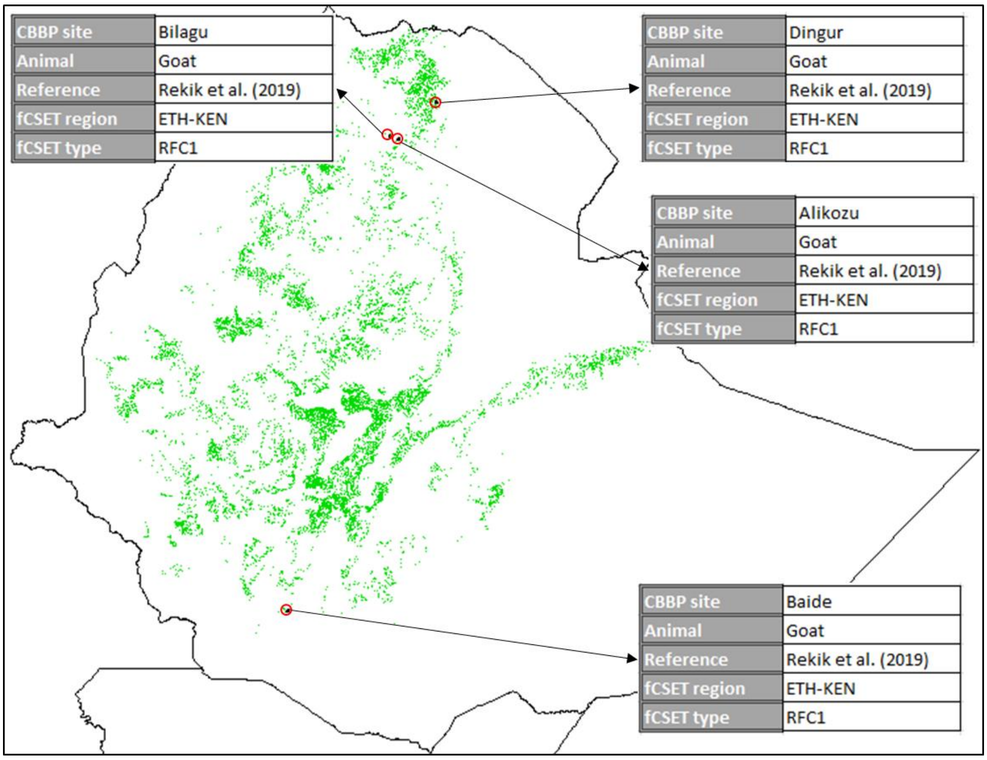

Figure 5. Searched CBBP sites (with linked SLiM OxC data stored in GeOC4SLiM) located in extrapolation/recommendation domain RFC1 (Rainfed cropland - Humid - High elevation - Good soil - Scattered trees - Medium livestock - Remote - Less populated - Very poor).

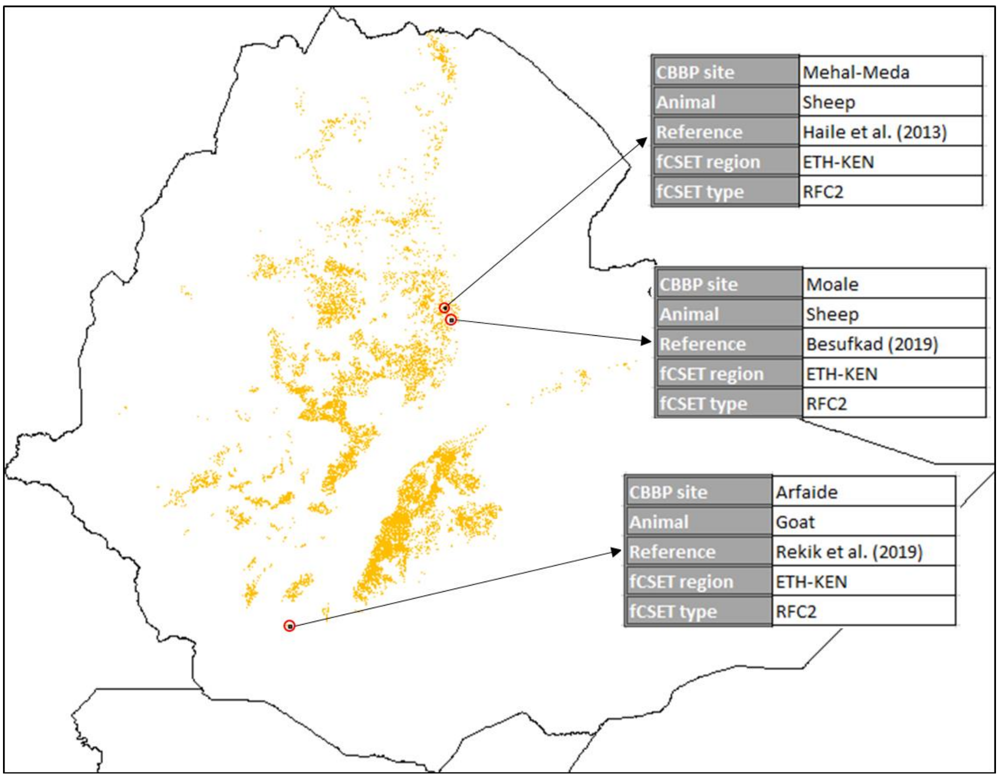

Figure 6. Searched CBBP sites (with linked SLiM OxC data stored in GeOC4SLiM) located in extrapolation/recommendation domain RFC2 (Rainfed cropland - Humid - High elevation - Good soil - Scattered trees - High livestock - Remote - Less populated - Very poor).

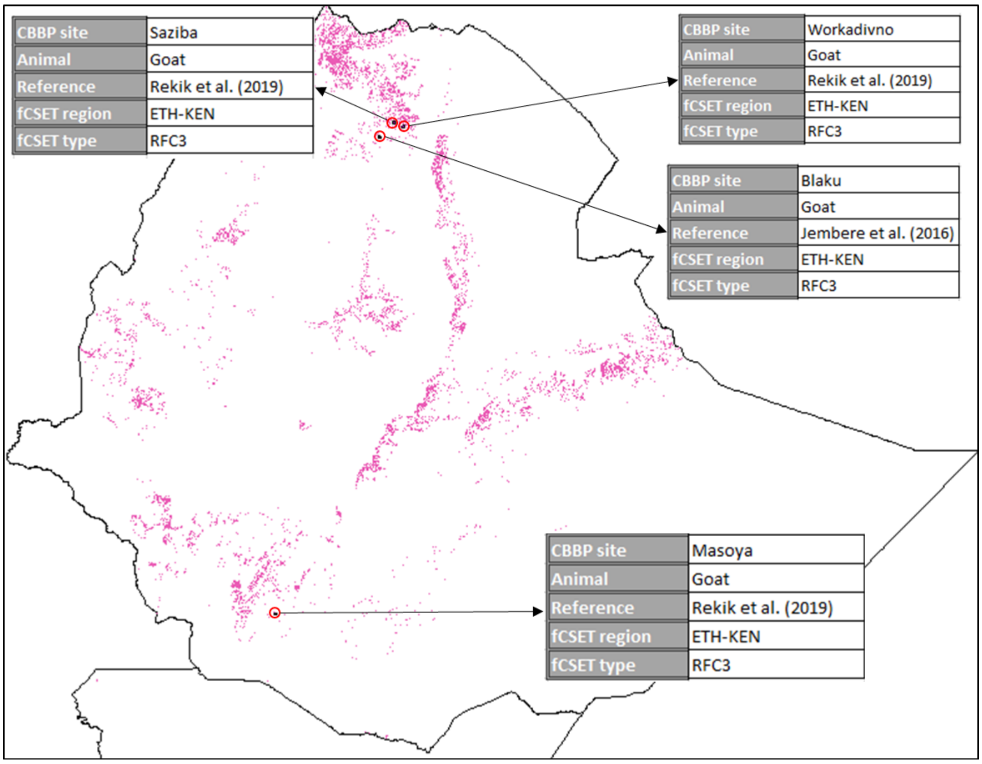

Figure 7. Searched CBBP sites (with linked SLiM OxC data stored in GeOC4SLiM) located in extrapolation/recommendation domain RFC3 (Rainfed cropland - Semi-arid - Medium elevation - Good soil - Scattered trees - Low livestock - Remote - Less populated - Very poor).

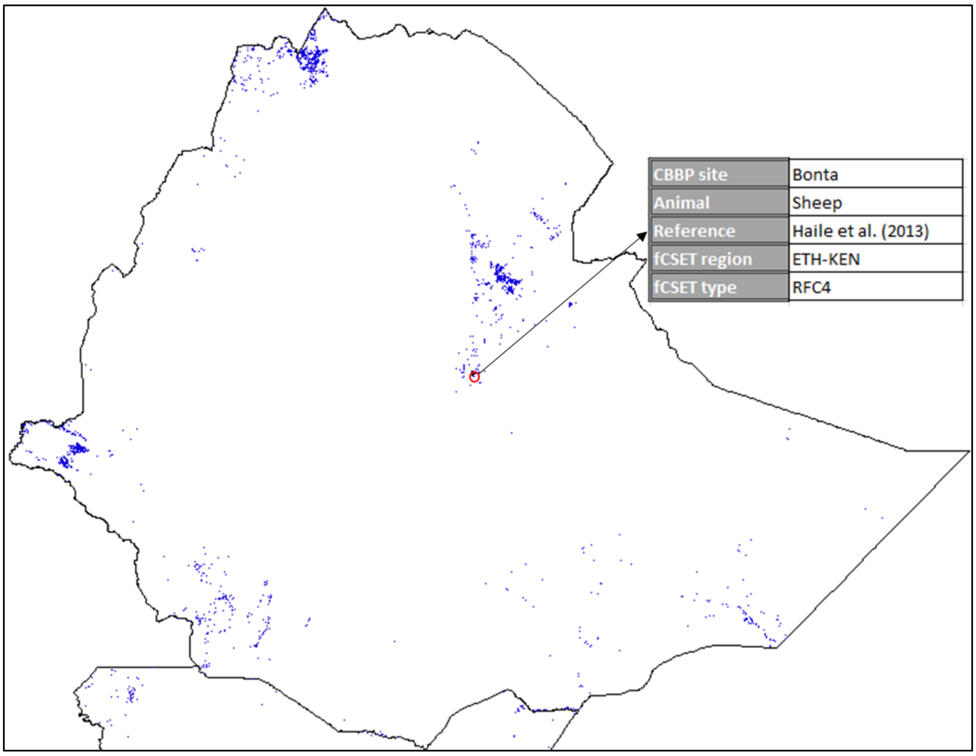

Figure 8. Searched CBBP sites (with linked SLiM OxC data stored in GeOC4SLiM) located in extrapolation/recommendation domain RFC4 (Rainfed cropland - Semi-arid - Low elevation - Medium soil - Sparse trees - Low livestock - Very remote - Sparse population - Very poor).

3.2 Mapping integrated extrapolation/recommendation domains for context-specific CBBPs

From the evaluated[5] CBBP sites, the GeOC4SLiM was used to map relevant extrapolation/recommendation domains across all rainfed cropland in Ethiopia and Kenya. The mapping results are presented in Figures 9-12. The map of relevant extrapolation/recommendation domains can be download in both bitmap files (.jpeg) and raster GIS (geo-tif).

With the tool, users can request the area tabular calculation that quantify the area of each extrapolation/recommendation domains versus polygons of administration units at different levels. Table 3 presents the result of area tabular analysis aggregated at country level. With the current Global Administration Map (GADM) data available in GeOC4SLiM WebGIS, users can request area tabular calculation at the most detailed administration units being available in the GADM dataset. The GADM's smallest administrative unit for Ethiopia and Kenya are District (Wodera) (level 3) and Sub-location (Kata Nalogo) (level 5), respectively. Both maps and area tabular (relevant fCSET vs administration unit) would be useful for improving geographic targeting in outscaling efforts in the face of contextual diversity and prioritization needs.

Table 3. Summary of evaluated CBBP sites for outscaling and areas of potential extrapolation over Ethiopian-Kenyan rain-fed cropland

Evaluated CBBP sites in Ethiopia for outscaling	*Extrapolation /Recommendation domain (fCSET)*	*Area (km2)*		
		Ethiopia	*Kenya*	*Total*
CBBP for goats, Bilagu CBBP for goats, Dingur CBBP for goats, Alikozu CBBP for goats, Baide	RFC1	53,781	12,614	66,396
CBBP for sheep, Mehal-Meda CBBP for sheep, Molale CBBP for goats, Arfaide	RFC2	48,672	5,327	53,999
CBBP for goats, Saziba CBBP for goats, Workadivno CBBP for goats, Blaku CBBP for goats, Masoya	RFC3	30,179	14,647	44,825
CBBP for sheep, Bonta	RFC4	7,693	36,290	43,983
	Total	**86,544**	**56,264**	**142,807**

[5] Good performance (genetic gains, productivity improvement and socio-economic benefits) of the site-specific CBBPs were done and demonstrated in related references listed in Table 1.

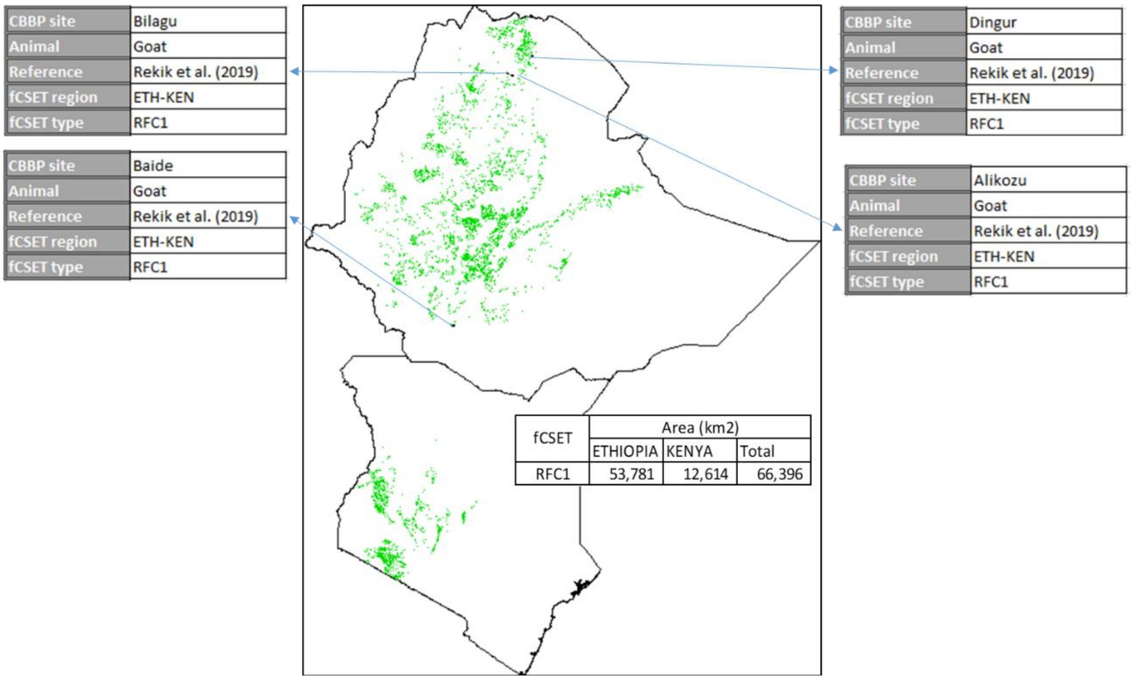

Figure 9. Areas in Ethiopia and Kenya for potential out-scaling of CBBP implemented in 4 Ethiopian sites within RFC1 (site labels and locations on the map).

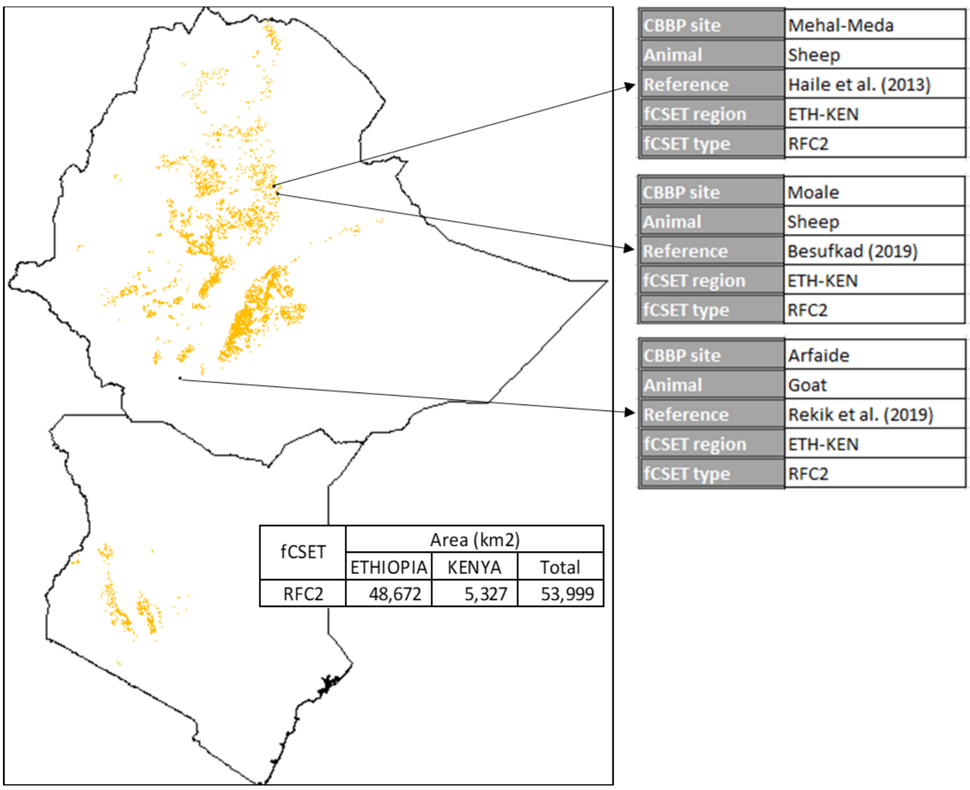

Figure 10. Areas in Ethiopia and Kenya for potential out-scaling of CBBP implemented in 3 Ethiopian sites within RFC2 (site labels and locations on the map).

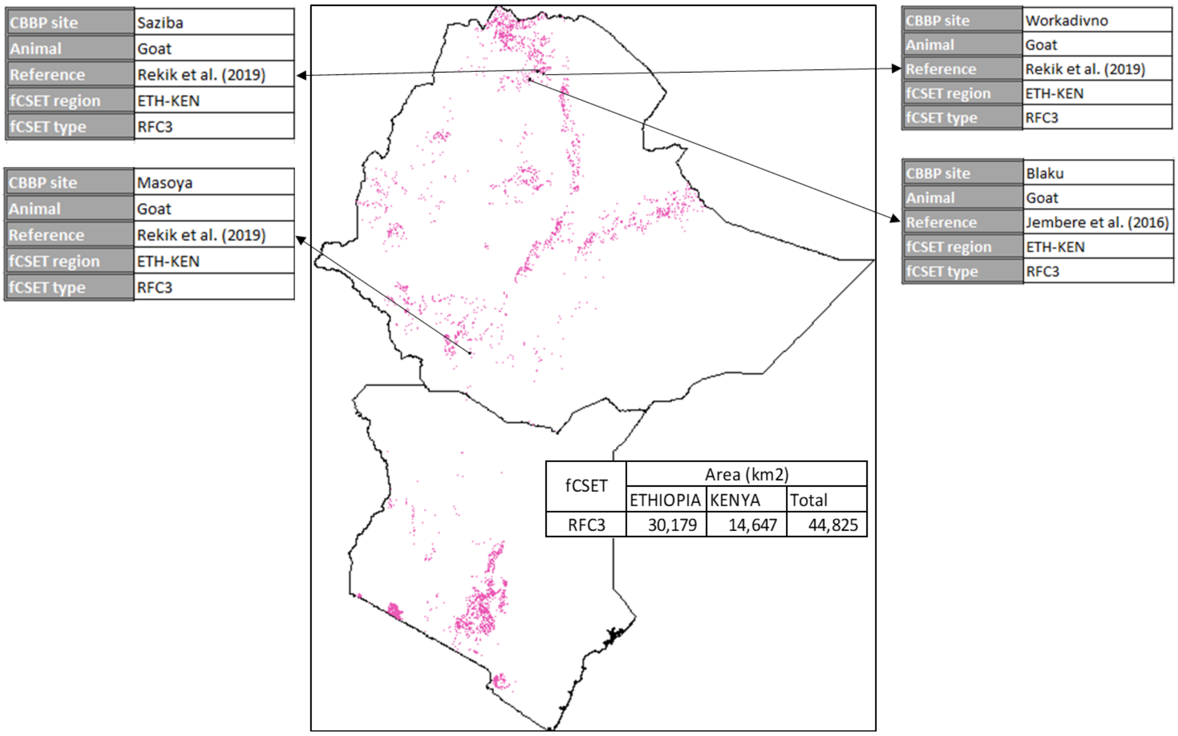

Figure 11. Areas in Ethiopia and Kenya for potential out-scaling of CBBP implemented in 4 Ethiopian sites within RFC3 (site labels and locations on the map).

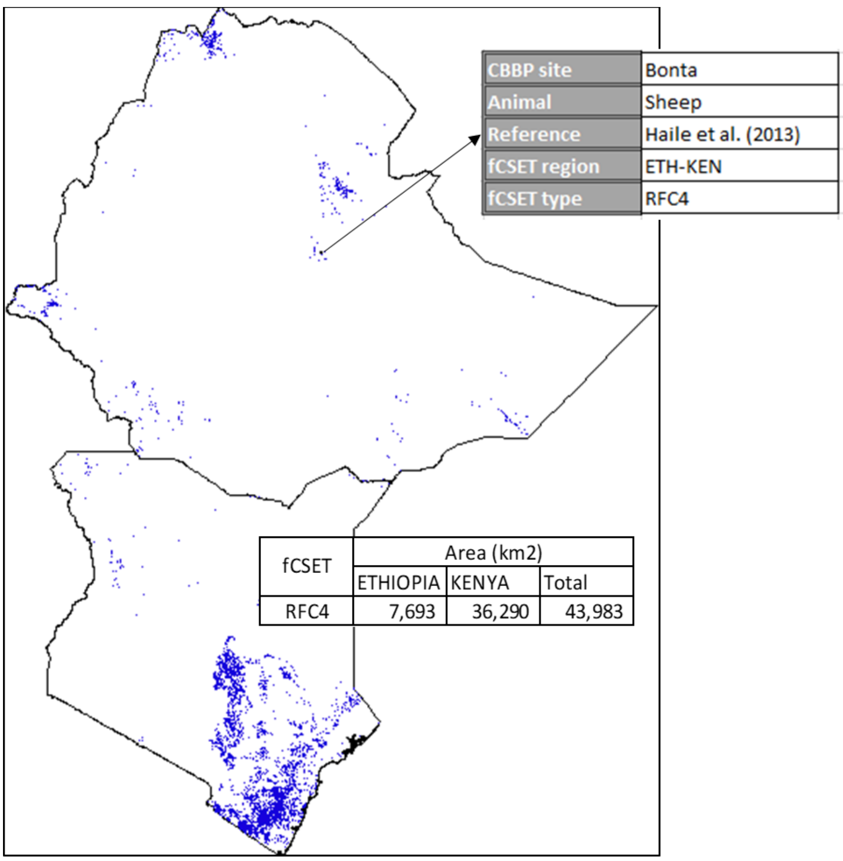

Figure 12. Areas in Ethiopia and Kenya for potential out-scaling of CBBP implemented in 1 Ethiopian site within RFC4 (site label and location on the map).

4. Discussions

The first development and presented pilot application of the GeOC4SLiM tool help demonstrate particular features of innovation:

A means for data and knowledge integration

The tool offers unique integration between descriptive data on SLiM options and GIS data on socio-ecological context. So far, it is hardly to find a geoinformatics tool accommodating similar integration. The data/knowledge integration aspect is also strong in the SLiM data template and WebGIS sub-tools.

Tested spatial extrapolation/recommendation domains based on typologies of socio-ecological context

Our multivariate statistics-based approach to identify extrapolation/recommendation domains have two advantages compared to multi-criteria hierarchical nesting methods previously used by other research groups (e.g. Vlek *et al.* (2010), Herrero *et al.* (2014)):

- *"Everything should be made as simple as possible, but no simpler":* Obtaining a simplest typology for acceptable representation of complex reality is needed for management in coping with contextual diversity. Given that there are 8 contextual aspects and each has 3 sub-categories, the multi-criteria nesting method would have derived 3 x 8 = 24 contextual types that may be too many for use in practice. Our method found 6 contextual types.
- *Tested functionality*: Many other studies on extrapolation/recommendation domains classify contextual types and *assume* (*as a priori*) they are functional regarding they shapes the performance and impact of the management options. In our approach, the functionality of defined contextual types regarding land productivity outcomes were tested with inferential statistics using independent land productivity dataset.

It provides stakeholders with multiple entry points to view and evaluate SLiM options in context and visualize potential areas for scaling.

Its design is open for continuous improvement, customization. The version-to-version approach, applied to both data and tool's functional capacity, offers chances to improvement in adaptive to needs and new data availabilities. Meanwhile, users are encouraged to use of the current version with informed limitations.

Supporting information

Table S1. List of contextual variables, their definitions and data sources that are used for spatial multi-variate statistics in fCSET identification in Ethiopia and Kenya. Notes: all data are rasterized and resampled to the resolution of 1x1 km^2

Variable	*Definition*	*Data sources*
PREC-MEAN	Mean annual precipitation over 1982-2006 (mm/year)	Calculated from CRU TS 3.1 dataset (Harris *et al.*, 2014; Le *et al.*, 2016)
HUMIDITY	CGIAR-CSI's aridity index	Trabucco and Zomer (2009)
ELEVATION	Above sea level elevation (m)	Global 30 Arc-second Elevation (GTOPO30) (USGS, 1998)
SLOPE-DEG	Surface slope (degree)	Calculated from GTOPO30 data (USGS, 1998)
SQC-NUAV	Constraint in soil nutrient availability [b]	Harmonized World Soil Database (HWSD) supplementary data (Fischer *et al.*, 2008)
SQC-NURET	Constraint in soil nutrient retention capacity [b]	HWSD supplementary data (Fischer *et al.*, 2008)
SQC-ROOTCD	Constraint in soil root condition [b]	HWSD supplementary data (Fischer *et al.*, 2008)
SQC-OXYGEN	Constraint in soil nutrient availability [b]	HWSD supplementary data (Fischer *et al.*, 2008)
SQC-SALT	Constraint in soil oxygen condition [b]	HWSD supplementary data (Fischer *et al.*, 2008)
SQC-TOXIC	Constraint in soil toxicity [b]	HWSD supplementary data (Fischer *et al.*, 2008)
SQC-WORK	Constraint in work capacity of the soil [b]	HWSD supplementary data (Fischer *et al.*, 2008)
TREE-DEN	Tree density (% coverage)	
COVER-BROAD	Broad land use/cover zones	Re-classed from ESA-LC-CCI dataset 2015
SHEEP-DEN	Sheep density (head/km2)	Gridded Livestock of the World (GLW) (Robinson *et al.*, 2014)
GOAT-DEN	Sheep density (head/km2)	Gridded Livestock of the World (GLW) (Robinson *et al.*, 2014)
CATTLE-DEN	Cattle density (head/km2)	Gridded Livestock of the World (GLW) (Robinson *et al.*, 2014)
DIST-ROAD	Distance to the nearest road (km)	ICARDA (2016)
DIST-TOWN	Distance to the nearest town (km)	ICARDA (2016)

POP-DEN	Population density in 2015 (person/km^2)	Extracted from Gridded Population of the World, Version 3 (GPWv3) (CIESIN and CIAT, 2005)
POP-CHANGE	Change in population density in over 2000 - 2015 (person/km^2)	Calculated from Gridded Population of the World, Version 3 (GPWv3) (CIESIN and CIAT, 2005)
GDP-PERS	Gross Domestic Production (GDP) per capita per 15 x 15 minutes in 2008	Global 15 x 15 Minute Grids of the Downscaled GDP Based on the SRES B2 Scenario, averaged for 1990-2025 (Gaffin *et al.*, 2004)
GDP-GRW	Growth of GDP per capita over 1990 – 2025 (% of baseline value in 1990)	Calculated using gridded downscaled GDP (SRES B2 Scenario) (Gaffin *et al.*, 2004)

Table S2. Productivity-based indicators of land degradation/improvement for long-term

Variable	*Definition*	*Indicating aspect*	*Data sources*
NPP-TREND	Annual change in Net Primary Productivity (NPP) over 2000-2014 (unit: annual change in gC/m2)	Periodic trend of biomass productivity of the land, a proxy for soil productivity.	Extracted from (Le, 2016)
NPP-TRENDP	Relative annual change in Net Primary Productivity (NPP) over 2000-2014 (unit: annual change in % of NPP in the base year, i.e. 2000)	Periodic trend of biomass productivity of the land, a proxy for soil productivity. Relative measuring scale eases comparison among heterogeneous sites.	Extracted from (Le, 2016)
NPP-GAP	Gap between actual and potential Net Primary Production (NPP) (unit: % of potential NPP)	Extended concept of crop yield gap to biomass yield gap. Lower value indicates higher potential for intensification.	Krausmann et al. (2013), Haberl et al. (2002)
HANPP	Human appropriation of natural NPP (unit: % of natural NPP)	Human pressure on land resources. Very high value, e.g. > 70%, indicates not much remaining fraction of natural biomass for ensure regulating/protecting ecosystem services	Krausmann et al. (2013), Haberl et al. (2002)

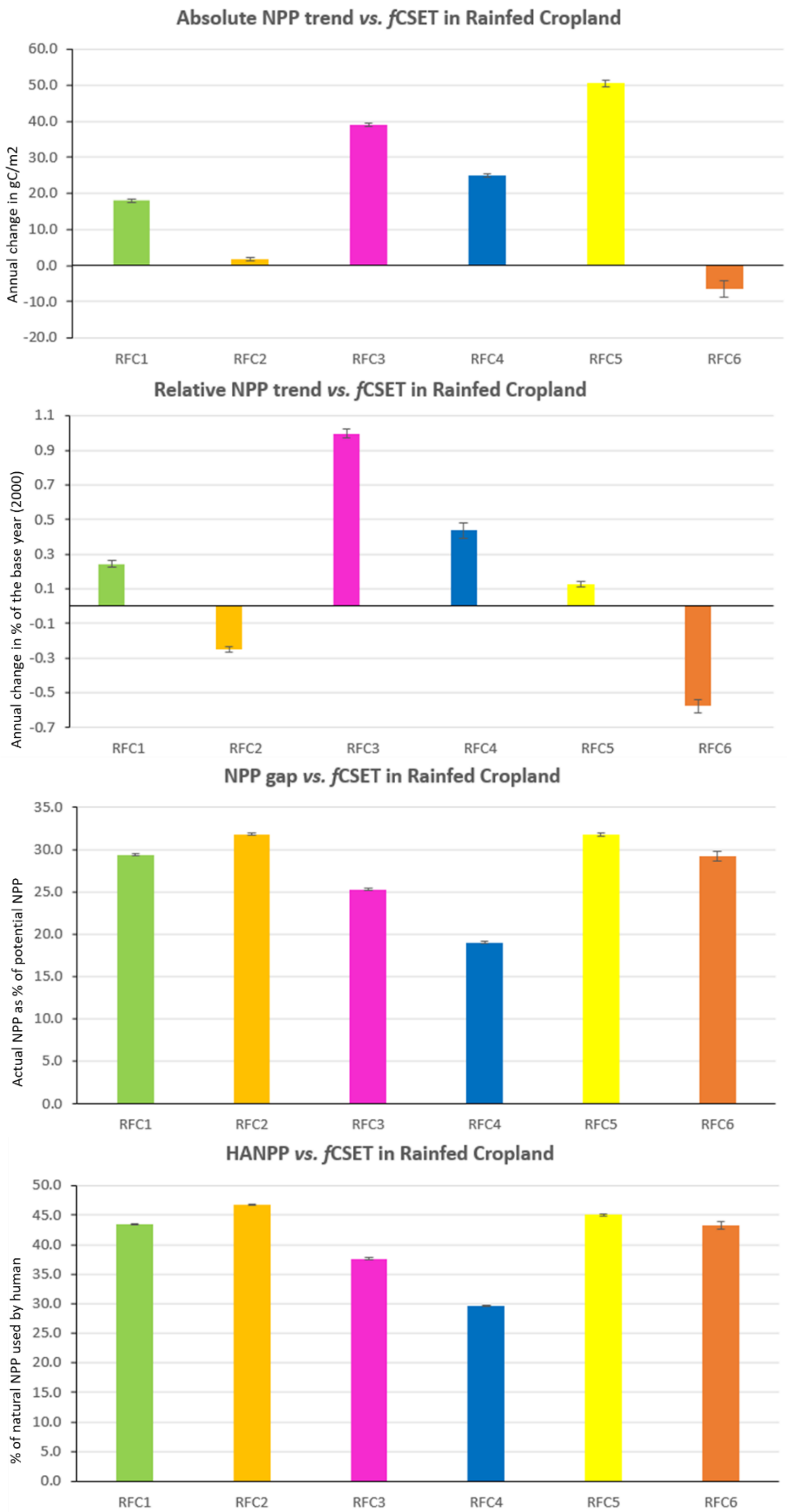

Figure 1S. NPP trend (absolute and relative), NPP gap and HANPP versus fCSET in Ethiopian-Kenyan rain-fed cropland. Source: (Le and Rischkowsky, in prep)

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