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A standardized land capability classification system for land evaluation using mobile phone technology

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Abstract: One of the major causes of poverty globally is land degradation and poor natural resource conservation, leading to reduced agricultural productivity. This degradation is often caused by a mismatch between land use and land potential, specifically using marginal lands for agriculture. For over 50 years the Land Capability Classification (LCC) system has been used globally for land evaluation to support soil and natural resource conservation. The LCC system classifies the land into eight classes; however, its use is currently limited by two factors: the lack of digital platforms for data input, storage, and management, and an insufficient technical capacity in many regions necessary to generate the required inputs. This paper describes the development of a system to facilitate rapid, flexible, and transparent determinations of LCC by non-soil scientists using a newly developed function of the Land-Potential Knowledge System (LandPKS) mobile app. Inputs include soil texture and rock fragment volume by depth, slope, and site observations of soil limiting factors. A standardized system for evaluating inputs and calculated indicators was developed based on US and international implementations of LCC. The system was evaluated using USDA Natural Resources Conservation Service soil survey data in eight US counties. Results show that the standardized system predictions were within one class for 73.8% of the 1,312 soils tested, despite a high level of variability in how LCC was determined within the US database. The LandPKS LCC system was further tested in Tanzania and Ethiopia to examine site-specific applications, usability, and usefulness of the system for national land use planning efforts. It was concluded that the LandPKS app automates a globally applied system (LCC) for supporting natural resource conservation and sustainable land management and can serve as a foundation for crop-specific land suitability evaluations. More generally, improved land evaluation efforts can contribute to better soil and natural resource conservation, more sustainable agricultural systems, and increased food security.

Key words: Ethiopia—land capability classification—land evaluation—LandPKS—natural resource conservation—Tanzania

Improving soil and natural resource conservation should be a priority for poverty alleviation efforts globally. Poverty remains one of the most serious issues facing humanity (United Nations 2015), and 70% of the world's poor live in rural areas and depend on agriculture for their livelihoods (IFAD 2011). Many of these farmers have limited access to fertilizers, improved crop varieties, and information on appropriate and sustainable natural resource conservation techniques. In addition, as demand for food grows, there is increasing pressure to develop marginal lands for agriculture, including areas where soils are shallow, saline, or on steep slopes (FAO 2016). When marginal lands are cultivated or when more fertile landscapes are not managed sustainably, it can lead to soil erosion and degradation, loss of livelihoods, and a decrease in the overall resilience of the social-ecological system (Liu et al. 2014).

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Soils are an important natural resource for agriculture. Soils are often heterogeneous across the landscape and at the spatial scale of many smallholder farms (1 to 2 ha). However, soils assessment and mapping are often not available at the fine scales needed for effective natural resource conservation and sustainable land management at the farm level (Smith et al. 2016). For example, the "betterment" schemes that took place in South Africa in the 1960s aimed to demarcate arable areas for agriculture for local communities (Laker 2004). During the land evaluation process, the upper limit for agricultural areas was set to a slope of 12%. However, by the mid-1970s many of the areas demarcated for agriculture suffered from severe soil erosion and degradation. What was not accounted for during the land evaluation process was that within the demarcated areas were highly unstable, nonarable soil types that erode at slopes much less than 12% (Laker 2004). Thus, despite planning efforts, an inattention to detailed information about soil and site characteristics led to severe land degradation.

Relevant to the South African example, the IPBES (2018) report on land degradation states that, "more relevant, credible, and accessible information is needed to allow decision makers, land managers, and purchasers of goods to improve the long-term stewardship of land and sustainability of natural resource use." However, in many developing countries, access to knowledge, human capacity,

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and financial resources to effectively conserve natural resources and manage the land sustainably are often lacking (Kisambu et al. 2017). Given these limitations, there has been great interest in the potential for information communication technologies to fill the gap in knowledge provisioning and decision support (Yonazi et al. 2012; UNEP 2016).

The Land Capability Classification (LCC) is a system of classifying land primarily on the basis of its capability to produce crop and pasture plants, as well as how cultivation will impact long-term sustainability. However, its use is currently limited by two factors: the technical capacity (particularly to characterize soil morphology) necessary to generate the required inputs, and the lack of a digital platform for data input, interpretation, storage, and management. Therefore, the objective of this paper is to (1) discuss how these limitations have been addressed through the development of a digital system to facilitate rapid, flexible, and transparent determinations of LCC using a newly developed function of the Land-Potential Knowledge System (LandPKS; landpotential.org) mobile app, and (2) evaluate the system through Tanzanian and Ethiopian case studies and comparisons with independent LCC determinations by the USDA. The aim of comparing the standardized LCC system with USDA soils data is to compare the consistency of LCC determinations from LandPKS with varying LCC systems within the USDA database, while the empirical case studies from Tanzania and Ethiopia aim to test the consistency, usability, and usefulness of the system in real-world contexts. By addressing the current limitations of the LCC system, this new tool aims to bridge the gap in accessibility to relevant knowledge and contribute to natural resource conservation efforts and sustainable land management globally.

Land Capability Classification. The LCC was originally developed by the US Soil Conservation Service (USDA 1939), and an early version was first published in 1939 (USDA 1939; Helms 1992). While developed in the United States, the LCC system is actively used in land evaluation efforts in countries all over the world. It was born out of an attempt to farm land while maintaining the quality of the soil (Helms 1992). The LCC system assigns land to one of eight classes (table 1) based on the degree of specific limitations of the land such as erosion (e), excess wetness (w), problems in the rooting zone (s), and climatic limitations (c) (Helms 1992). The specific limitations included in any given LCC system vary, as do the degree of each limitation needed to receive a specific class score. The LCC system emphasizes soil erosion hazards (Young 1976) due to the relative irreversibility of degradation caused by soil erosion for most land.

Table 1

Descriptions of the Land Capability Classification classes from the *USDA National Soil Survey Handbook* Part 622 (USDA NRCS 2007).

Class	Description
1	Slight limitations that restrict their use
2	Moderate limitations that reduce the choice of plants or require moderate conservation practices
3	Severe limitations that reduce the choice of plants or require special conservation practices, or both
4	Very severe limitations that restrict the choice of plants or require very careful management, or both
5	Little or no hazard of erosion but have other limitations, impractical to remove, that limited their use mainly to pasture, rangeland, forestland, or wildlife habitat
6	Severe limitations that make them generally unsuited to cultivation and that limit their use mainly to pasture, rangeland, forestland, or wildlife habitat
7	Very severe limitations that make them unsuited to cultivation and that restrict their use mainly to rangeland, forestland, or wildlife habitat
8	Limitations that preclude use for commercial plant production and limit use mainly to recreation, wildlife habitat, water supply, or esthetic purposes

However, there are some limitations of the LCC system. First, the inclusion of climate in these LCC determinations is a limitation of the original LCC system. According to the Food and Agriculture Organization of the United Nations (FAO 2019), globally it is difficult to adequately consider climate limitations due to the variations of climate requirements between crops and cultivators, and the kinds of climatic hazards. Second, the different factors used to categorize land into LCC classes and subclasses is not standard and does vary between states within the United States and among countries. For example, according to the *US National Soil Survey Handbook* (USDA NRCS 2007), part 622.22 explains how a slope of <2% in California is used to determine Class 1, while part 622.25 states that a slope of up to 3% in Indiana delineates Class 1 land. The FAO (1974) *Soil Bulletin 22* documents modifications to LCC criteria made by other countries. Table 2 provides the details of the LCC system used in Ethiopia for land use planning, which was used to analyze the LandPKS LCC presented here. It is important to note that the LCC class of a site is not necessarily permanent, and any number of changes in the land, such as accelerated erosion, accumulation of salts, or the application of irrigation water, could require a reclassification of that land (Helms 1992). In addition, land capability differs from land suitability. Land suitability for the production of specific crops is based on both the fundamental land capability (LCC) and other factors, such as the relative potential productivity of the particular crop. For example, crop tolerance to frost and drought, which is affected by the plant-available water holding capacity of the soil, vary widely both within and among crops. A study in Ethiopia by Girmay et al. (2018) outlines how an LCC assessment based on physical and chemical properties of the soil was able to determine areas that are capable of supporting rain-fed crop production, while a land suitability assessment for the major rain-fed crops in the area identified specific arable areas best suited to barley (*Hordeum vulgare* L.), wheat (*Triticum aestivum* L.), and faba bean (*Vicia faba* L.). The more detailed suitability assessment was based on the specific crop requirements for climate and soil properties, such as pH, organic matter, and electrical conductivity. It also considered landform attributes that could determine the suitability of the land for specific tillage systems used to produce these crops in these areas. Therefore, in determining crop suitability, LCC is necessary but not sufficient for crop-specific land suitability evaluations.

Materials and Methods

Developing a Standardized Land Capability Classification System. In order to create a standardized LandPKS LCC system, the national-level USDA guidelines and criteria

Table 2
Matrix for Ethiopia's Rural Land Administration and Use Directorate Land Capability Classification (LCC) determinations.

	LCC class							
Criteria	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Slope (%)	0 to 2	2 to 8	8 to 15	15 to 30	0 to 30	30 to 50	>60	0 to 50
Soil depth (cm)	>150	100 to 150	100 to 150	50 to 150	25 to 150	50 to 150	25 to 150	0 to 150
Past erosion	None	None	None to slight	None to moderate	None to moderate	None to moderate	None to severe	None to very severe
Surface texture (Class)	L, SL, CL	L, SiL, CL, SL	L, SL, CL, SiC, HC	SL, L, SiL, CL, SiC, C, HC	SL, L, SiL, CL, SiC, C, HC	SL, L, SiL, CL, SiC, C, HC	S, SL, L, SiL, CL, SiC, C, HC	S, SL, L, SiC, CL, SiL, C, HC
Water logging (Class)	None	None	None to intermittently water-logged	None to regularly water logged	None to regularly water logged	None to regularly water logged	None to regularly water-logged	Water-logged to swamps
Infiltration (Class)	Good	Good	Good, moderate	Good, moderate, poor	Good, moderate, poor	Good, moderate, poor	Moderate, poor	Good, moderate, poor
Length of growing period (d)	120 to 240	120 to 240	120 to 240	90 to 240	>90	>90	0 to >240	0 to >240
Stoniness/ rockiness (%)	No stone or few	No stone or few, moderately stony, stony	No stone or few, moderately stony, stony	No stone or few, moderately stony	No stone or few, moderately stony, stony	No stone or few, moderately stony, stony, very stony	No stone or few, moderately stony, stony, very stony, rock out crops	No stone or few, moderately stony, stony, very stony, rock out crops

Notes: L = loam. SL = sandy loam. CL = clay loam. SiL = silt loam. SiC = silty clay. HC = heavy clay. C = clay.

were used to begin. These guidelines were then modified to support global application, following the lead of other countries and organizations that have developed modified versions (table 3). Modifications were selected based on their pervasiveness in other LCC systems, importance for land capability, and the ease that a minimally trained user can make the necessary observations (table 3). Detailed and specific rationale for each modification is provided in table 3. Through this process, the LandPKS LCC system was standardized, meaning it can be used globally by a minimally trained user.

The Land Potential Knowledge System Mobile Application. The LandPKS mobile app was created to help put information about land, including climate, soils, and vegetation into the hands of land managers, farmers, and land use planners across the globe, and to allow them to characterize these attributes of their own land. The LandPKS app is free to download and use for both Android and iPhone mobile devices. The LandPKS app uses a geolocated, point-based model for data collection and delivering results. At the time of writing, the LandPKS app had three input modules: LandCover, LandManagement, and LandInfo (landpotential.org). LandCover helps users monitor vegetation change, LandManagement is for tracking basic agricultural outputs and inputs, and LandInfo uses short, animated, and icon-based tutorials to help the user characterize soil properties and limitations. A key component of the LandInfo module is that it guides users through hand texturing their soil. Previous research has found the LandPKS approach to hand texturing of the soil to be relatively accurate compared to laboratory tests, which also have a certain degree of error (Salley et al. 2018). Accuracy was 91% for professional soil scientists, and 71% to 78% for nonexperts (Salley et al. 2018). In addition to delivering results directly to the phone, the user inputs for all three modules can be uploaded from the user's smartphone to the cloud and then accessed through the LandPKS Data Portal (https://landpotential.org/data-portal/). This also ensures automatic access to data when the app is loaded on a different phone.

The LandPKS LCC system uses inputs from the LandInfo module (slope, soil texture and rock fragment volume by depth, and soil limiting factors) and uses this information to determine the LCC class and subclass. It is important to note that the LandPKS LCC system integrated into the LandPKS app does not take into account climate limitations (temperature and effective moisture) for four reasons: (1) climate limitations are generally already well understood in most regions, (2) temperature and moisture limitations are much more crop dependent than limitations such as erosion risk (see above discussion of land suitability in the LCC section), (3) relative cost and availability of irrigation water is highly variable, and (4) the LandPKS app is focused on soils and the LCC outputs can be easily integrated into broader crop suitability assessments that do include climate considerations. The United States addresses the third issue in some areas by reporting LCC for both irrigated and nonirrigated conditions.

The Standardized Land Potential Knowledge System Land Capability Classification System. The overall workflow of the standardized LandPKS LCC system is outlined in figure 1. First, using the LandInfo module, users collect data necessary to evaluate the 10 criteria that are used to determine the LandPKS LCC class and subclass. Once the user begins collecting data, the LandPKS app automatically calculates the LandPKS LCC class for each criterion that the user has completed, based on the matrix in table 4, as well as an overall LCC class for the site. The LandPKS LCC class for the site is determined by the most limiting criteria from table 4. For example, if surface stoniness is rated a 5, and the other 9 criteria all receive a class rating less than 5 (LCC class of 1 to 4), the LandPKS LCC class for the site would be calculated as a 5 with surface stoniness as the limiting criterion and LandPKS LCC

Table 3

Description of the systems, modifications, and rationale used for developing the standardized Land Capability Classification (LCC) system.

LCC criteria	System used	Modifications	Rationale	LandPKS inputs
Erosion risk: slope (%): K factor of >32*	USDA NRCS (2007), Pacific Northwest National Laboratory (2018)	Slope breaks modified	Modified to utilize the slope ranges that are available in the LandPKS app	Slope and soil texture 1 to 10 cm
Erosion risk: slope (%): ≤32*	USDA NRCS (2007), Pacific Northwest National Laboratory (2018)	Slope breaks modified	Modified to utilize the slope ranges that are available in the LandPKS app	Slope and soil texture K factor of 1 to 10 cm
Soil depth (cm)	State of New South Wales and Office of Environment and Heritage (2012)	USDA only uses four depth breaks, the LCC system uses five breaks	Modified to utilize the depth breaks that are available in the LandPKS app	Soil depth
Surface soil texture	USDA NRCS (2007)	Only includes soil texture classes, not the subclasses	LandPKS only captures soil texture classes and not subclasses	Soil texture 1 to 10 cm
Salinity	LandPKS	None	Easily observable measures of salinity	Salt on soil surface
Surface stoniness (%)	USDA NRCS (2007)	Same breakpoints as utilized by the USDA	Compatibility of existing USDA system with the LandPKS app	Surface stoniness
Soil water storage capacity (cm to a depth of 1 m)*	USDA NRCS (2007)	Modified from inches to centimeters and to a depth of 1 m	Conversion done to internationalize the LCC system	Soil texture to 100 cm
Lime requirement	LandPKS	Used instead of the USDA soil reaction (pH)	Lime requirement provides some pH information that is easily observable	Lime requirements
Flooding during the growing season	USDA NRCS (2007)	Uses same values as USDA	Compatibility of existing USDA system with the LandPKS app	Flooding (growing season)
Water table depth during the growing season (cm)	USDA NRCS (2007)	Same values as USDA, just converted from inches to centimeters	Conversion done to internationalize the LCC system	Water table depth
Permeability (mm h^{-1})*	USDA NRCS (2007), Schoeneberger et al. (2012)	Inches per hour comes from the *Field Book for Describing and Sampling Soils*. Converted inches per hour to millimeters per hour	Conversion done to internationalize the LCC system	Soil texture to 100 cm

Notes: LandPKS = Land-Potential Knowledge System.

*Calculated values using LandPKS algorithms.

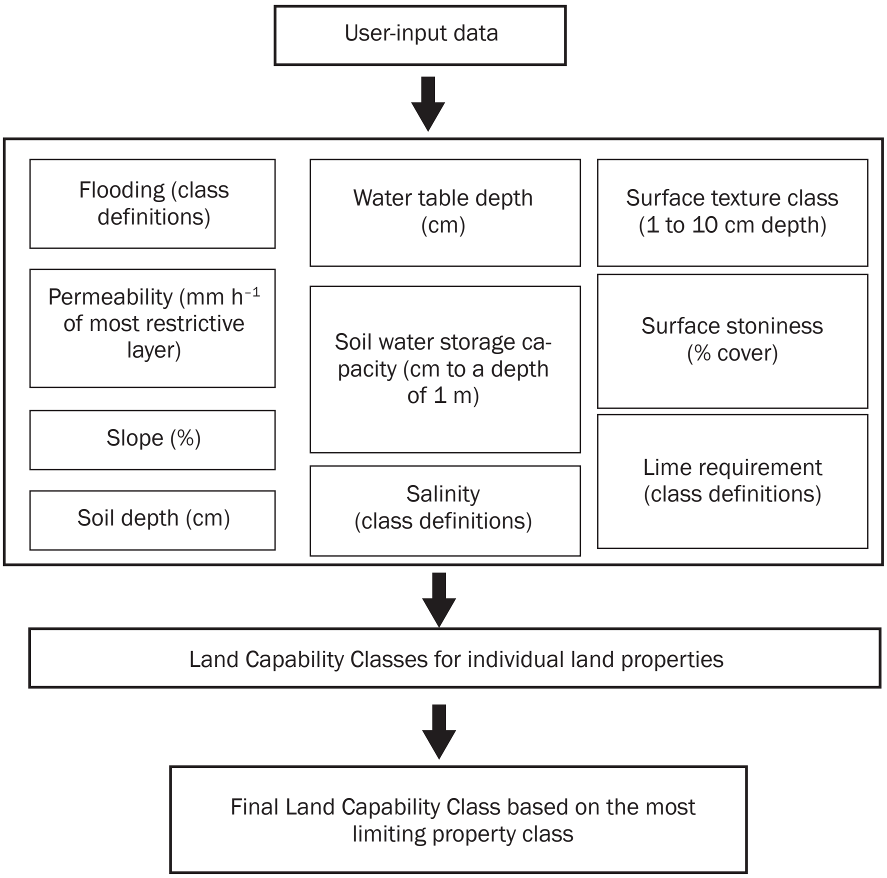
subclass. Users receive results without collecting data for all 10 criteria; however, the more criteria collected, the more reliable the LandPKS LCC outputs will be. For example, if a user does not collect data on the most limiting criteria, the LandPKS LCC class reported would misrepresent the actual capability of the land. The LandPKS app clearly highlights missing data on the LandPKS LCC output screen.

Users are also provided the option to determine whether or not each criterion is relevant to the particular site. Turning individual criteria off automatically modifies the user-adjusted class. This feature is useful in situations where the user is an expert land evaluator or land use planner who has significant experience with the LCC system or in situations where what would normally be considered a soil limitation, such as high water table depth, is actually considered an asset, such as for irrigated rice (*Oryza sativa* L.) cultivation. The calculations to determine LandPKS LCC outlined in table 4 are done directly on the phone and require no data connection to complete. See figure 2 for an example of the LandPKS Report Screen.

Evaluating the Consistency of Land Capability Classification Determinations with USDA Soil Survey Data. The extent to which the standardized LandPKS LCC system is likely to be consistent with other implementations of LCC was evaluated using preexisting USDA Natural Resources Conservation Service (NRCS) soil survey data. One major goal in designing the integrated system within the LandPKS app was to avoid consistently over- or underestimating the LandPKS LCC class compared to the LCC classes already designated by the NRCS. The NRCS soil data set, which already includes LCC determinations, was selected because it includes both (1) soil and topographic information necessary to complete an LCC determination using LandPKS and (2) independent determinations of LCC based on different implementations. This variety exists because each state in the United States has implemented their own LCC, applying the same generalizable criteria, but with different thresholds for one or more of the eight classes. The rules and methods utilized to generate the LandPKS LCC class from the soil and topographic data in the USDA NRCS soil database is available in table 5. The objective of this step was to statistically test the compatibility of the LandPKS LCC system with the USDA NRCS systems in various locations and did not involve any field testing of the LandPKS app.

Figure 1

Workflow of Land Capability Classification (LCC) within the Land-Potential Knowledge System mobile app. This includes the 10 variables collected to determine the LCC score.



Comparisons were completed for 1,312 soils (map unit components) distributed among eight counties (one county in eight different US states) using NRCS soil survey data to generate the required inputs (table 6). Because climate is not considered in our standardized LandPKS LCC system, seven of the eight counties were selected randomly from the eastern regions of the United States, where the soil (rather than climate) limitations are generally the most class-defining factors due to relatively high growing season rainfall (Salley et al. 2016). This limited the impact of climate on the determination of LCC class for this comparative analysis. Doña Ana County, in the state of New Mexico, was included because most of the soils there were classified based on their potential with irrigation (in addition to without irrigation), effectively eliminating LCC climate limitation while allowing soils from an arid region to be included. Together, soils in these eight US counties represent some variability of soil properties used globally for LCC determination and include eight unique implementations of the LCC system, reflecting the breadth of variability in how the LCC system has been adapted globally. None of the state-specific LCC systems were identical to the USDA national version used as a starting point for developing the LandPKS LCC system described in this paper. Consequently, the differences between this classification and those generated by the USDA NRCS in each of these counties provides some indication of the relative consistency of the LandPKS LCC determinations with other implementations of the LCC system that use differing inputs and thresholds. Lastly, these data were analyzed using Microsoft Excel and Stata 14IC statistical analysis software.

Two Land-Potential Knowledge System Land Capability Classification Case Studies in Tanzania and Ethiopia: Enhancing Land Evaluation Efforts. Preliminary field-piloting of the LandPKS LCC system in the community of Nyamihuu, located near Iringa, Tanzania, was completed to better understand the usability of LandPKS LCC in a real-world setting with real-world users of the LandPKS app. In June of 2017, with local farmers, village representatives, and staff from Tanzania's National Land Use Planning Commission (figure 3), the LandPKS team characterized soil and topographic conditions using LandPKS at three locations within a short distance (less than 100 m) from each other on a hillslope (Outcrop, Upper Field, and High Production). These sites are all mapped within the same Harmonized World Soil Database (Nachtergaele et al. 2008) soil map unit.

Building upon this, in September of 2018, in order to increase the scale of pilot field testing of the LandPKS LCC, four villages were visited: Marumbo, Murungu, Mhaga, and Mtamba, all in Kisarawe District, located in the Coast Region approximately 26 km outside of Dar es Salaam, Tanzania. In collaboration with staff from Tanzania's National Land Use Planning Commission and Kisarawe District land, agriculture, and livestock officers, one LCC assessment in each village was completed alongside village government representatives and local farmers, with approximately 25 participants in each village. In the field activities and pilot-testing in both 2017 and 2018, the assessments were conducted by the local farmers and land use planning experts, with instruction from LandPKS members. In both instances, the land use planning experts received minimal one to three hour trainings that included instructions for using the LandPKS app with a particular focus on the soil texture inputs. The local farmers received only 30 minutes of training on the LCC evaluation and LandPKS app. The purpose of these case studies was to evaluate the standardized LCC system for real-world applications and not necessarily to validate the LandPKS LCC system (as stated in objective two in the introduction).

In Ethiopia, the LandPKS team has been working with the Rural Land Administration and Use Directorate (LAUD) since January of 2019. In June of 2019, LAUD staff conducted pilot testing of the LandPKS LCC system for potential integration into their national-level land evaluation protocol. As with the testing with the USDA NRCS data, climate was not included as a limitation in

Table 4
Matrix for the Land-Potential Knowledge System Land Capability Classification (LCC) determinations.

		LCC class							
Criteria	**Subclass**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**
Erosion risk: slope (%): K factor of >32	e	≤2	>2 and ≤5	>5 and ≤10	>10 and ≤15	—	>15 and ≤30	>30 and ≤60	>60
Erosion risk: slope (%): K factor of ≤32	e	≤5	>5 and ≤10	>10 and ≤15	>15 and ≤30	—	—	>30 and ≤60	>60
Soil depth (cm)	s–d	≥100	—	≥70 and <100	≥50 and <70	—	>20 and <50	—	≤20
Surface soil texture	s–t	SL, SIL, L, Si, SCL, SICL, CL	S, LS, SC, SIC	C	—	—	—	—	—
Salinity	s–k	No	Small, temporary, patches	—	Yes, most of the surface	—	—	—	—
Surface stoniness (%)	s–r	<0.1	≥0.1 to <3	≥3 to <15	—	≥15 to <50	—	≥50 to <90	≥90
Soil water storage capacity (cm to a depth of 1 m)	s–a	>18	≥18 and >12	≤12 and >6	<6	—	—	—	—
Lime requirement	s–l	Little or no lime required	—	High amounts of lime required	Very difficult to modify with lime	—	—	—	—
Flooding during the growing season	w–f	None during growing season. Crop selection not restricted.	Rare to occasional. Slight crop damage; 0% to 20% yield reduction or crop selection slightly limited.	Occasional. Moderate crop damage; 20% to 35% yield reduction or crop selection moderately limited.	Frequent. Severe crop damage; 35% to 50 % yield reduction or crop selection severely limited.	Very frequent. Prevents normal production of crops.	—	—	—
Water table depth during the growing season (cm)	w–d	≥120	≥75 and <120	≥ 45 and <75	≥30 and <45	—	<30	—	—
Permeability (mm h^{-1})	w–p	≥5	≥1.5 to <5	<1.5	—	—	—	—	—

Notes: L = loam. SL = sandy loam. CL = clay loam. Si = silt. SCL = sandy clay loam. SICL = silty clay loam. SIL = silt loam. S = sand. LS = loamy sand. SC = sandy clay. SIC = silty clay. C = clay.

field testing because (1) it is often not used by the LAUD in determining LCC due to the localized climate variability that exists in many districts and (2) of the use of irrigation in agricultural production in many lowland areas. Field pilot testing took place at seven sites in Sari'a Kebele in the Amhara Region and eight sites in Kokate Kebele in the Southern Nations, Nationalities, and Peoples' region by a different group of LAUD staff. The goals of the field pilot test were to compare the time requirements and classes predicted by the LandPKS LCC system with the LAUD's current paper-based implementation of their LCC system (table 2). The Ethiopian implementation of LCC uses a different set of criteria for determining LCC (table 2), so it is helpful to see how these LCC scores compared with the LandPKS LCC determinations. Furthermore, after completion of the field work, 39 LAUD staff (including federal, regional, Zonal, Woreda, and Kebele level-staff members) participated in an Online LandPKS Pilot Test User Experience Questionnaire about the usability of the LandPKS app.

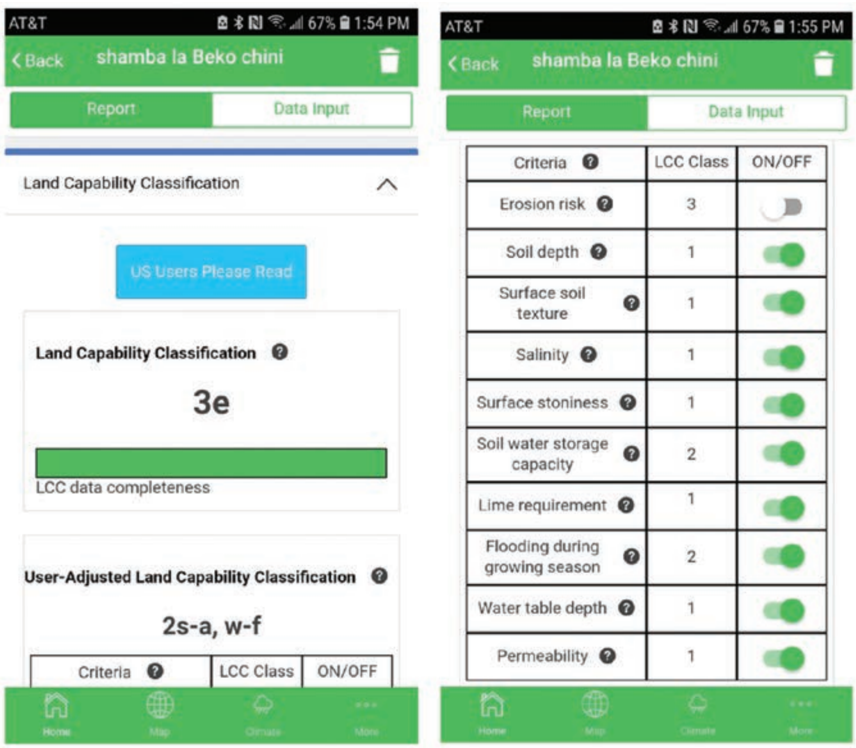
Prior to each of the two sets of tests, a three-day training was provided to the participants, which included a practical demonstration of the LandPKS app and a refresher training of the conventional Ethiopian Local Level Participatory Land Use planning approach. During the training, the groups decided to include the 15 sites in the pilot tests, based on predelineated Land Slope Map strata, as the slope is a governing criterion in establishing land planning/mapping units. The three-day training was concluded by practical field demonstrations on how to collect soil and determine soil texture and soil color at different depths using LandPKS. At each site, four individuals were involved in the pilot test, including a federal government senior land use expert, a LandPKS data collector, a LAUD data collector, and a local farmer. Each group collected samples using both LandPKS and LAUD methods at a single sample collection point, simultaneously but independently.

Results and Discussion

Testing the Consistency of the Land-Potential Knowledge System Land Capability Classification System with USDA Soil Survey Data. Overall, the results of the tests of consistency of the LandPKS LCC determinations with the USDA NRCS soil survey data indicated that the LandPKS LCC results were generally similar to NRCS LCC results, even though different LCC systems were implemented for the eight different

Figure 2

Land Capability Classification results screen within the Land-Potential Knowledge System app. This example shows the ability of the user to turn off and on the different criteria in order to change the User-Adjusted Land Capability Classification.



US counties tested (table 6). Comparing all results, 33.4% of the LandPKS LCC and NRCS LCC results were in the same class, 73.8% were within one class, and 91.2% were within two classes (table 6). For Doña Ana County, New Mexico, the LandPKS LCC results matched well with the NRCS irrigated LCC. Overall, average LCC was slightly overestimated by LandPKS in three counties and marginally underestimated in five counties (table 6, the average difference for county column). The data were also analyzed with a Pearson χ^2 test in order to analyze if the observed differences between the LCC simply arose by chance. Results found a Pearson χ^2 of 814.4152 with a *p*-value of 0.0000, which supports the null hypothesis that the probability that the LCC results are independent is very low.

Land Capability Classification Case Study in Tanzania. Results from the Nyamihuu, Tanzania, case study highlight the heterogeneous nature of soils at small scales (table 7), which further underscores the importance of biophysical assessments. While these three sites were located in close proximity (approximately 100 m) and within the same Harmonized World Soil Database (Nachtergaele et al. 2008) soil map unit,

Table 5

Rules and methods utilized to generate the Land-Potential Knowledge System (LandPKS) Land Capability Classification (LCC) soil class from the soil and topographic data in the USDA Natural Resources Conservation Service soil database.

LandPKS LCC variable	Query logic
Erosion risk	• Utilized slope breaks from LandPKS LCC matrix (table 4). • Kw factor >0.32 or ≤0.32 of top horizon.
Soil depth	• Depth to paralithic or lithic bedrock. • Restriction kinds not present within top 100 cm, then soil depth was assumed to be 100 cm or greater.
Surface soil texture	• Utilized soil texture classes from LandPKS LCC matrix (table 4).
Salinity	• EC value of top horizon. • If EC ≤2, then LCC = 1. If EC > 2 and ≤4, then LCC = 2. If EC > 4, then LCC = 4.
Surface stoniness	• Utilized percent surface stoniness from LandPKS LCC matrix (table 4).
Soil water storage capacity	• Utilized AWC breaks from LandPKS LCC matrix (table 4). • Calculated AWC for each horizon to 100 cm and summed values.
Flooding during growing season	• Utilized the highest flooding frequency class for any month of the year. • If highest flooding frequency class = None or Very Rare, the LCC = 1. If highest flooding frequency class = Rare, the LCC = 2. If highest flooding frequency class = Occasional, the LCC = 3. If highest flooding frequency class = Frequent, the LCC = 4. If highest flooding frequency class = Very Frequent, the LCC = 5.
Water table depth	• Utilized water table depths from LandPKS LCC matrix (table 4). • Utilized April thru September as growing season months. Determined shallowest water table depth during any of these months.
Permeability	• Utilized permeability breaks from LandPKS LCC matrix (table 4). • Converted Ksat high values for each horizon to mm h^{-1} then utilized the minimum horizon Ksat value.

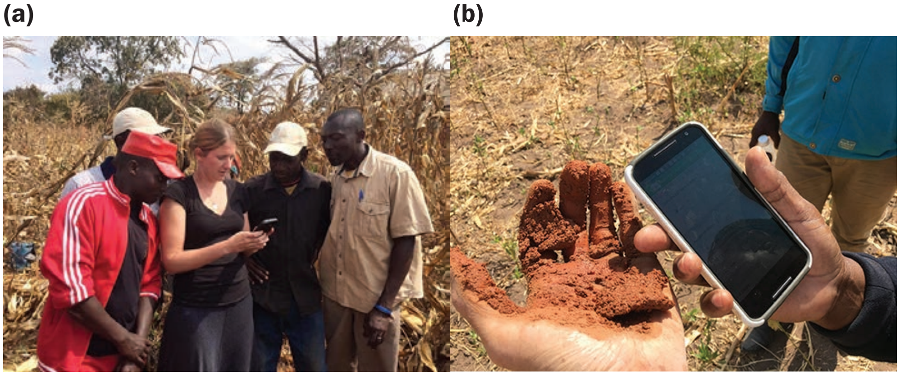
Note: AWC = available water capacity. EC = electrical conductivity.

Table 6
Comparison of Land-Potential Knowledge System (LandPKS) Land Capability Classification (LCC) results with USDA Natural Resources Conservation Service (NRCS) LCC results. Analysis between both soil data sets found a Pearson χ^2 of 814.4152 with a *p*-value of 0.0000.

County, state	Number of soil components assigned LCC class by NRCS	Number of soil components with same LCC class	Number of soil components with difference of 1 LCC class (±1)		Number of soil components with difference of 2 LCC classes (±2)		Number of soil components with difference of 3 LCC classes (±3)		Number of soil components with difference of 4 LCC classes (±4)		Average difference for county
		LandPKS = NRCS	LandPKS > NRCS	NRCS > LandPKS	LandPKS > NRCS	NRCS > LandPKS	LandPKS > NRCS	NRCS > LandPKS	LandPKS > NRCS	NRCS > LandPKS	
Barbour Co., Alabama	186	72	38	41	9	20	0	4	0	2	−0.2
Gates Co., North Carolina	83	31	10	27	11	1	0	3	0	0	−0.1
Sumtes Co., Florida	299	109	58	69	31	8	12	12	0	0	0.1
Polk Co., Tennessee	87	33	15	12	5	22	0	0	0	0	−0.4
Knox Co., Ohio	281	91	68	19	29	20	28	4	22	0	0.8
Livingston Co., Louisiana	60	3	14	6	21	3	10	0	3	0	1.4
Hill Co., Texas	134	19	19	46	6	30	1	8	3	2	−0.7
Dona Ana, Co., New Mexico (irrigated)	174	77	38	47	0	11	0	1	0	0	−0.2
Total	1,304	435	260	267	112	115	51	32	28	4	—
Percentage	—	33.4	40.4		17.4		6.4		2.5		—

Figure 3
Field work photos in Nyamihuu, Tanzania. (a) Quandt demonstrating the Land-Potential Knowledge System app with local farmers and village representatives. (b) Suzana Mwangoka, Tanzania National Land Use Planning Commission, hand texturing soil using the Land-Potential Knowledge System app.

(a) **(b)**



many of the soil properties were different. For example, the available soil water storage capacity deviated substantially (high production = 9.6 cm, upper field = 6.6 cm, outcrop = 1 cm), with the high production site able to hold almost one-third more plant-available water than the upper field. Additionally, the LCC subclasses varied between the three sites, reflecting different land use limitations.

In contrast, the four LCC determinations in the four villages in the Kisarawe District, Tanzania, were very similar, with sandy loam and loamy sand soil textures. These textures resulted in an LCC class of 3s–a of all four sites due to their limited available soil water holding capacity. The similarity of the soils in the four Kisarawe locations may reflect a preference for locating villages on relatively well-drained soils on flat slopes. Much steeper slopes (which would have resulted in 4–8e classifications), inundated areas (3–5w–f and 3–6w–d), and shallow soils (3–8s–d) were encountered while travelling to the villages. These two case studies highlight the importance of collecting biophysical information when conducting land evaluations in a real-world context and how sampling strategies may also depend on the local context.

Land Capability Classification Case Study in Ethiopia. Results from comparing the compatibility of the LandPKS LCC determinations and the LAUD determinations

Table 7
Land Capability Classification (LCC) for three Land-Potential Knowledge System (LandPKS) sites in Tanzania.

	High production		Upper field		Outcrop	
LCC criteria	User input data	LCC	User input data	LCC	User input data	LCC
Erosion risk	3% to 5%	1	11% to 15%	3	16% to 30%	4
Soil depth*	>100	1	>100 cm	1	23 cm	6
Surface soil texture	Loamy sand	2	Loamy sand	2	Loamy sand	2
Salinity	No	1	No	1	No	1
Surface stoniness*	<0.1	1	<0.1	1	<0.1	1
Soil water storage capacity	9.6 cm	3	6.6 cm	3	1.0 cm	4
Lime requirement*	None	1	None	1	None	1
Flooding (growing season)*	None	1	None	1	None	1
Water table depth*	>120 cm	1	>120 cm	1	>120 cm	1
Permeability†	0.7 mm h^{-1}	3	4.7 mm h^{-1}	2	45.9 mm h^{-1}	1
LCC rating	3s–a, w–p		3e, s–a		6s–d	
Most limiting soil characteristics	Soil water storage capacity, permeability		Erosion risk, soil water storage capacity		Soil depth	

*Values estimated after the site was evaluated.
†Calculated.

shows that 60% of the sites (nine sites) had the same LCC score, and 40% (six sites) had a marginal difference of only one class (table 8). This reflects general compatibility between the two different systems for determining LCC. Furthermore, on average, the LandPKS assessment took 40 minutes, while the LAUD paper-based assessment took 30 minutes. However, the 30 minutes only included field data collection/input and not data processing. In subsequent conversations, LAUD personnel indicated that they believe the total time, including data processing, would be less for LandPKS than for the current LAUD approach using paper forms, while the automated LandPKS cloud back-up provides greater data security. No Pearson χ^2 test was completed for the Ethiopia data because of the small sample size.

In the online survey, 100% of LAUD staff strongly agreed or agreed that the LandPKS app was easy to use (n = 39 responses). Additionally, 97.4% of LAUD staff strongly agreed or agreed that the pictures and terminology used in the LandPKS app were easy to understand, and 97.4% strongly agreed or agreed that the app has adequate guiding documentation. Importantly, LAUD staff were asked if the LandPKS LCC system could be compatible with current Ethiopian land use planning procedures. Based on 39 responses, 28.2% strongly agreed that it was compatible, 66.7% agreed, approximately 2.6% were undecided, and 2.4% disagreed.

Discussion. This paper has outlined the design of a standardized global LCC system and its integration into the LandPKS mobile app. The standardized LandPKS LCC system helps to address the lack of technical capacity (particularly to characterize soil morphology) necessary to generate the required inputs to generate LCC, and the lack of a digital platform for data input, interpretation, storage, and management.

The Standardized Land Capability Classification System. Given the variability of different LCC systems developed within the United States, the LandPKS LCC system outlined in this paper proved to be relatively consistent with the various LCC implementations, without consistent over- or underestimation. For example, testing found that when compared to the USDA NRCS soil survey data, three counties on average were slightly overestimated and five were marginally underestimated (table 6). Similar conclusions can be made from the LAUD LCC determinations (table 8). Furthermore, the case study in Tanzania highlights the importance of conducting biophysical assessments in land evaluation and land use planning efforts given the often small-scale variability of soils. Lastly, the findings from Ethiopia show (1) consistency of the LandPKS and LAUD LCC determinations and (2) generally positive perceptions of usability and usefulness of the LandPKS LCC classification and mobile phone app.

Achieving the goal of reduced soil degradation and improved natural resource conservation will require an incredible mobi-

Table 8
Comparison of Land-Potential Knowledge System (LandPKS) Land Capability Classification (LCC) results with Ethiopia's Land Administration and Use Directorate LCC results.

	Number of sites with same LCC class	Number of sites with difference of 1 LCC class		Number of sites with difference of 2 LCC classes		
Region	LandPKS = LAUD	LandPKS > LAUD (+1)	LAUD > LandPKS (–1)	LandPKS > LAUD (+2)	LAUD > LandPKS (–2)	Average class difference for region
Amhara	3	3	1	0	0	0.3
SNNPR	6	1	1	0	0	0
Total	9	4	2	0	0	—
Percentage (%)	60	40		0		—

Notes: SNNPR = Southern Nations, Nationalities, and Peoples region. LAUD = Land Administration and Use Directorate.

lization of people and resources, and the standardized LandPKS LCC system presented here provides a new resource that is accessible, free to use, and requires little formal training. Shortfalls in global food production have highlighted the importance of devoting land to its "optimal" use, where the land can make its maximum contribution to feeding the human population, while maintaining long-term sustainability of land uses (Lambin et al. 2014; Rudle and Meyfroidt 2014; UNEP 2016). By determining which lands are not suitable for cultivation, the LandPKS LCC system may help avoid land conversions to agriculture and promote sustainable agriculture in areas well suited for cropping.

In the future, the LandPKS team plans to make more interpretive information available to users in order to better interpret the LCC classes and subclasses. Furthermore, the accessibility of the LandPKS app has already been increased by translating the app into several languages, including Spanish, Swahili, and French. However, there are other limitations of the LandPKS LCC system and the LandPKS app. First, the lack of integration with climate means that users must understand the local climate limitations separate from the LCC class. While the LandPKS app does provide the user with basic climate information, more localized information may be required. Second, the LandPKS LCC class is only part of a crop suitability determination and must be integrated with other information to be used for crop suitability assessments. Third, the LandPKS LCC results are only as accurate as the user inputs, and while our previous work (Salley et al. 2018) shows that nonexperts can still achieve accurate results, training can improve accuracy in hand texturing the soil. In the initial field testing in Tanzania of the LandPKS LCC, it only took about one to three hours to fully train someone on how to use the LandPKS app and the LCC function.

Implications for Natural Resource Conservation in Resource-Poor Contexts. The LandPKS case studies in Tanzania and Ethiopia highlight the usefulness and usability of the LandPKS LCC system for both small and large-scale land evaluation and planning. Furthermore, the LandPKS LCC system partially addresses the call by IPBES (2018) for "more relevant, credible, and accessible information … to improve the long-term stewardship of land and sustainability of natural resource use." Namely, (1) it is accessible because it does not require high levels of literacy or education to use (Herrick et al. 2018; Salley et al. 2018); (2) is free and available to everyone, not just local elites; and (3) is a tool to integrate local and scientific knowledge. Furthermore, LandPKS is a global app, and the LandPKS LCC system can be used to calculate the capability and potential of land, regardless of the geographic location (as demonstrated by assessments in this paper in both developed—United States—and developing—Tanzania and Ethiopia—country contexts highlights) or social/economic/political context.

Tanzania provides an excellent example of a country that has ambitious land use planning goals but often lacks the tools to carry out expensive surveys and biophysical assessments (personal communication, C. Mkalawa, 2018). Tanzania currently uses a six-step process for participatory land use planning and management, involving community members and stakeholders at every step. In order to ensure that village land use plans are technically sound, it is the responsibility of the Participatory Land Use Management team to conduct a systematic assessment of both the biophysical and socioeconomic conditions. The LandPKS team has been working with the National Land Use Planning Commission on the development of the LandPKS LCC system, and the two Tanzanian case studies highlight the importance of integrating biophysical assessments into their land use planning process.

The Ethiopia case study highlights both the compatibility of the LandPKS LCC system with the current LAUD system and also the usability of the system for national to local LAUD staff and administrators. Established by the Ethiopian government, the LAUD is mandated to spearhead activities related to land tenure security, land use planning, and development based on the *Local Level Participatory Land Use Planning Manual*. This manual is a guiding document for the decision-making of optimized and sustainable land use options based on socio-economic, institutional, and natural resource constraints and potentials. Likewise, the general objective of the manual is to facilitate optimum economic benefits and sustainable rural land use through appropriate land use planning, without causing land degradation and environmental pollution in a planning area (Negash 2012). To be an effective system for the LAUD data collection, the LandPKS LCC system must be usable and understandable, and LAUD staff in Ethiopia overwhelmingly found it to be both. The Ethiopian case study also shows how the LandPKS LCC can address issues of access to knowledge, human capacity, and financial resources that can hinder biophysical assessments and land evaluation in the developing world context (Kisambu et al. 2017). Overall, improved land use planning efforts will contribute to improving natural resource conservation, creating more sustainable agricultural systems, and increasing food security in Ethiopia, Tanzania, and beyond.

Summary and Conclusions

This paper (1) outlined the development of a system to facilitate rapid, consistent, and transparent determinations of LCC by nonspecialists using the LandPKS app and (2) evaluated the system through Tanzanian and Ethiopian case studies and comparisons with independent USDA determinations. The system generates results that are comparable with a variety of implementations of the LCC system, and it can be flexibly applied. The LandPKS LCC system helps fill the need for a digital platform for data input, storage, and management (Yonazi et al. 2012; UNEP 2016; IPBES 2018), as well as the lack of technical capacity to collect biophysical data (Kisambu et al. 2017). Through more sustainable land use planning and management, land can become a springboard for those in poverty to improve their socioeconomic condition. The LandPKS app with the integrated LandPKS LCC system is one tool for more scientific, affordable natural resource conservation and sustainable land management.

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