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Executive Summary

Unmanned aerial vehicles (UAV) are evolving as an alternative tool to acquire land tenure data. UAVs can capture geospatial data at high quality and resolution in a cost-effective, transparent and flexible manner, from which visible land parcel boundaries, i.e., cadastral boundaries are delineable. Even though physical objects recognizable with image analysis methods make up a large portion of cadastral boundaries, their delineation is not fully automatable.

WP5 contributes to advancements in developing an efficient methodology for the delineation of cadastral boundaries visible in imagery collected by UAVs. Designed for areas, in which object outlines are clearly visible and coincide with cadastral boundaries, the methodology partly automates and facilitates the delineation of visible cadastral boundaries as follows: it combines image analysis methods with machine learning, and interactive delineation. In detail, the workflow consists of Multiscale Combinatorial Grouping (MCG), Random Forest Classification (RF), and a BoundaryDelineation QGIS plugin.

In D5.1, we proposed a workflow consisting of image segmentation, line extraction and contour generation. In D5.2, we now describe an improved version in which the steps of image segmentation and line extraction have been combined, the features used during classification have been optimized, and the interactive delineation has been redesigned to be more intuitive. To facilitate the subsequent integration in the its4land Publish & Share platform, the entire workflow has – in close collaboration with WP6 – undergone a stringent refactoring and restructuring which also lead to more stability and efficient applicability.

In D5.2, we describe the improved version of the WP5 tool and introduce a use case, in which we combine the delineation of land tenure with sketchmaps from WP3: the sketchmaps developed during past WP3 fieldwork are used to attribute the boundaries derived from WP5. This combined interpretation of the current land tenure situation provides georeferenced accurate boundaries labelled with non-spatial information. We thereby demonstrate an innovative fit-for-purpose approach that allows a comprehensive documentation of currently unrecorded land rights capturing spatial and non-spatial information on land tenure in one process.

Contents

1. Introduction

its4land is a European Commission Horizon 2020 project funded under its Industrial Leadership program, specifically the 'Leadership in enabling and industrial technologies – Information and Communication Technologies ICT (H2020-EU.2.1.1.)', under the call H2020-ICT-2015 – and the specific topic – 'International partnership building in low and middle income countries' ICT-39-2015.

Its4land aims to deliver an innovative suite of land tenure recording tools that respond to sub Saharan Africa's immense challenge to rapidly and cheaply map millions of unrecognized land rights in the region. ICT innovation is intended to play a key role. Many existing ICT-based approaches to land tenure recording in the region have failed: disputes abound, investment is impeded, and the community's poorest lose out. its4land seeks to reinforce strategic collaboration between the EU and East Africa via a scalable and transferrable ICT solution. Established local, national, and international partnerships seek to drive the project results beyond R&D into the commercial realm. its4land combines an innovation process with emerging geospatial technologies, including smart sketchmaps, UAVs, automated feature extraction, and geocloud services, to deliver land recording services that are end-user responsive, market driven, and fit-for-purpose. The transdisciplinary work also develops supportive models for governance, capacity development, and business capitalization. Gender sensitive analysis and design is also incorporated. Set in the East African development hotbeds of Rwanda, Kenya, and Ethiopia, its4land falls within TRL 5-7: 3 major phases host 8 work packages that enable contextualization, design, and eventual land sector transformation. In line with Living Labs thinking, localized pilots and demonstrations are embedded in the design process. The experienced consortium is multi-sectorial, multi-national, and multidisciplinary. It includes SMEs and researchers from 3 EU countries and 3 East African countries: the necessary complementary skills and expertise is delivered. Responses to the range of barriers are prepared: strong networks across East Africa are key in mitigation. The tailored project management plan ensures clear milestones and deliverables, and supports result dissemination and exploitation: specific work packages and roles focus on the latter.

The following introduction contextualizes automatic feature extraction from high resolution UAV data. Sections 1.1 to 1.4 provide general context information relevant for WP5 and are identical to those in D5.1. The focus of D5.2 is outlined in section 1.5.

1.1. Application of Unmanned Aerial Vehicles

Unmanned Aerial Vehicles (UAVs) have emerged as rapid, efficient, low-cost and flexible acquisition systems for remote sensing data [1]. The data acquired can be of high-resolution and accuracy, ranging from a sub-meter level to a few centimes [2,3]. A photogrammetric UAV workflow includes flight planning, image acquisition, image orientation and data processing. The results include Digital Terrain Models (DTMs), Digital Surface Models (DSMs), orthoimages and point clouds [4]. UAVs are described as capable sourcing tools for remote sensing data, since they allow flexible maneuvers, capture of high-resolution imagery, flights under clouds, easy launch and landing and fast data acquisition at low cost. Disadvantages include payload limitations, uncertain or restricting airspace regulations, battery induced short flight duration, and time consuming processing of large volumes of data gathered [5,6]. In addition, multiple factors that influence the accuracy of derived products require extensive consideration. They include the quality of the camera, the camera calibration, the number and location of ground control points and the choice of processing software [7]. UAVs have been employed in a variety of applications such as the documentation of archaeological sites and cultural heritage [8,9], vegetation monitoring in favor of precision agriculture [10,11], traffic monitoring [12], disaster management [13,14] and 3D reconstruction [15].

Another emerging application field for UAV-based surveys is cadastral mapping. Cadastral maps are spatial representations of cadastre surveys, showing the extent, value and ownership of land [16]. Cadastral maps are intended to provide a positional description and identification of land parcels, which are crucial for a continuous and sustainable recording of land rights [17]. Furthermore, cadastral maps support land and property taxation, allow the development and monitoring of a land markets, support urban planning and infrastructure development and allow the production of statistical data. An extensive review on concepts and purposes of cadasters in relation to land administration is provided in [18,19]. UAVs are proposed as a new tool for fast and cheap spatial data acquisition and production enabling the production of cadastral maps. UAVs facilitate land administration processes and contribute to securing land tenure rights and provide a new approach to the establishment and updating of cadastral maps [20]. This contributes to new concepts in land administrations such as fit-for-purpose [21], pro-poor [22] and responsible land administration [23].

1.2. Application of UAV-based Cadastral Mapping

In the context of contemporary cadastral mapping, UAVs are increasingly emerging as tools to generate accurate and georeferenced high-resolution imagery. From these image data, cadastral boundaries can be visually detected and digitized [24-26]. In order to support digitization, existing parcel boundaries can be automatically superimposed, which could facilitate and accelerate cadastral mapping [27]. With the exception of [1,28], cadastral mapping is not mentioned in review papers as one of the application fields of UAVs [29-31]. This might be due to the small number of case studies in this field, the often highly prescribed legal regulations relating to cadastral surveys, and the novelty of UAV in mapping generally. Nevertheless, all existing case studies underline the high potential of UAVs for cadastral mapping – in both urban and rural contexts for developing and developed countries.

In developing countries, cadastral mapping contributes to the creation of formal systems for registering and safeguarding land rights. According to the World Bank and the International Federation of Surveyors (FIG), 75% of the world’s population do not have access to such systems. Further, they state that 90 countries lack land registration systems, while 50 countries are in the process of establishing such systems [21]. In these countries, cadastral mapping is often based on ground survey methods or on partly outdated or unrectified aerial or satellite imagery of low-resolution, which can include areas covered by clouds. Numerous studies have investigated cadastral mapping based on orthoimages derived from satellite imagery [23,32-38] or aerial photography [39]. The definition of boundary lines is often conducted in a collaborative process among members of the communities, governments and aid organizations, which is referred to as 'Community Mapping' [40], 'Participatory Mapping' [23] or 'Participatory GIS' [32]. Outdated satellite imagery of low-resolution can be substituted for up-to-date high-resolution orthoimages derived from UAVs as is shown in case studies in Namibia [25] and Rwanda [24]. The latter case shows the utility of UAVs to partially update existing cadastral maps.

In developed countries, the case studies focus on the conformity of the UAV data's accuracy with local accuracy standards and requirements [41,42]. Furthermore, the case studies tend to investigate possibilities of applying UAVs to reshape the cadastral production line efficiency and effectiveness [7,43,44]. When applying UAVs, manual boundary detection with all stakeholders is conducted in an office, eliminating the need for convening all stakeholders on the parcel. In developed countries, UAV data are frequently used to update small portions of existing cadastral maps rather than creating new ones. Airspace regulations are the most limiting factor that hinder the thorough use of UAVs. Currently, regulatory bodies face the alignment of economic, information and safety needs or demands connected to UAVs [31,45]. Once these limitations are better aligned with societal needs, UAVs might be employed for land administration, as well as for further purposes such as the monitoring of public infrastructure like oil and gas pipelines, power lines, dikes, highways, and railways [46]. Nowadays, some national mapping agencies in Europe integrate, but mainly investigate, the use of UAVs for cadastral mapping [45].

Overall, UAVs can be employed to support land administration both in creating and updating cadastral maps. The entirety of case studies confirms that UAVs are suitable as an addition to conventional data acquisition methods in order to create detailed cadastral maps including overview images or 3D models [41,42,47]. The average geometrical precision is shown to be the same, or better, compared to conventional terrestrial surveying methods [7]. UAVs will not substitute conventional approaches, since they are currently not suited to map large areas such as entire countries [48]. The use of UAVs supports the economic feasibility of land administration and contributes to the accuracy and completeness of cadastral maps.

1.3. Boundary Delineation for UAV-based Cadastral Mapping

In published case studies, cadastral boundaries are manually detected and digitized from orthoimages. This is realized either in an office with a small group of stakeholders – for one parcel or in a community mapping approach for several parcels at once. None of the case studies applies an automatic approach to extract boundary features from the UAV data. An automatic or semi-automatic feature extraction process would facilitate cadastral mapping: manual feature extraction is generally regarded as time-consuming, wherefore an automation will bring substantial benefits [4].

Jazayeri et al. (2014) state that UAV data are an accurate and low-cost approach for automated object reconstruction and boundary extraction. This is especially true for visible boundaries, physically manifested by objects such as hedges, stone walls, large scale monuments, walkways, ditches or fences, which often coincide with cadastral boundaries [50,51]. Such visible boundaries bear the potential to be automatically extracted from UAV data. However, to the best of the authors' knowledge, no research has been done on expediting cadastral mapping through automatic boundary delineation from UAV data.

1.4. Cadastral Boundary Characteristics

Different approaches exist to categorize concepts of cadastral boundaries. The boxes around different categories visualized in Figure 1 can be understood as fuzzy. From a technical point of view, cadastral boundaries can be divided into two categories: (i) fixed boundaries, whose accurate spatial position has been recorded and agreed upon and (ii) general boundaries, whose precise spatial position is left undetermined [52]. Both require surveying and documentation in cadastral mapping.

Cadastral surveying consists of (i) direct techniques, in which the accurate spatial position of a boundary is measured and fixed on the ground using theodolite, total stations and Global Navigation Satellite System (GNSS); and (ii) indirect techniques, in which remotely sensed data such as aerial or satellite imagery are applied with minimal ground verification. The spatial position of boundaries is derived from these data in a second step [33]. Fixed boundaries are commonly measured with direct techniques, which provide the required higher accuracy. Indirect techniques, including UAVs, are able to determine fixed boundaries only when based on data of sufficiently high resolution. Indirect techniques are mostly applied to extract visible boundaries through image interpretation and boundary tracing. These boundaries are represented by physical objects, which coincide with the concept of general boundaries [50,51].

In Kenya for example, the general boundaries were originally derived from ground survey methods of chain, campus and plane table. These boundaries were instantly drawn onto a sheet of paper attached to the plane table. This method was later found to be too slow for the vast area to be covered and the government reverted to the use of aerial photos. Initially, these photos were ortho-rectified to take care of tilt and relief distortions. These surveys were carried out in the Central Region of Kenya at the time of the Mau Mau wars in order to check the quality of the Plane Table surveys.

The ortho-rectifications were carried out in London as the technology was not yet available in Kenya. This process was later abandoned as it was too slow and expensive for the African local communities who were eagerly waiting for first registration. The government thereafter used simple tracings from the photos to produce temporary and interim maps called the Preliminary Index Diagrams (PIDs) for the first registration [53]. These PIDs are still being used for registration of land adjudicated areas to the present day.

This report concentrates on methods delineating general, i.e., visible cadastral boundaries from high-resolution data applying indirect surveying techniques. The methods are used to automatically extract boundary features from UAV data.

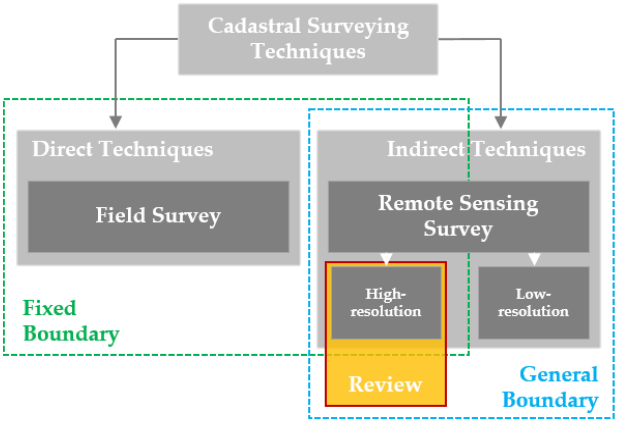

Figure 1. Overview of cadastral surveying techniques and cadastral boundary concepts that contextualize the scope of this research. The lines between different categories are fuzzy and should not be understood exclusively. They are drawn to give a general overview.

In order to understand, which visible boundaries define the extents of land and to identify common boundary characteristics, literature on 2D cadastral mapping – based on indirect techniques – was reviewed. Man-made objects are found to define cadastral boundaries as well as natural objects. Studies name buildings, hedges, fences, walls, roads, footpaths, pavement, open areas, crop type, shrubs, rivers, canals and water drainages as cadastral boundary features [7,25,32,33,35,54-56]. Trees are named as the most limiting factor since they often obscure the view of the actual boundary [42,57].

No study summarizes characteristics of detected cadastral boundaries, even though it is described as crucial for feature recognition to establish a model describing the general characteristics of the feature of interest [58]. Common in many approaches is the linearity of extracted features. This may be due to the fact that some countries do not accept curved cadastral boundaries [34]. Even if a curved river marks the cadastral boundary, the boundary line is approximated by a polygon [33].

When considering named features, the following characteristics can be observed: most features have a continuous and regular geometry expressed in long straight lines of a limited curvature. Furthermore, features often share common spectral properties, such as similar values in color and texture. Moreover, boundary features are topologically connected and form a network of lines that surround land parcels of a certain (minimal) size and shape. Finally, boundaries can be indicated by a special distribution of other objects such as trees. In summary, general boundary features are detectable based on their geometry, spectral property, topology, and context.

This report focusses on methods that extract linear boundary features, since cadastral boundaries are commonly represented by straight lines with exceptions outlined in [59,60]. Cadastral representations in 3D as described in [61] are excluded.

UAVs cannot detect all cadastral boundaries. Only visible boundaries that are detectable with an optical sensor can be extracted using UAVs. This approach does not consider socially perceived boundaries not marked by a physical object.

Figure 2 provides an overview of visible boundary characteristics mentioned above and commonly raised issues in terms of their detection. The cadastral boundaries are derived based on (a) roads, power lines and pipelines [48]; (b) fences and hedges [25]; (c), (d) crop types [42]; (f) roads, foot paths, water drainage, open areas and scrubs [62] and (e) adjacent vegetation [57]. Figure 2 (d) shows the case of a nonlinear irregular boundary shape. The cadastral boundaries in (e) and (f) are often obscured by tree canopy. Cadastral boundaries in (a), (b), (c) and (d) are derived from UAV data; in (e) and (f) from HRSI. All of the boundaries are manually extracted and digitized.

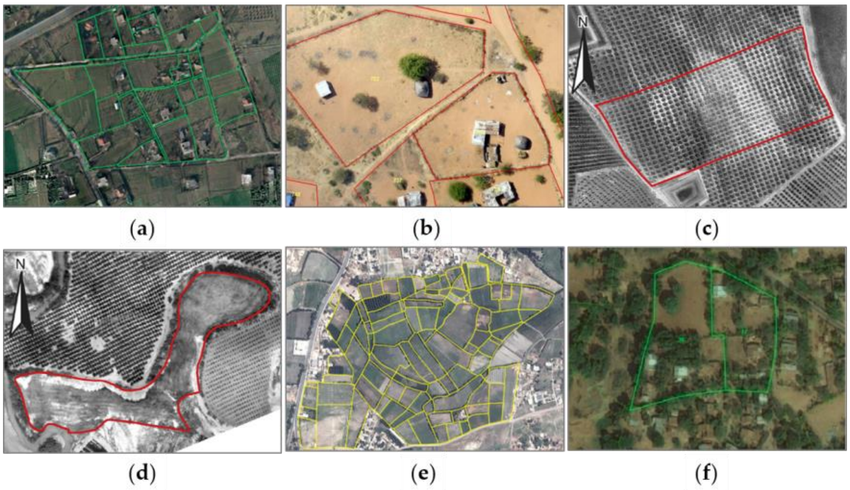

Figure 2. Characteristics of cadastral boundaries extracted from high-resolution optical remote sensors.

1.5. Report Objective and Structure

While bearing potential to make cadastral mapping more reproducible, transparent, automated, scalable and cost-effective, the literature review shows that automating UAV-based cadastral mapping is little investigated. Addressing this research gap is the aim of WP5 in the its4land project. This is done by designing and implementing a methodology for an automated delineation of visible cadastral boundaries from UAV data. This report describes the current functioning of such a methodology and provides implementation details.

We demonstrate the tool for a specific its4land use case scenario: the delineation of pastoralists' land tenure. This is done by applying the tool to delineate visible boundaries in UAV imagery of a rural Kenyan area. In addition, we combine WP5 with Sketchmaps from WP3: the sketchmaps developed during past WP3 fieldwork are used to attribute visible boundaries derived from WP5. WP3 sketchmaps requires a geo-references base map to which sketched spatial features can be aligned. WP5 simplifies the delineation of visible features from remote sensing data, which can be used in the base map for WP3. The qualitative alignment method in WP3 enables users to classify the extracted features in both the base map and the sketched map: the user can add non-spatial information to the extracted features. We thereby demonstrate an innovative fit-for-purpose approach that allows a comprehensive documentation of currently unrecorded land rights capturing spatial and non-spatial information on land tenure.

2. Materials and Methods

2.1. Study Area and UAV Data

As a study area, we selected the rural area of the Mailua group ranch in Kajiado County, Kenya (Figure 3). The area is governed by a local pastoralist Masaii community with collectively registered land rights. The local pastoralists live jointly in homesteads around which they undertake pastoralist activities. Neither the homesteads, nor the pastoralist activities are currently spatially documented in a formal land administration system. Challenges arise due to increasing subdivision processes without adequate survey control.

UAV data were captured with indirect georeferencing, i.e., Ground Control Points (GCPs) were distributed in the field and measured with a Global Navigation Satellite System (GNSS). The orthoimage captures an extent of 2500 x 1500 m and has a Ground Sample Distance (GSD) of 0.06 m. It was captured with a fixed-wing UAV through WP4. The orthoimages were generated with Pix4DMapper software.

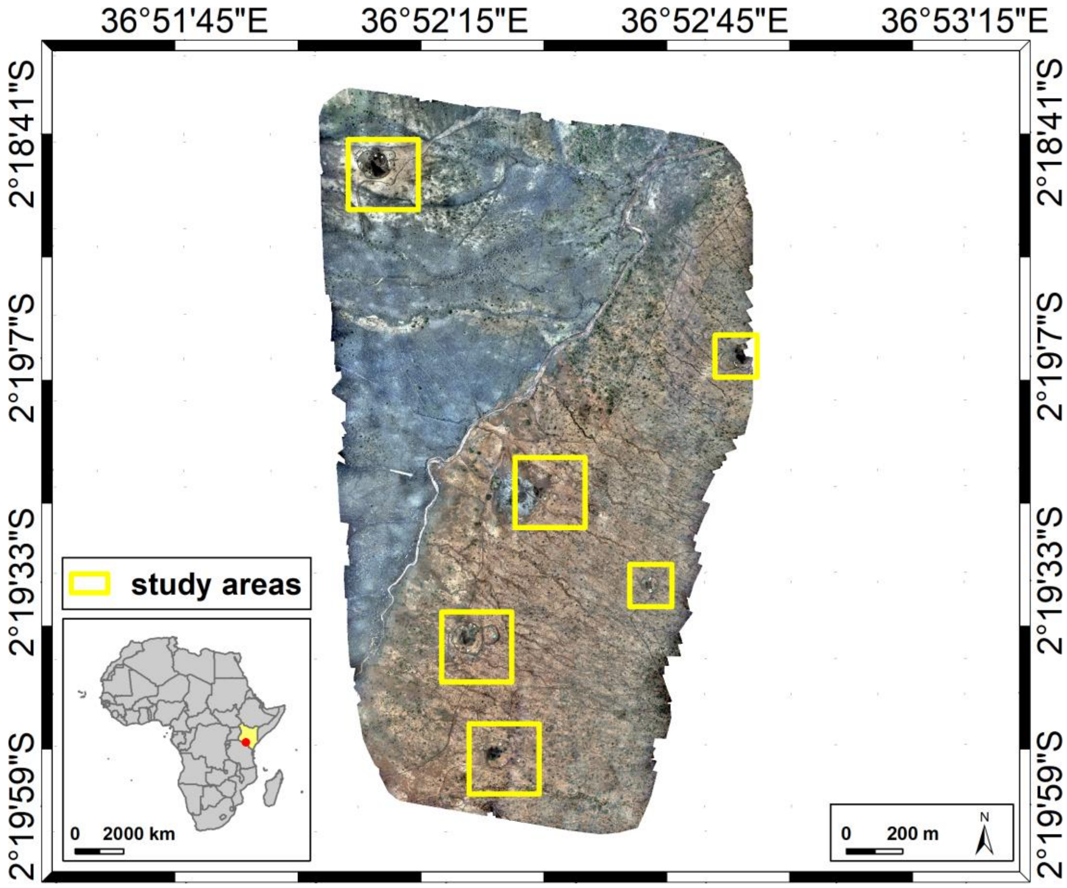

Figure 3. UAV data of Mailua, Kenya covering a rural side of approximately 2500 x 1500 m with a Ground Sample Distance (GSD) of 0.06 m. The tiles of 250 x 250 m and 150 x 150 m mark the study areas in which a local homestead is located.

2.2. Boundary Delineation

The applied boundary delineation approach supports the delineation of boundaries by automatically retrieving information from RGB data to guide an interactive delineation [63]. It consists of three parts (Figure 4): (i) **image segmentation**, (ii) **boundary classification** and (iii) **interactive delineation**. The source code is publically available [64].

(i) **Image segmentation** delivers closed contours capturing the outlines of visible objects in the image. The workflow described in [63] proposes to use Globalized Probability of Boundary contour detection (gPb) [65] and Simple Linear Iterative Clustering superpixels (SLIC) [66]. We now propose to use an extended version of gPb developed by the same authors: Multiresolution Combinatorial Grouping (MCG) [67]. This allows combining the previous steps into one method while increasing spatial accuracy compared to using gPb and decreasing over-segmentation compared to using SLIC.

(ii) **Boundary classification** requires labeling the outline contours from the image segmentation in step (i) into 'boundary' and 'not boundary' to generate training data. A set of features is calculated per line capturing its geometry (i.e., length, number of vertices, azimuth, sinuosity) and its spatial context (i.e., gradients of RGB and DSM underlying the line). A description of each feature can be found in Table 1. These features together with the labels are used to train a Random Forest (RF) classifier [68]. The trained classifier predicts boundary likelihoods for unseen testing data for which the same features have been calculated. An open-source RF implementation [69] is used.

(iii) **Interactive delineation** allows a user to start the actual delineation process: the RGB orthomosaic is displayed to the user, who is asked to create parcels based on the automatically generated boundary features: e.g., a least-cost-path algorithm searches for the lines from (i) that connect the user-selected nodes taking into account the boundary likelihood from (ii). We implemented (iii) as publically available plugin [70] for the open-source geographic information system QGIS [71].

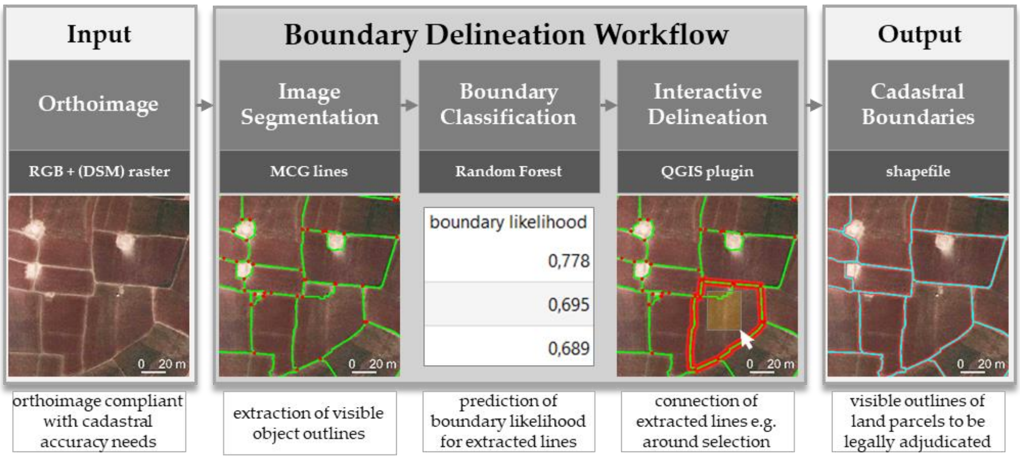

Figure 4. Boundary delineation approach consisting of image segmentation, boundary classification and interactive delineation.

Table 1. Features calculated per line to be used by the Random Forest (RF) classifier for boundary classification. The first two features are not used for the classification.

Name	Description
ID	Unique number per line
boundary	Boundary label or likelihood in range [0; 1]
vertices	Number of vertices per line
length [m]	Length per line
azimuth [°]	Bearing in degrees between start and end of each line
sinuosity	Total line length divided by the shortest distance between start and end of each line
red_grad	Abs. difference between median of all red values lying within a 0.4 m buffer right and left of each line
green_grad	Same as red_grad for green of RGB
blue_grad	Same as red_grad for blue of RGB
dsm_grad	Same as red_grad for DSM

2.3. Sketchmap Workflow

The SmartSkeMa system is a community based mapping system using sketch maps as input. It is developed to support a bottom-up approach in land tenure, land rights, and land resource mapping using freehand maps. The following description of its workflow is taken from D3.5. A video that illustrates how SmartSkeMa works can be found at www.smartSkeMa.eu. SmartSkeMa processes spatial and non-spatial information from sketch maps, annotates the sketched features with semantic concepts from the local domain model, and aligns or integrates this information with spatial information in the existing base map (Figure 5).

Input: SmartSkeMa relies on input data from three sources: First and as base data it uses cartographic information from base maps which may be complemented with data acquired from UAV images, processed in work package 4 and 5 of the its4land project (Figure 5 left side). The second and major source of input is the sketch maps drawn by local communities. The spatial information in sketch maps is further processed in the object detection component (D3.2) of SmartSkeMa. For processing the non-spatial information associated with the sketch map, SmartSkeMa uses information registered in the local domain model (LDM) (D3.1) as the third source of input.

Step D3.1 When members of local communities draw a feature, they also annotate relationships of this feature to other non-spatial concepts. The LDM specifies concepts and relationships in a common ontological perspective in order to allow different sketches to be compared and automatically interpreted with a uniform conceptual language. LDMs are developed beforehand: LDM consist of a generic part and can be extended with concepts specific to the area of interest. The concepts and relationships specified in the LDM are used to annotate a sketch map in step D3.1.

Step D3.2 The object recognition component extracts the boundaries of objects in the sketch map, stores the classification into categories (i.e. tree, dwelling, house, etc.) using the LDM and generates a vector representation of the sketch map.

Step D3.3 The qualitative representation component takes this vector representation and calculates the qualitative relations among the drawn objects. Given that sketch maps are drawn based on observations and memories, but not based on measurements, we can interpret the geo-locations only qualitatively.

Step D3.5 The sketch-to-geo component compares sketch maps with base maps: If both maps contain the same features, they are aligned, and non-spatial information is transferred from the sketch to the base map. If the sketch map contains additional information, this information is integrated into the base map using the calculated qualitative relations to previously aligned features. For the geo-localization of sketched objects, we need enough common spatial objects in both input maps and need to ensure mutually consistent qualitative constraints across both input maps.

Step D3.4 and **D3.6** The alignment of spatial objects allows us to integrate annotated non-spatial information in the official database. The developed adapter model and extension of LADM facilitates the transfer of the local knowledge of situation on the ground to the land administration system (LAS).

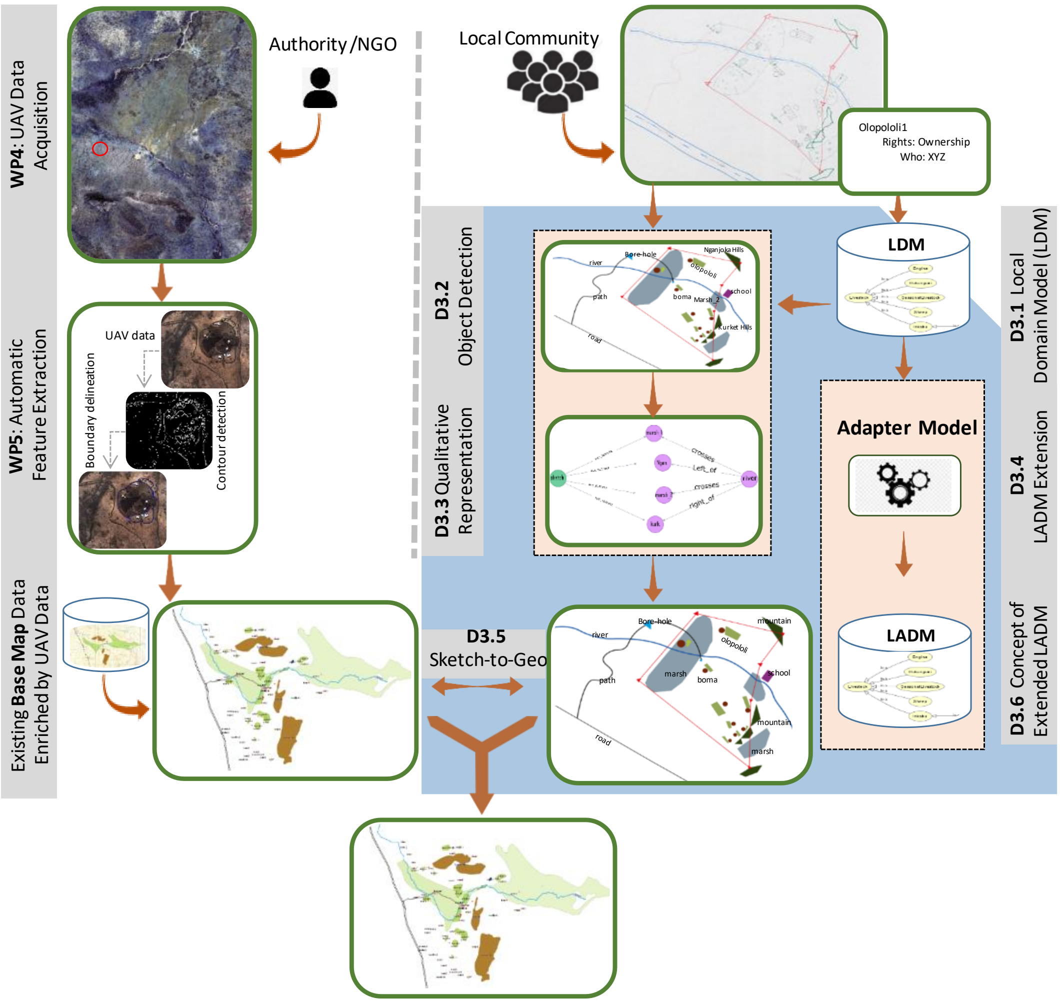

Figure 5: Workflow of SmartSkeMa within the its4land system: Right side: local communities provide spatial and non-spatial information via sketch maps. Non-spatial information is processed via LDM (D3.1) and connected via the adapter model to a Land Administration Domain Model (LADM) (D3.4 and D3.6). Spatial information is recognized via the object detection (D3.2) and captured qualitatively via the qualitative representations (D3.3). Left side: Authorities or NGOs provide base data – either in the form of a map or as aerial images. WP4 and WP5 process UAV images such that relevant features are automatically extracted. This data is used to match with the sketched data in D3.5.

3. Results

Applying the methods described above in our study area in Kenya, we first summarize the findings of WP2 on the needs assessment for WP3 and WP5 for Kenya. Thereafter, we apply the WP5 tool to delineate visible boundaries in UAV imagery of our rural Kenyan study area to derive pastoralists' land tenure boundaries. Then, the sketchmaps developed during past WP3 fieldwork are used to attribute these visible boundaries.

3.1. Needs assessment

For Kenya, WP2 analysed the applicability of the boundary delineation approach, referred to as automated feature extraction and sketchmaps as follows: "The applicability of the technology of the automated feature extraction (AFE) tool was mostly perceived to lie with meeting cadastral data needs, while smart sketchmaps were mainly perceived to have the potential to meet non-cadastral data needs. The differences in perceptions around these technologies are outlined in Table 2. The automated feature extraction tool was often difficult for stakeholders to grasp. Similar to their perspective on UAVs, some stakeholders also felt that the AFE tool could support data analysis functions like data integration. Again, this is not immediately possible, but the discussion around this item indicates that stakeholders felt that AFE would facilitate the production of data that was suited to data integration."

Table 2. Perceived potential of automated feature extraction and Sketchmaps to meet Kenyan land information needs observed in D2.5.

	Sketchmaps	**Automated Feature Extraction**
Cadastral data needs	▪ Location and extent of tenure type according to administrative boundaries ▪ Identification and documentation of public land ▪ Accurate and up-to-date spatial and non-spatial parcel information ▪ Community land and associated land and grazing rights	▪ Georeferenced parcel information ▪ Identification and documentation of public land ▪ Accurate and up-to-date spatial and non-spatial parcel information ▪ Community land and associated land and grazing rights ▪ Urban and rural boundaries
Non-cadastral data needs	▪ Develop/update spatial development plans ▪ Resource mapping and documentation ▪ Historical land injustices ▪ Rural boundaries	▪ Accurate and up-to-date information about infrastructure ▪ Resource mapping and documentation
Data analysis		▪ Providing georeferenced data for data analysis
Stakeholder engagement	▪ Community involvement in data collection	
Land transactions		▪ Alternative dispute resolution process

3.2. Boundary Delineation

The Boundary Delineation workflow was applied on each of the study areas identified before. Each of the workflow steps is visualized in Figure 6. Two of the five study areas where used to train the Random Forest classifier that then predicted boundary likelihoods for the lines used during the interactive delineation. Since the UAV data did not contain DSM information, corresponding features where not used during the boundary classification. A comprehensive evaluation of the approach on further datasets can be found here [72].

Input UAV Imagery	**Image Segmentation**	**Boundary Classification**	**Interactive Delineation** initial	**Interactive Delineation** result

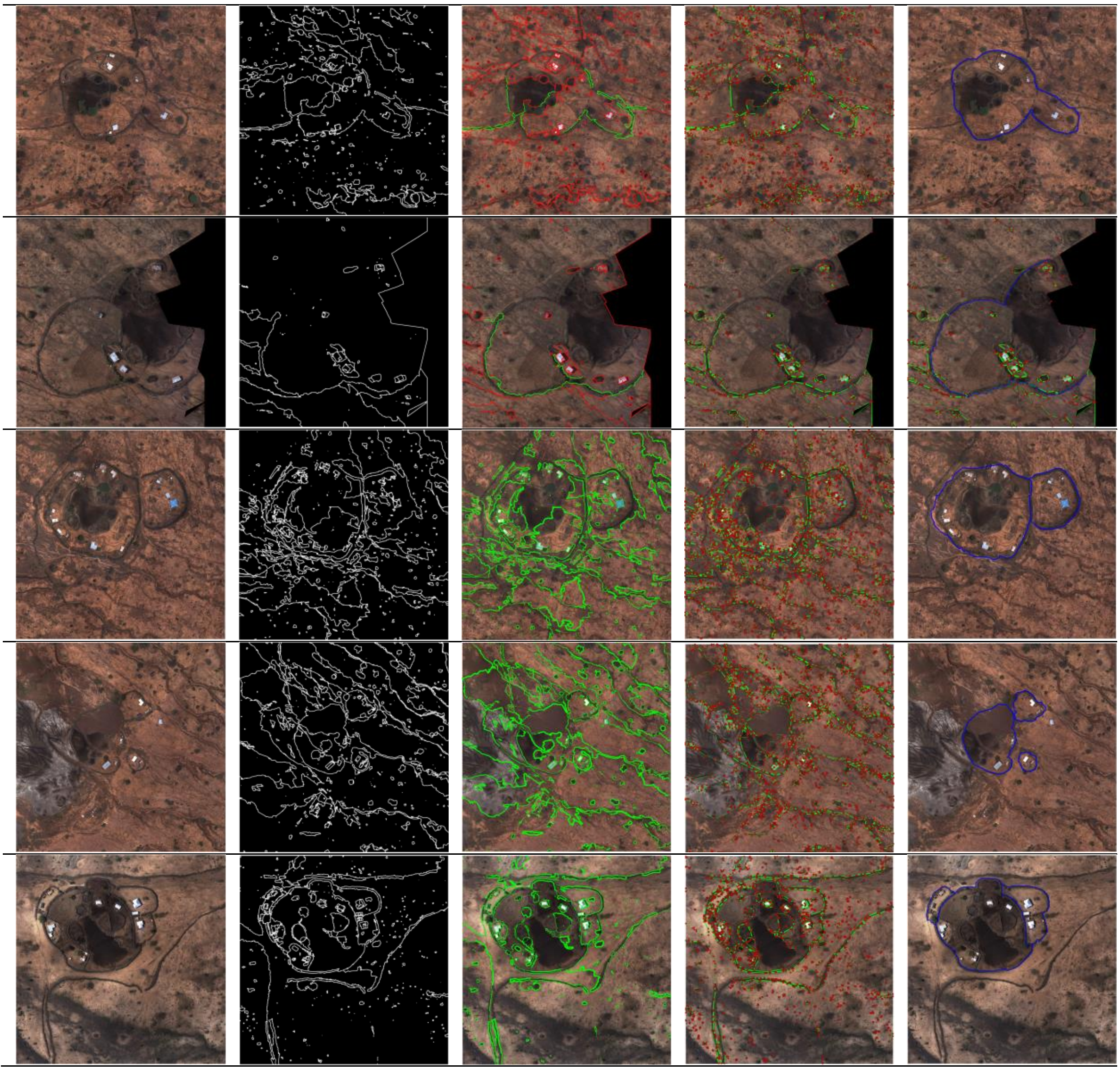

Figure 6. Boundary delineation results: image segmentation, boundary classification and interactive delineation applied to delineate visible boundaries of pastoralists' homesteads from UAV data.

3.3. Sketchmaps

For the alignment of spatial features in sketch maps, SmartSkeMa requires the existence of corresponding features in the base map. Due to a lack of survey data, certain feature may not be available in the base map, e.g., when the base map does not contain newly built bomas or oligopolies. In such cases, WP5s Boundary Delineation tool comes in to play: it enables a user to populate the base map by extracting boundaries of missing features from UAV images. This spatial information extracted from UAV images allows local users to populate existing geo-referenced maps. Afterward, the qualitative alignment method in the SmartSkeMa (D3.5) enables users to classify the extracted geometries based on the alignment of features in both input maps: SmartSkeMa aligns features from sketch maps with automatically extracted features in the base map and the user can add non-spatial information to the extracted features.

Figure 7 visualizes this concept: spatial information is extracted from UAV images using the boundary delineation tool and non-spatial information is assigned to the feature using the SmartSkeMa tool: community members from the study location in Mailua, Kajiado have jointly drawn sketch maps of natural features, the community land's boundary, bomas, olopololis and documented the associated land tenure attributes. The tool operator (mapping officer from a local authority or NGO) wants to update the base map with the boundaries and geometries of bomas and olipololis currently not captured in the base map. The user's action in SmartSkeMa can be stated as follows:

"Extract and geolocalize the geometries of ***sketched features*** *from the sketch map, annotate them with* ***land rights*** *attributes."*

As described in the workflow (Figure 5), SmartSkeMa extracts geometries in the sketch map (D3.2) and allows the user to assign non-spatial attributes to them (D3.1). These steps are illustrated in Figure 7 on the right side and bottom row. Independently, boma and olopololi outlines are extracted with the boundary delineation tool (WP5) and added to the base map (Figure 7 left).

After the first step SmartSkeMa has extracted 38 sketched objects corresponding to:

- 7 natural features: 2 marshy regions, 5 mountains, and a river
- 23 man-made features: 2 pathways (the small path and the main road), 2 boreholes, 9 bomas, 9 olopololis, and a school
- 7 boundary features: 6 boundary beacons and the boundary itself
- 1 periodic event feature: the elephant corridor shown in the map

These feature types are inferred from the symbols attached to the hand drawn objects in the input sketch map. The user has the option to update or edit the geometries of the digitized sketch map objects and their inferred types. SmartSkeMa computes the qualitative relations between all the features establishing facts, e.g. that two bomas and two olopololi's are on the same side of the river as one of the mountains. The user can quickly check by hovering over the feature in the map that this mountain is called *Nganjoka*. SmartSkeMa uses these facts to decide which sketch map feature corresponds to which base map feature (alignment).

Once the alignment is done, the user can add more information about the features such as rights, restrictions, and responsibilities (RRR) associated with them: for example, the communities list of rights indicate that the boma with id **boma_1** has the right "*usage*" for the family named **James family**. SmartSkeMa suggests based on distance that **olopololi_2** should have the right "*usage*" and the responsibility "*maintenance*" for the same individual. All classes of RRR are retrieved from the domain model and therefore only the RRRs specified in the domain model can be used.

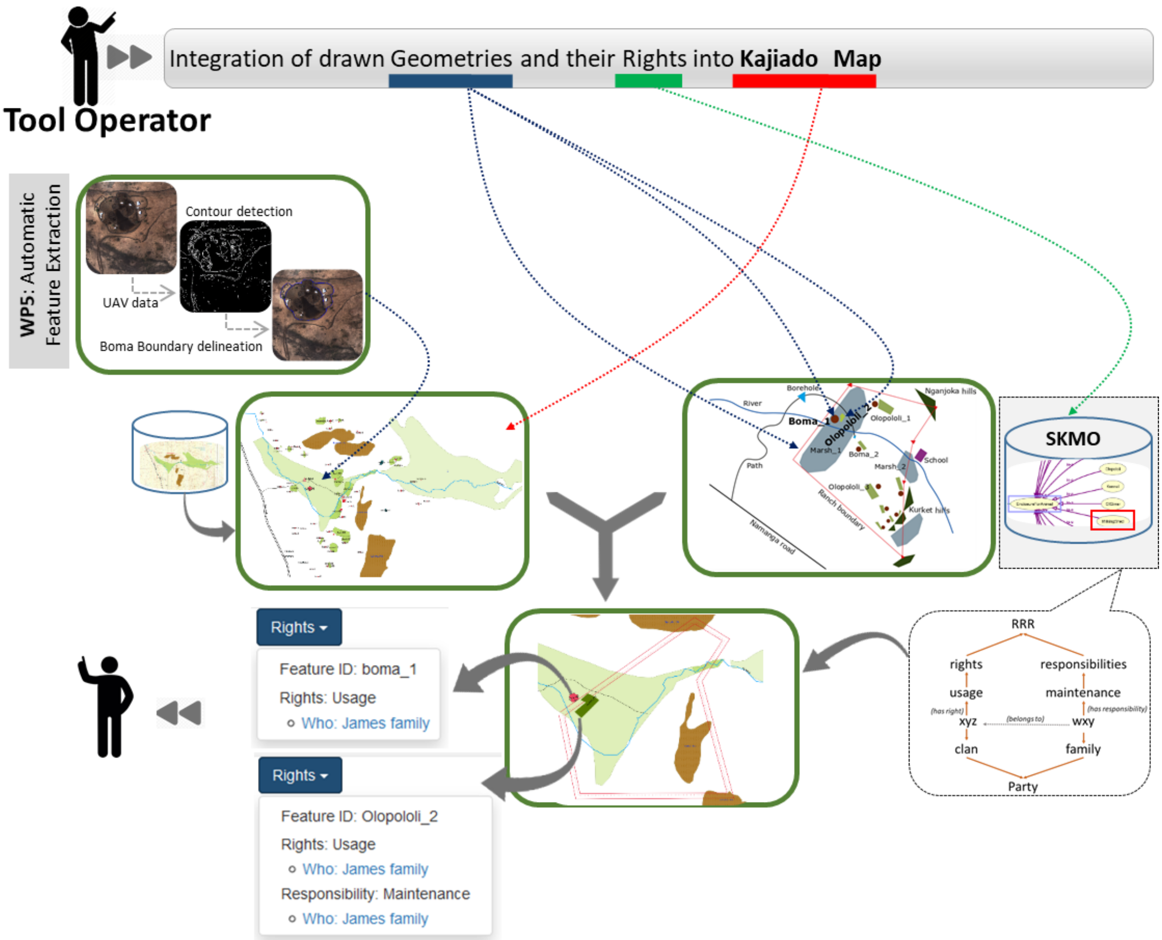

Figure 7: The local authority or an NGO updates their map with information from a sketch map drawn by the community. Sketch map identifies bomas, olopololis, boreholes, as well as the ranch boundary.

Information from the sketchmaps is linked to the delineated visible boundaries based on the sketch map alignment procedure described in D3.5: the alignment is achieved by applying graph matching methods. A mapping dictionary with unique IDs is created that allows linking sketch map information to a basemap. In the sketch map process a user can assign rights to a sketched feature based on information retrieved through annotations during the map creation process. This allows integrating sketched information into metric maps (Figure 8).

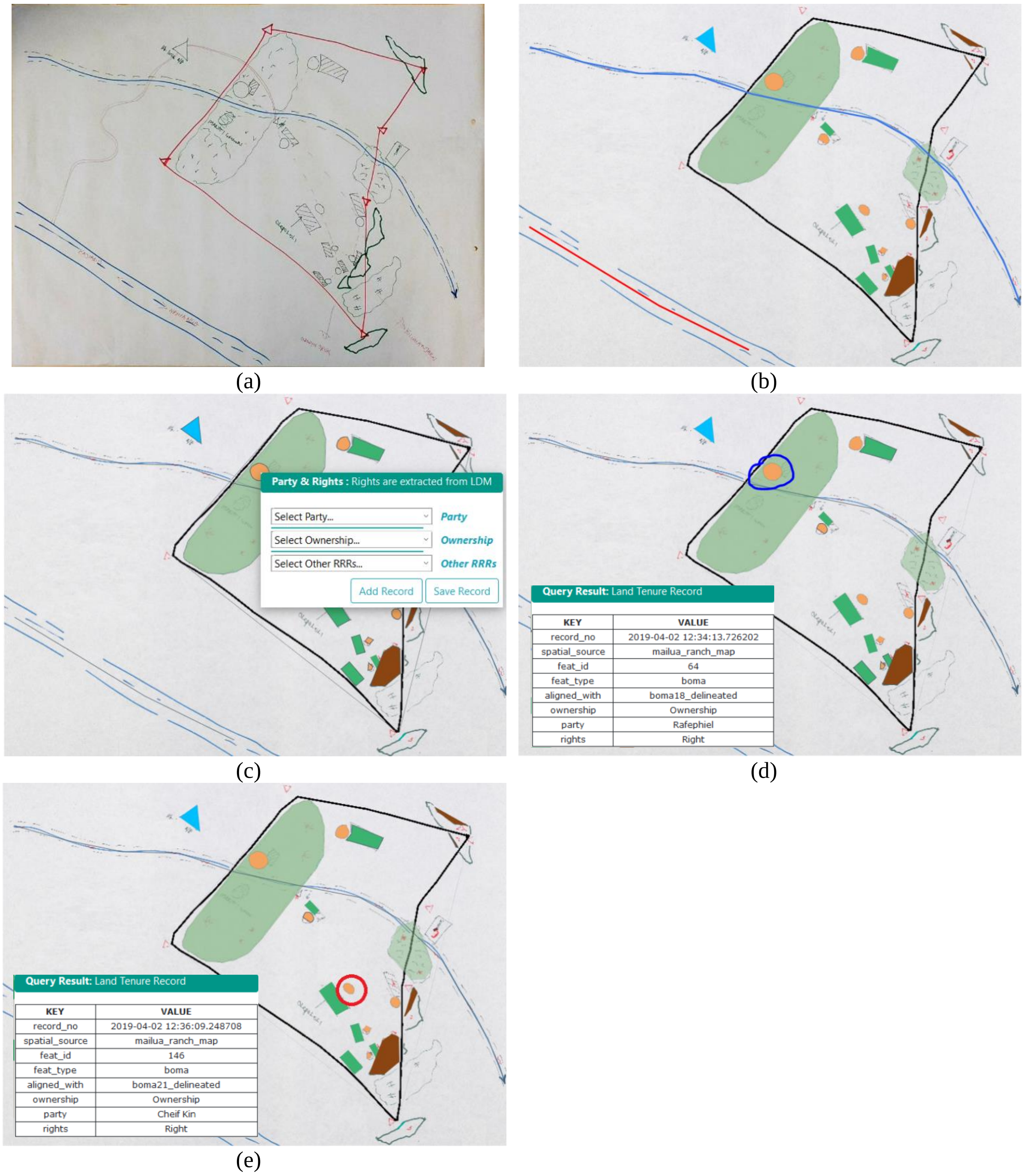

Figure 8. (a) Sketch map drawn by community members, (b) for which objects such as bomas are recognized by a matching algorithm. The objects are thus vectorized and attributed. (c) The SmartSkeMa interface allows to assign LDM attributes and (d, e) display them by clicking on an object (indicated by blue and red circle).

4. Conclusion

The work on WP5 presented in this report contributes to advancements in developing a methodology for UAV-based delineation of visible cadastral boundaries. The goal was to develop a methodology for cadastral boundary delineation that is highly automatic, generic and adaptive to different scenarios. This has been addressed by proposing a methodology that partially automates and simplifies the delineation of outlines of physical objects demarcating cadastral boundaries. It is designed for areas, in which physical object contours are clearly visible and coincide with cadastral boundaries. The approach has shown promising results for reducing the effort of current indirect surveying approach based on manual delineation. In general, the methodology could improve current indirect mapping procedures by making them more reproducible and efficient. However, a certain skill level of the surveyors in geodata processing is required as well as the presence of visible cadastral boundaries. With cadastral boundaries being a human construct, certain boundaries might not be automatically detectable.

A comprehensive description and analysis of the approach is currently being prepared and will be published in a Ph.D. thesis, a journal paper, and the final report for its4land. In addition, WP5 is developing documentation and testing material that enables surveyors and policy makers in land administration to easily understand, test and adapt our approach.

In this report, we have applied the tool to delineate visible boundaries in UAV imagery of a rural Kenyan area and combined WP5 with Sketchmaps from WP3: the sketchmaps developed during past WP3 fieldwork were used to attribute visible boundaries derived from WP5. Combining the delineated visible boundaries with non-spatial information derived from Sketchmaps integrates geometric and semantic information undetectable by the boundary delineation and thus enhances the recorded information with local spatial knowledge. Future work could focus on integrating socially perceived boundaries, which are not visible to optical sensors, but could be captured by the described Sketchmap approach.

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