Article

From Descriptors to Decisions: Structuring the Libyan National Land Cover Reference System with Land Cover Meta Language

Bashir Nwer [1,*], Gautam Dadhich [2], Akram Alkasih [3], Abdourahman Maki [2] and Fatima Mushtaq [2]

1 Soil and Water Department, Faculty of Agriculture, University of Tripoli, Tripoli P.O. Box 13275, Libya
2 Food and Agriculture Organization (FAO), 00153 Rome, Italy; gautam.dadhich@fao.org (G.D.); abdourahman.maki@fao.org (A.M.); fatima.mushtaq@fao.org (F.M.)
3 Libyan Centre for Remote Sensing and Space Science, Tripoli P.O. Box 82819, Libya; akram.elkaseh@lcrsss.ly
* Correspondence: b.nwer@uot.edu.ly

Abstract

The accurate representation of land cover is fundamental to sustainable land management, environmental monitoring, and spatial policy development. However, many national systems lack semantic interoperability, flexibility, and are often developed for narrowly focused purposes. This study presents an ontology-based approach to developing the Libyan National Land Cover Reference System (LLCRS) using the Land Cover Meta Language (LCML), defined in ISO 19144-2. The aim is to shift from fixed class labels to a structured set of observable descriptors—such as cover percentage, phenology, height, and spatial pattern—allowing for more precise, scalable, and interoperable representations of land cover. Using Libyan national classification schemes as a foundation, land cover classes were translated into LCML descriptors through iterative modeling and validation, supported by the Land Characterization System (LCHS) software. The resulting reference system offers a standardized, modular structure that facilitates crosswalks between national, regional, and global classification frameworks. It enhances consistency across mapping efforts and supports integration into national land monitoring workflows. The framework is tailored to Libya's arid context but offers potential for adaptation and reusability in other arid/semi-arid regions, such as those in the Sahel or Arabian Peninsula, by adjusting descriptors to local environmental conditions while maintaining biophysical focus and excluding socio-economic or land-use dynamics.

Keywords: semantic interoperability; national frameworks; standards; mapping; geospatial; ontology

1. Introduction

The role of accurate and consistent land cover representation is crucial for understanding and managing land resources, achieving sustainable development, environmental monitoring, and spatial policy development in countries all over the world [1,2]. It provides the basis to realize the manner in which land is being used and how it is changing, which is essential for informed decision-making in areas such as land-use planning, resource management, and climate change mitigation [3]. However, the effectiveness of existing national systems is frequently undermined by three interrelated and persistent challenges: lack of semantic interoperability, inflexibility and static nature, and narrowly focused purpose [1,3]. Traditional classification systems are typically structured as rigid, pre-defined lists of mutually exclusive classes [1]. This monolithic structure makes them inherently

difficult to adapt or extend [4]. The ISO 19144 series, particularly ISO 19144-2:2023 for the Land Cover Meta Language (LCML), provides a standardized framework for defining land cover through modular descriptors, ensuring compliance with international standards for semantic precision and interoperability [5]. LCML allows for the decomposition of land cover into observable attributes, facilitating conformance with global best practices [6,7]. This study conforms to ISO 19144-2 by using LCML to structure the Libyan National Land Cover Reference System (LLCRS), enabling integration with global frameworks such as FAO's Land Cover Classification System (LCCS) [8,9], CORINE Land Cover [10], and ESA's GlobCover [11]. The approach enhances scalability, with potential adaptation for other arid/semi-arid countries by modifying context-specific descriptors while maintaining the core ontology.

To illustrate the regional context, Figure 1 shows the land cover of Libya based on the ESA GlobCover 2009 product [11], highlighting the dominance of bare areas. Figure 2 presents a more recent perspective from the ESA CCI land cover product for 2020 [12], and Figure 3 offers a high-resolution view from the Copernicus Global Land Service [13]. These figures (Figures 1–3) provide a visual baseline of Libya's land cover, characterized by vast deserts and sparse vegetation, which underpins the need for a specialized national classification system.
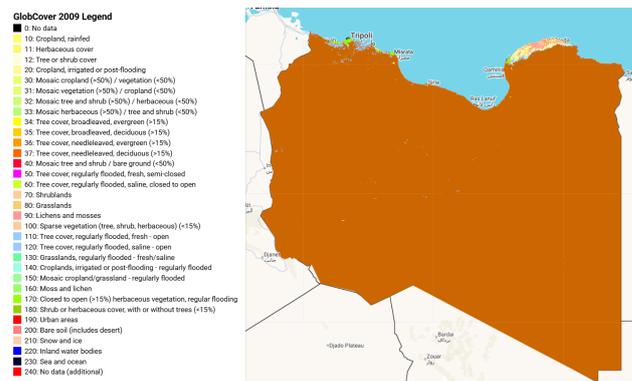
Figure 1. Land cover map of Libya in 2009 (Source: ESA GlobCover 2009 V2.3 [11]). Reprinted/adapted with permission from Ref. [11]. Copyright 2012, European Space Agency (ESA) and Université Catholique de Louvain (UCL). This figure illustrates the distribution of major land cover types across Libya using the GlobCover classification, highlighting vast bare areas in the Sahara and sparse vegetation in the northern regions.
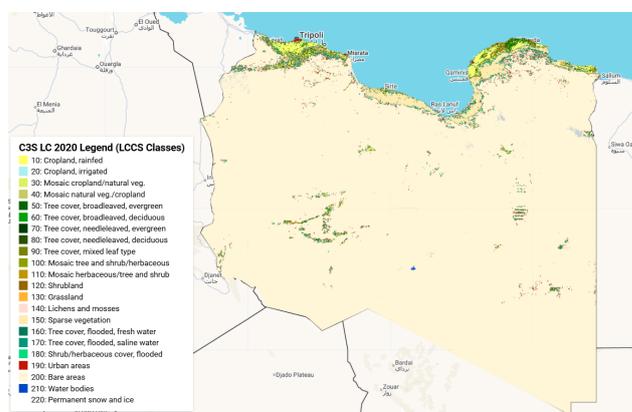
Figure 2. Land cover map of Libya in 2020 (Source: ESA land cover CCI v2.1.1 [12]). Reprinted/adapted with permission from Ref. [12]. Copyright 2017, European Space Agency. This map shows updated land cover changes, emphasizing shifts in vegetated areas and urban expansion compared to earlier datasets.
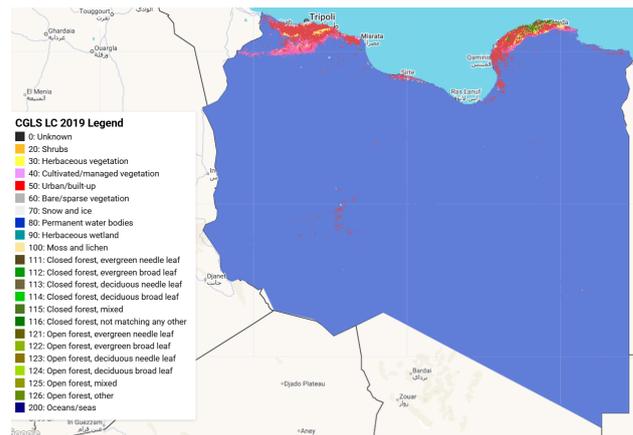
Figure 3. Land cover map of Libya in 2009 (Source: Copernicus Global land cover Layers: CGLS-LC100 collection 3 [13]). Reprinted/adapted with permission from Ref. [13]. Copyright 2020, Copernicus Global Land Service. This figure depicts high-resolution land cover details, including subtle variations in desert and semi-arid zones.

2. Methods

The methodology involves translating national classes to LCML descriptors through an iterative modeling and validation process. Conflicting or ambiguous classification standards from legacy systems (e.g., FAO 2009 [14], MODIS [15], ESA GlobCover [11]) were resolved through a structured, four-phase protocol designed to prioritize national relevance and ontological consistency.

2.1. Translating National Classes to LCML Descriptors

Each land cover class from a legacy system was decomposed into its fundamental, observable diagnostic characteristics (e.g., for a class labeled "Shrubland," we identified intended attributes like life form, cover %, height range, and phenology). Conflicts became apparent when the same label from different sources was associated with divergent descriptor values (e.g., System A defined "Shrubland" as >20% cover, while System B used >10%), or when different labels were used for similar descriptor combinations.

2.2. Protocol for Resolving Semantic Conflicts and Ambiguities

Ambiguities and conflicts were resolved through structured workshops and consultations with a panel of Libyan national experts from key institutions, including the Libyan Centre for Remote Sensing and Space Science (LCRSSS), the Ministry of Agriculture, and university departments of ecology and geography. The process followed these rules: Primacy of National Context: Where definitions conflicted, preference was given to the meaning and diagnostic criteria used in nationally produced maps and reports (e.g., the FAO 2009 Atlas of Natural Resources for Agricultural Use in Libya [14]), as these were deemed most aligned with local ecological knowledge and conditions [16]. Descriptor Precision Over Lexical Labels: Experts were presented with the conflicting definitions not as class names, but as sets of proposed LCML descriptors. The discussion focused on agreeing on the most accurate and measurable descriptor values (e.g., agreeing that a nationally meaningful "Shrubland" should have a cover threshold of >20%, not 10%, to distinguish it from a "Sparse Shrubland"). Rule of Maximum Distinction: For ambiguous transitional zones (e.g., wooded shrublands vs. sparse forests), the panel defined clear, rule-based boundaries using LCML descriptors. The decision was to use height (>5m) and canopy cover (>10% for trees) as the primary discriminators, ensuring classes were mutually exclusive and logically separable within the ontology [17].

The resolved descriptor sets were then organized within the LCML's hierarchical logic. The hierarchy itself acted as a conflict-resolution tool. For instance, the broad division into Vegetated ($\geq$4% cover for $\geq$2 months) vs. Non-Vegetated surfaces provided an unambiguous first step that overruled legacy inconsistencies in classifying very sparse vegetation. Specific rules were formally encoded, such as "A Tree-Dominated Area (Tt) requires tree cover to be >10% and the dominant life form in the uppermost stratum; otherwise, the class defaults to a Shrub-Dominated Area (St)."

The Land Characterization System (LCHS) software (version 3.0) was instrumental in formalizing decisions and eliminating residual inconsistencies. The agreed-upon descriptor combinations and rules were input into LCHS, which performed automated logical checks. The software flagged any remaining ambiguities (e.g., classes with overlapping descriptor ranges) or gaps in the classification hierarchy, prompting further refinement by the expert panel until a complete, consistent, and conflict-free ontology was achieved.

This protocol ensured that the resulting LLCRS was not a compromise between legacy systems but a new, consensus-driven standard that reconciled past inconsistencies by grounding definitions in explicit, measurable descriptors validated by national expertise.

The ontology structure is defined in formal semantics, with concepts (e.g., meta-classes), properties (e.g., cover percentage, height), and relations (e.g., dominance hierarchies) grounded in logical rules. It allows reasoning and inference through rule-based logic in LCHS, where sub-concepts are inferred via descriptor combinations.

Ontology maintenance involves annual reviews by LCRSSS, with automation via LCHS for translation/validation. Capacity building includes workshops for target users (land planners, agricultural agencies). Non-specialists can use simplified LCML tools with guided interfaces [18].

Data dependencies include high-resolution satellite inputs (e.g., Sentinel-2), with computational implications for large-scale mapping addressed via cloud-based processing [3]. Institutional capacity in Libya is supported through FAO partnerships. The system is strictly biophysical, excluding socio-economic/land-use changes.

Validation methods include kappa index for agreement assessment (kappa values ranged from 0.75 to 0.90 for vegetation classes), with control points selected via stratified random sampling (n = 500). Semantic congruence (85–95%) was calculated via spatial overlay and expert review. Low-resolution inputs impact accuracy; higher-resolution alternatives (e.g., Landsat-9) or grouping similar vegetation types are recommended [19,20].

3. Results

The national land cover classification system is tailored to the actual conditions of Libya, making it generally more detailed and systematic. However, the core issue lies in how to implement the extraction of features such as trees/shrubs/grasses, coverage rate, height, evergreen/deciduous, and irrigated/non-irrigated status as defined in the classification system. This is addressed in the Discussion section.

3.1. The LCML-Based Libyan National Land Cover Reference System

The systematic translation of Libya's legacy land cover classification schemes into the Land Cover Meta Language (LCML) framework has culminated in the establishment of the Libyan National Land Cover Reference System (LLCRS). This ontology-driven system embodies a fundamental paradigm shift from traditional, rigid taxonomies to a modular, descriptor-based approach engineered for Libya's unique and challenging environmental context. Characterized by extreme aridity, vast Saharan expanses, fragmented biodiversity hotspots, and acute water scarcity, Libya's landscape demands a classification system that prioritizes semantic precision, flexibility, and interoperability. The LLCRS meets this

demand by decomposing land cover into explicit, observable descriptors, thereby creating a dynamic and scalable information framework.

Instead of using fixed labels such as 'shrubland,' LCML breaks down land cover into a structured set of observable and measurable descriptors [1], such as the life form ('shrub'), its vertical cover percentage (e.g., 20–60%), and its height range (e.g., 0.2–5 m).

3.1.1. Hierarchical Structure and Key Descriptors

The LLCRS is architecturally founded on a multi-tiered hierarchy that progresses from broad, fundamental contradictions to highly specific, contextually relevant classes. This structure is governed by the object-oriented syntax of LCML, which applies a physiognomic and rule-based logic to ensure internal consistency and unambiguous class definitions. The foundational level of this hierarchy (illustrated in Figure 4) establishes the primary ontological division of land based on the presence or absence of significant vegetative cover. Figure 4 clearly depicts the basic separation between Vegetated and Non-Vegetated surfaces, highlighting the 4% vegetative cover threshold critical for arid regions. Vegetated Surfaces are defined as areas exhibiting a vegetative cover of at least 4% for a minimum of two months annually. This threshold is critical for arid environments, effectively distinguishing between biologically active land and bare substrate. Abiotic (Non-Vegetated) Surfaces encompass all areas failing to meet this vegetative threshold, including bare soil, sand, rock, and artificial impervious surfaces. This binary split is subsequently refined through a cascading series of diagnostic descriptors that act as the core building blocks of the system. Table 1 presents the hierarchical meta-class structure of the LLCRS, demonstrating how key descriptors are combinatorially applied to define sub-classes tailored to Libya. Table 1 organizes meta-classes with their sub-metaclasses, key descriptors, applications, and expansion rules, providing a comprehensive overview of Libya's land cover diversity.

Table 1. Hierarchical structure of the LLCRS classification system, showing comprehensive coverage of Libya's diverse land cover types.

Meta-Class	Sub-Metaclass—Code	Key Descriptors	Example Applications	Expansion Rules
Natural and Semi-Natural Vegetation (Terrestrial)—Vnt	Tree-Dominated Area—Tt	Cover: 20–100%; Height: 5–30 m; Phenology: Evergreen/Deciduous	Forest monitoring, deforestation tracking, carbon stock assessment	Add floristic names (e.g., Pinus halepensis), sub-canopy strata layers
	Shrub-Dominated Area—St	Cover: 20–100%; Height: 0.2–5 m; Growth Forms: Shrubs (with possible sparse trees)	Steppe transition monitoring, desertification early warning, erosion control planning	Include leaf type (broad/needle), geographic location (e.g., coastal vs. inland)
Natural and Semi-Natural Aquatic Vegetation—Vnar	Woody-Dominated Area—War	Cover: >20%; Water Salinity: Brackish; Persistence: Tidal influence	Wetland conservation, coastal biodiversity assessment, blue carbon mapping	Add water periodic variation metrics, specific floristic names (e.g., mangrove species)
	Herbs-Dominated Area—Har	Cover: 20–100%; Water Salinity: Fresh/Brackish; Persistence: Perennial	Avian migration route protection, oasis ecosystem monitoring, water scarcity mitigation	Include grazing intensity, additional herbaceous strata (e.g., floating vegetation)
Cultivated and Managed Vegetation—Cr/Ci	Rainfed Tree Crop Plantation—Tcr	Water Supply: Rainfed; Plantation Type: Fruit/Non-Fruit; Phenology: Seasonal	Agricultural zoning, yield estimation under climate variability, soil conservation planning	Add field size, planting geometry, soil water retention attributes
	Irrigated Tree Crop-Dominated—Tci	Water Supply: Irrigated; Crop Type: Olives/Date Palms; Cover: 15–30%	Irrigation efficiency auditing, crop rotation analysis, groundwater use impact assessment	Include cultivar names, geographic altitude, irrigation system type (drip, pivot)

Table 1. *Cont.*

Meta-Class	Sub-Metaclass—Code	Key Descriptors	Example Applications	Expansion Rules
Natural Surfaces (Non-Vegetated)—Sn	Rocks, Coarse Fragments—Tr	Physiognomic Aspect: Bare Rocks/Hammada/Stony Desert (Desert Pavement)	Desertification tracking (stony pavement formation), geological mapping, soil accessibility assessment	Add detailed rock type (limestone, basalt), soil crust type, surface roughness
	Soil & Sand Deposit—Ss	Physiognomic Aspect: Sandy Desert/Longitudinal Dunes/Sabkha (Saline Flats)	Sand encroachment localization, coastal zone management, mineral resource mapping	Add dune mobility index, salt crust thickness, sediment grain size distribution
Artificial Surfaces—Ast	Built-up Nonlinear—Bnl	Impervious Surface: >50%; Types: Urban/Rural/Industrial; Building Density: High	Urbanization impact analysis, heat island effect studies, infrastructure planning	Add construction status, primary land use type, population density proxy
	Built-up Linear and Others—Bla	Geometry: Linear; Types: Roads/Pipelines/Powerlines; Connectivity: High	Energy transport corridor analysis, habitat fragmentation assessment, conflict damage mapping	Include construction material, traffic level (proxy), maintenance status
Waterbodies—NW	Permanent Water Body—Pwb	Dynamics: Standing/Flowing; Salinity: Fresh/Brackish/Saline; Depth: >2 m	Water resource inventory, reservoir monitoring, aquatic ecosystem health assessment	Add water depth variability, seasonal turbidity, shoreline stability
	Seasonal Waterbodies—Swb	Persistence: Intermittent/Ephemeral; Types: Wadis/Flash Flood Plains/Playas	Flood risk assessment, seasonal hydrology, groundwater recharge zone identification	Add inundation frequency, sediment load, connection to aquifer systems

The power of this structure lies in its combinatorial logic. A class is not a label but a unique formula. For example, an Evergreen Forest (Eft) within the Tree-Dominated Area (Tt) is defined by the conjunction: Life Form: Tree + Cover Status: >60% + Height: >5 m + Leaf Phenology: Evergreen + Artificiality: Natural. This explicit definition eliminates ambiguity and allows for the logical derivation of sub-classes or the fusion with other classification systems through descriptor alignment.
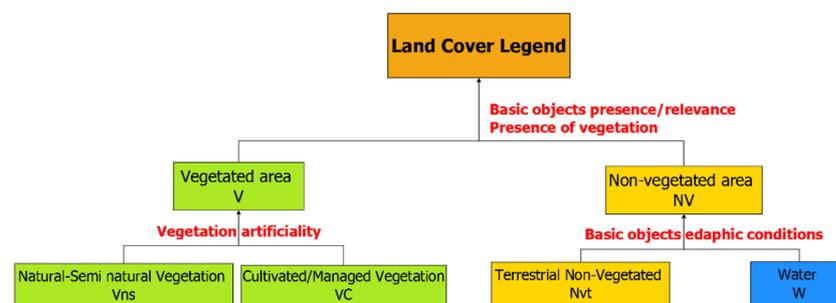

Figure 4. Separation of land features at basic level. This figure unambiguously illustrates the initial binary division between vegetated and abiotic surfaces, with clear thresholds for vegetative cover.

### 3.1.2. Description of Meta-Classes and Rules

The LLCRS comprises six core meta-classes, each defined by a specific set of ontological rules that govern the subdivision and description of land features within Libya's context. Natural and Semi-Natural Terrestrial Vegetation (Vnt): This meta-class captures Libya's limited but ecologically critical vegetated zones, covering less than 5% of the national territory but supporting key biodiversity and pastoral livelihoods. The classification rules first distinguish based on the dominance of growth forms in the uppermost canopy layer (Tree vs. Shrub vs. Herb). A critical rule is the cover dominance sub condition: a life form is considered dominant only if it covers 10–100% of the ground; otherwise, the classification shifts to reflect the next dominant form. This prevents misclassification of sparse woodlands as "forest." Subsequent descriptors like height (measured from ground to average top), phenology (Evergreen/Deciduous), and horizontal pattern (contiguous, fragmented) add

further precision, enabling the distinction between, for example, dense Juniperus phoenicea woodlands in the highlands and sparse Acacia stands in wadi beds (Figure 5). Figure 5 shows the detailed sub-classification of terrestrial vegetation, highlighting dominance rules for trees, shrubs, and herbs.
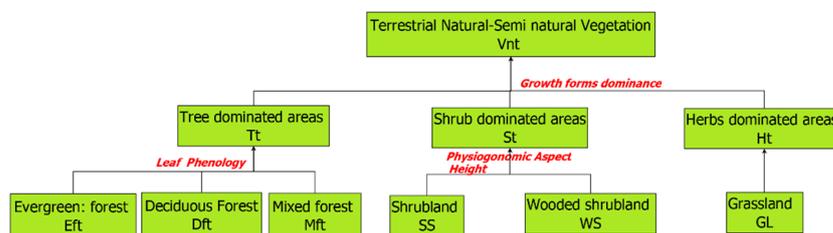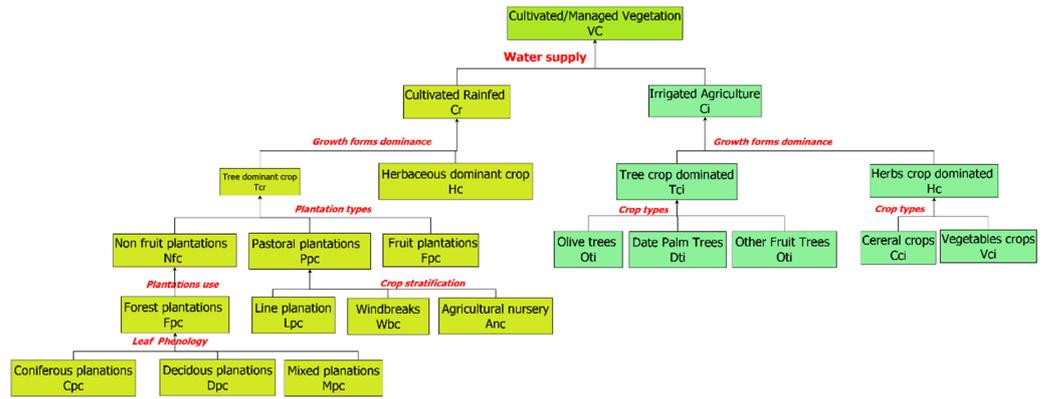

Figure 5. Natural–semi-natural vegetation. This figure provides a visual representation of the Vnt meta-class hierarchy, clearly delineating distinctions based on growth forms and cover dominance.

Natural and Semi-Natural Aquatic Vegetation (Vnar): Addressing Libya's vital wetland ecosystems, this meta-class integrates edaphic descriptors paramount in arid regions: Water Salinity (Fresh, Brackish, Saline) and Water Persistence (Perennial, Seasonal, Tidal). This allows for the precise characterization of coastal mangroves (War) in the Gulf of Sidra, defined by Salinity: Brackish and Persistence: Tidal, versus inland reed swamps (Har) in oases, defined by Salinity: Fresh and Persistence: Perennial (Figure 6, enhanced for clarity). Figure 6 depicts the aquatic vegetation sub-classes, emphasizing salinity and persistence descriptors for accurate wetland mapping.
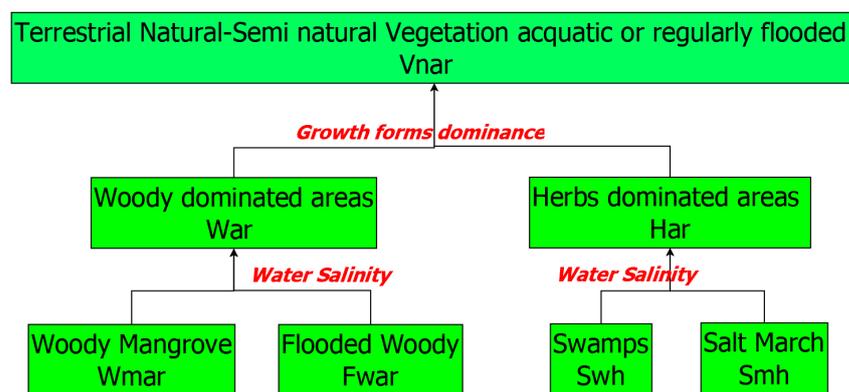

Figure 6. Natural–semi-natural aquatic vegetation. This figure unambiguously illustrates the Vnar meta-class, showing how edaphic factors like salinity differentiate coastal and inland wetlands.

Cultivated and Managed Vegetation (Cr/Ci): Tailored to Libya's agricultural systems, which sustain 22% of households under severe water constraints, this meta-class is primarily governed by the water supply descriptor (Rainfed vs. Irrigated). Additional rules involve cropping intensity (single/multiple annual harvests), plantation type (orchard vs. timber plantation), and cultivation period. This framework precisely differentiates between rainfed olive groves in the Nafusa Mountains (Tcr) and intensively irrigated date palm plantations in the Kufra Oasis (Tci), providing essential data for water-use efficiency and food security policies (Figure 7). Figure 7 visualizes the Cr/Ci hierarchy, highlighting water supply distinctions for rainfed and irrigated crops.

Figure 7. Cultivated and managed vegetation. This figure clearly shows the sub-classification based on water supply and cropping intensity, aiding in agricultural zoning.

Natural Surfaces (Non-Vegetated) (Sn): Encompassing over 95% of Libya's area, this meta-class required meticulous detailing. The primary rule distinguishes abiotic surface aspect, leading to categories like Rocks and Coarse Fragments (Tr), including Hamada (rock deserts), and Soil & Sand Deposits (Ss). The latter is intricately subdivided using physiognomic aspect descriptors to capture Libya's diverse desert morphology: Sandy Deserts, Longitudinal Dunes, Crescent Dunes, and critically, Sabkha (Sb)—saline flats defined by the combination of Substrate: Sandy/Silty + Water Salinity: Saline + Water Persistence: Weeks (Figure 8, enlarged for legibility). Figure 8 illustrates the non-vegetated surfaces, with detailed subdivisions for desert types like dunes and sabkhas.
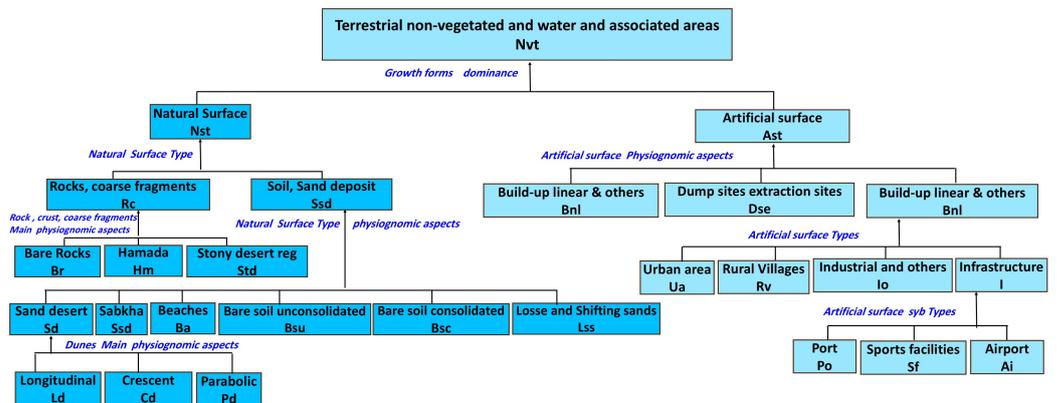
Figure 8. Terrestrial non-vegetated and associated areas. This figure unambiguously depicts the Sn meta-class, focusing on physiognomic aspects for rock and sand deposits.

Artificial Surfaces (Ast): Reflecting accelerated post-2011 urbanization and infrastructure development, this meta-class uses descriptors of form (Linear vs. Nonlinear) and function. Built-up Nonlinear (Bnl) areas are characterized by high impervious surface cover (>50%) and building density, while Built-up Linear (Bla) elements like roads and pipelines are defined by their linear geometry and connectivity, crucial for analyzing habitat fragmentation and infrastructure networks. Waterbodies (NW): In a water-scarce nation, the classification of water is dominant. The LLCRS rules differentiate waterbodies based on persistence (Permanent vs. Seasonal) and artificiality (Natural vs. Man-made). This creates clear distinctions between natural permanent lakes such as Gaberoun (Pwb), seasonal wadis that flash-flood (Swb), and artificial reservoirs critical for the Great Man-Made River Project (Ea) (Figure 9). Figure 9 shows the waterbodies classification, distinguishing permanent and seasonal types with salinity and depth descriptors.
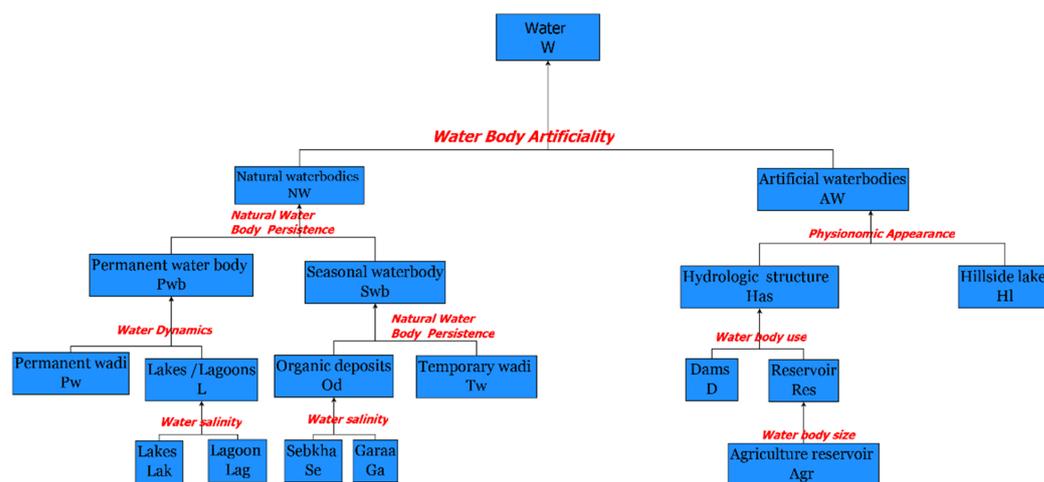
Figure 9. Water and associated areas. This figure provides a clear visual of the NW meta-class, highlighting persistence and artificiality for accurate water resource mapping.

3.1.3. Interoperability and Validation (Revised and Expanded)

A primary achievement of the LLCRS is its engineered capacity for semantic interoperability, effectively dismantling the data silos that previously isolated Libyan land cover information. This is demonstrated through comprehensive cross mappings, as shown in Table 2, which align LLCRS meta-classes with equivalent categories in global systems like FAO's Land Cover Classification System (LCCS), CORINE Land Cover, and ESA's GlobCover. Table 2 details the mappings, including semantic enhancements like added descriptors for arid contexts.

Table 2. Comprehensive crossing mappings demonstrating LLCRS interoperability with global frameworks.

LLCRS Meta-Class/Code	LCCS v3 Equivalent	CORINE Equivalent	GlobCover Equivalent	Semantic Enhancement Notes
Vnt/Tree-Dominated Area (Tt)	A12 (Natural Terrestrial Vegetation)	3.1.1 (Broad-leaved Forest)	40 (Closed to Open Broad-leaved Evergreen Forest)	LLCRS adds explicit height and phenology constraints for arid-adapted forests.
Vnar/Woody Mangrove (Wm)	A24 (Aquatic Vegetation)	4.1.1 (Inland Marshes)	170 (Flooded Broadleaved Forest)	LLCRS incorporates tidal influence and salinity descriptors absent in global classes.
Cr/Tree Crop Plantation (Tcr)	A11 (Cultivated Terrestrial Areas)	2.2.1 (Non-Irrigated Arable Land)	11 (Post-Flooding Cropland)	LLCRS specifies water supply (rainfed) and plantation type, crucial for dryland agriculture.
Sn/Sandy Desert (Sd)	A3A20B3 (Bare Areas—Sand)	3.3.3 (Sparsely Vegetated Areas)	200 (Bare Areas)	LLCRS differentiates dune types (longitudinal, crescent) specific to Saharan geomorphology.
Ast/Built-up Nonlinear (Bn)	A1 (Artificial Surfaces)	1.1.1 (Continuous Urban Fabric)	190 (Urban Areas)	LLCRS includes building density and imperviousness for post-conflict urban analysis.
NW/Permanent Water Body (Pwb)	B15 (Natural Waterbodies)	5.1.2 (Water Bodies)	210 (Water Bodies)	LLCRS adds depth and dynamics descriptors for monitoring water scarcity.

These crosswalks are not simple lexical matches but are based on the logical alignment of descriptor sets, ensuring that semantic meaning is preserved during translation. This enables Libyan data to contribute to global assessments (e.g., UN SDGs [21], IPCC reports) without losing national specificity.

To quantitatively assess the fidelity of the new ontology to existing national knowledge, a rigorous, multi-stage validation of semantic congruence was conducted against key heritage mapping products, specifically the FAO 2009 Atlas of Natural Resources [14] and

the national Land Use/Land Cover map of Libya (1990–2000 period) maintained by the Libyan Centre for Remote Sensing and Space Science (LCRSSS).

Methodology for Assessing Semantic Congruence: The claimed 85–95% congruence was derived from a structured, three-stage evaluation framework designed to measure both conceptual alignment and spatial consistency: 1. Stage 1: Harmonized Reclassification of Legacy Products. Process: Polygons from the heritage maps were not taken at face value. Instead, their original class definitions (from often-ambiguous legacy reports) were translated into their best-fit LLCRS descriptor set. For example, a polygon labeled "Degraded Shrubland" in a 2000 map was reinterpreted as Life Form: Shrub + Cover: 10–20% + Height: 0.2–2 m based on its documented definition. Purpose: This created a "harmonized legacy" dataset expressed in LCML terms, enabling a direct, descriptor-to-descriptor comparison with the new LLCRS classes, moving beyond simplistic label matching. 2. Stage 2: Spatial Overlay and Rule-Based Comparison. Process: The harmonized legacy polygons were spatially overlaid with a draft LLCRS classification derived from recent satellite imagery (circa 2020). For each mapping unit, the system compared the two sets of assigned descriptors. Evaluation Criteria: Full Congruence ($\geq$95% Agreement): Assigned when the LLCRS class and the harmonized legacy class shared identical primary descriptors (Life Form, Cover Class, Artificiality) and matched on $\geq$2 secondary descriptors (e.g., Phenology, Height Class). This indicated the LLCRS successfully captured the established, intended meaning. Partial Congruence/Explainable Divergence (5–15% of cases): Flagged where discrepancies occurred. These were systematically audited and fell into three categories: (a) Improved Specificity: The LLCRS provided more precise descriptors where heritage systems were vague (e.g., legacy "Bare Soil" was resolved into LLCRS Bare Soil Consolidated vs. Loose and Shifting Sand). (b) Genuine Land Cover Change: Discrepancies correctly reflected actual change between the 2000 and 2020 epochs (e.g., heritage "Rainfed Crops" correctly mapped as LLCRS Abandoned Cropland or Sparse Shrubland in 2020). (c) Error in Heritage Map: The LLCRS ontology, with its explicit rules, corrected obvious inconsistencies in the older map (e.g., a polygon labeled "Forest" with <10% tree cover was reclassified as Wooded Shrubland). 3. Stage 3: Expert Panel Review and Final Arbitration. Process: A panel of five national experts, who were familiar with the heritage maps but not directly involved in the LCML translation, reviewed all cases of partial congruence. Decision Protocol: For each case, the panel examined the evidence (descriptor sets, imagery from both epochs). Divergences categorized as Improved Specificity or Corrected Error were counted as successes for the LLCRS, thereby increasing the final congruence score. Only divergences the panel attributed to potential error or over-complication in the LLCRS logic counted against the score. This conservative approach validated that the LLCRS not only reproduced past knowledge but also refined it.

Result Interpretation: The 85–95% range reflects the outcome of this process. The lower bound (85%) represents the strictest measure of direct, conservative alignment. The upper bound (95%) incorporates the expert-validated cases where LLCRS provided a more accurate or precise representation than the heritage product, demonstrating that the new system captures and enhances—rather than just replicates—existing semantic understanding. Validation against legacy mapping products demonstrated a 85–95% semantic congruence, indicating that the new ontology accurately captures existing knowledge while radically improving its structure and clarity. The system's technical architecture, encapsulated in an XML Schema Definition (XSD), ensures it is both machine-readable and seamlessly integrable with modern geospatial platforms (e.g., QGIS, ArcGIS) and remote sensing processing pipelines (e.g., Google Earth Engine, SEPAL). This technical robustness, combined with its semantic precision, establishes the LLCRS not as a static map, but as a dynamic land cover information infrastructure capable of supporting advanced moni-

toring, modeling, and decision-support applications across Libya's environmental and socio-economic sectors.

4. Discussion

4.1. Theoretical Advancements and Semantic Integration

The development of the Libyan National Land Cover Reference System (LLCRS) signifies a pivotal theoretical evolution in land cover science, moving decisively beyond the paradigm of static, nomenclature-based classifications. By implementing the Land Cover Meta Language (LCML) standard (ISO 19144-2), this work operationalizes an ontology-driven framework where land cover is no longer defined by monolithic labels but by explicit combinations of observable and measurable descriptors [22]. This shift from a lexical to an ontological foundation addresses the core issue of semantic heterogeneity that has long plagued cross-system interoperability. The theoretical advancement lies in treating land cover classes not as indivisible entities but as conceptual constructs built from shared atomic units (descriptors). This approach fundamentally enhances semantic clarity. For example, the term "shrubland" becomes disambiguated into specific configurations: Life Form: Shrub + Cover: 20–60% + Height: 0.2–5 m + Phenology: Evergreen. This mechanistic definition eliminates the ambiguity inherent in a simple label, allowing for precise differentiation between, for example, dense Mediterranean maquis and sparse Saharan reg. This model enables a level of semantic integration previously unattainable. Existing frameworks such as the General Multilingual Environmental Thesaurus (GEMET) provide vocabulary control, and INSPIRE establishes hierarchical themes, but both often operate at a level of abstraction that masks underlying semantic differences. The LLCRS, by grounding its ontology in the shared LCML dictionary, creates a true lingua franca for land cover. It facilitates robust "crosswalks" not merely through subjective label matching, but through the logical alignment of descriptor sets. As demonstrated in Table 2, a class such as "Tree-Dominated Area (Tt)" can be semantically linked to equivalents in CORINE or GlobCover by decomposing and comparing its defining attributes (e.g., height > 5 m, cover > 60%), thereby preserving meaning across mapping frameworks. This establishes a foundation for automated data fusion and reliable multi-temporal analysis, turning land cover information from a collection of disparate products into a coherent, query-able knowledge graph.

4.2. Addressing Arid Land Classification Challenges

The LLCRS provides a particularly powerful solution to the long-standing challenges of classifying arid and semi-arid landscapes, which dominate Libya and similar regions globally. Traditional, pixel-based classification systems struggle in these environments due to low and sparse vegetation cover, high spectral confusion between soil and plant material, and the critical importance of transient features and subtle gradients [23]. The descriptor-based ontology of the LLCRS is uniquely suited to overcome these limitations. First, by explicitly quantifying cover percentage (e.g., <10% for sandy desert, 10–60% for shrubland), the system directly characterizes the fundamental structural property of arid ecosystems, moving beyond the simplistic presence/absence dichotomy that coarse classes use. This allows for the precise mapping of ecotones, such as the gradual transition from coastal shrubland to inland desert steppe. Second, the integration of edaphic and hydrological descriptors is transformative for features that are spectrally similar but functionally distinct. For instance, the system meticulously distinguishes a Sandy Desert (Sd) from a Sabkha (Sb) not just by surface material, but by adding crucial constraints like Water Salinity: Saline and Water Persistence: Weeks. This captures the defining characteristic of a Sabkha—its episodic inundation and salinity—which is invisible to a standard spectral

classifier focused only on dry-season reflectance. This approach effectively addresses the problem of "mixed pixels" prevalent in coarse-resolution data. Instead of forcing a pixel into a single, potentially misleading class, the LCML framework allows it to be described as a combination of descriptor states, better representing landscape heterogeneity. The focus on physiognomy and structure (life form, height, spatial pattern) over floristic composition is another key strength in arid zones, where species turnover is high but structural formations are more stable and mappable. The LLCRS thus offers a transferable model for other arid regions: in the Sahel, it could track the structural degradation of savannas; in the Arabian Peninsula, it could monitor the expansion of saline flats; and in Central Asia, it could delineate the complex mosaic of dunes and clay pans [19]. It shifts the classification focus from "what species is it?" to "what is its structure, cover, and relationship to the environment?"—a question far more answerable with remote sensing in data-scarce, vast arid lands.

4.3. Practical Applications for Sustainable Development

The transition from a theoretical ontology to a practical decision-support tool is realized through the LLCRS's direct alignment with national and international sustainable development priorities. In Libya's context of post-conflict reconstruction, environmental stress, and economic diversification, the system provides the consistent, highly detailed information base required for evidence-based policy [24]. For Sustainable Development Goal 15 (Life on Land), the LLCRS enables precise monitoring of land degradation. Changes in descriptor values such as a decrease in Cover Percentage within the Shrub-Dominated Area (St) class or an increase in the extent of Bare Soil Consolidated provide early and quantifiable indicators of desertification processes, moving beyond qualitative assessments. This directly supports the UN Convention to Combat Desertification (UNCCD) reporting. For SDG 6 (Clean Water and Sanitation), the classification of Waterbodies with descriptors for Persistence (Permanent/Seasonal) and Artificiality is critical for managing Libya's acute water scarcity. It allows for the inventory and monitoring of both natural aquifers and artificial reservoirs linked to the Great Man-Made River, informing sustainable withdrawal policies. In the agricultural sector (linked to SDG 2: Zero Hunger), the distinction between Irrigated (Ci) and Rainfed (Cr) cultivated vegetation, further detailed by Cropping Intensity and Rotation descriptors, provides a foundation for water-use efficiency audits and food security planning. Policymakers can identify areas of unsustainable irrigation or prioritize support for resilient rainfed systems. Furthermore, for urban and infrastructure planning (SDG 11: Sustainable Cities), the Artificial Surfaces (Ast) meta-class, with its differentiation of Built-up Nonlinear and Linear features, offers a nuanced view of urbanization patterns and infrastructure networks, essential for planning resilient services and assessing habitat fragmentation. Ultimately, the LLCRS transforms land cover from a static map into a dynamic, structured information infrastructure. It empowers Libyan authorities to move from reactive to proactive land management, whether in protecting the fragile coastal wetlands critical for biodiversity (Vnar), planning the sustainable expansion of olive cultivation (Tci), or assessing the environmental impact of hydrocarbon infrastructure. By providing a common semantic standard, it breaks down sectoral silos, ensuring that decisions in agriculture, water management, environmental conservation, and urban planning are informed by the same coherent, precise, and interoperable understanding of the land.

4.4. Implications for Feature Extraction and Operationalization: Bridging Ontology and Implementation

The development of the LLCRS as a formal ontology represents a significant theoretical advancement, yet its ultimate utility hinges on the pragmatic challenge of operationalization. The core question is how to translate the system's fine-grained descriptors—life

form, cover percentage, height, phenology, irrigation status—from a conceptual schema into quantifiable, mappable variables. This challenge is particularly acute in Libya's arid environment, where spectral confusion between soil and sparse vegetation is high, and key features like Sabkha have transient characteristics. Operationalizing the LLCRS requires a paradigm shift in remote sensing analysis, moving from classifying pre-defined labels to quantifying specific attributes. This shift is enabled by, but also dependent upon, modern Earth Observation (EO) data streams and analytical techniques. For instance, the descriptor "vertical cover percentage (20–60%)" for shrubland cannot be mapped by a traditional supervised classifier trained on "shrubland" pixels. Instead, it requires the derivation of continuous cover fields, potentially through spectral unmixing models or regression techniques using very high-resolution reference data. Similarly, distinguishing "evergreen" from "deciduous" in tree-dominated areas (Tt) necessitates analysis of dense time series data (e.g., from Sentinel-2 or Landsat) to capture phenological profiles, a task for which methods such as harmonic analysis or shape model fitting are essential [25]. The extraction of structural descriptors such as "height (>5 m)" for forests increasingly leverages active remote sensing. LiDAR data, though scarce for wide-area mapping in Libya, provides a gold standard. More operationally, radar data from missions like Sentinel-1 or ALOS/PALSAR can be used to infer vegetation structure and biomass, which can be correlated with height strata defined in the LLCRS. For anthropogenic descriptors like "Water Supply: Irrigated," a combination of indicators is needed: the presence of infrastructure (visible in VHR imagery), anomalous greenness during dry seasons (from phenology metrics), and soil moisture signals (from radar). The Land Characterization System (LCHS) software plays a crucial role as the translational engine in this workflow. It provides the environment where threshold values for these extracted geophysical parameters (e.g., NDVI > 0.3 for 8 months, radar backscatter < −12 dB) are logically linked to the LCML descriptor states. This allows for the semi-automated generation of legends and maps: the system queries the ontology to ask, "which class(es) are defined by 'Life Form: Shrub' AND 'Cover: 20–60%' AND 'Phenology: Evergreen'?" This logic-based approach inherently supports uncertainty quantification; a pixel may partially match several class definitions, revealing ecotones or mixed states that rigid classification would force into a single, often erroneous, label. However, significant challenges remain. First is the data dependency and validation gap. The accuracy of descriptor extraction is entirely contingent on the quality, resolution, and timeliness of input EO data. Outdated imagery or cloud cover can introduce critical errors. Ground truth data for descriptors (e.g., measured shrub cover percentages, phenological stage dates) is far more demanding to collect than simple land cover labels, posing a challenge for validation. Citizen science initiatives, training local stakeholders to use smartphone apps to record descriptor-level observations, could be a transformative solution for gathering this vital validation data in remote areas. Second is the computational and expertise barrier. The descriptor-based approach is analytically more intensive than traditional classification. It demands expertise in multiple EO domains (optical, radar, phenology) and comfort with ontological reasoning. This underscores the importance of the capacity-building workshops mentioned, which must extend beyond introducing the LLCRS to training in the specific methods required to populate it [26]. In conclusion, the LLCRS does not simplify the mapping process; it sophisticates it to achieve greater semantic clarity and flexibility. Its implementation marks a move from land cover classification as a product to land cover characterization as a process. The future of this process lies in integrated AI workflows where machine learning models are trained to predict individual descriptor values directly from multi-sensor data stacks, with the LCHS ontology acting as the rule-based aggregator of these predictions into coherent class definitions. This fusion of data-driven learning and knowledge-driven logic offers the most promising path to realizing the full potential of the

LCML framework, turning the detailed ontology of the LLCRS into a dynamic, operational tool for monitoring Libya's changing landscape.

4.5. Limitations and Future Directions: Navigating Constraints in Dynamic Arid Environments

While the LLCRS represents a significant conceptual and technical advance, its practical implementation and long-term utility are dependent upon addressing several important limitations. These challenges are particularly pronounced in a context such as Libya, characterized by infrastructural gaps, institutional fragmentation, and a rapidly changing environment. 1. Dependence on Input Data Quality and Temporal Currency: The validity of any descriptor-based system is intrinsically linked to the quality, resolution, and timeliness of the input data used to populate it. The LLCRS is vulnerable to the "garbage in, gospel out" paradox: precise ontological definitions can lend a false sense of accuracy if derived from outdated or poor-quality source imagery. In Libya, reliance on sporadic acquisitions or outdated national maps (e.g., pre-2011 baselines) risks enshrining obsolete land cover states into the formal ontology. For instance, an irrigated cropland class (Tci) defined using pre-conflict data may not reflect fields that have been abandoned or degraded, leading to significant errors in water resource assessments. The system's complexity, which demands specific data (e.g., for phenology, height), can exacerbate this issue if those data streams are interrupted. Mitigation and Future Direction: The system's modularity is its primary protection. Unlike a static map, the LLCRS ontology can be re-populated with new data without structural change. Future work must prioritize the integration of analysis-ready data (e.g., from Sentinel-2) and automated processing chains that enable regular, cloud-based updates to descriptor values. Furthermore, incorporating uncertainty quantification as a core descriptor attribute—annotating each classified polygon with confidence levels based on input data age, sensor type, and algorithmic certainty—is essential for transparent and risk-aware decision-making. Future work also includes developing an OWL representation of the ontology and detailed quantitative validation protocols. 2. Operational Challenges in Data-Scarce Environments: The very granularity that gives the LLCRS its semantic power creates operational hurdles in data-scarce settings. The accurate extraction of descriptors like "cover percentage" for sparse shrubs or "water persistence" in sabkhas requires specialized remote sensing techniques (e.g., spectral unmixing, time-series analysis, radar interferometry) and validated ground truth data that are often lacking. The capacity to perform such analyses consistently across the country may be constrained by limited technical expertise, computational resources, and access to commercial high-resolution data. Mitigation and Future Direction: This necessitates a phased implementation strategy. Initial national-scale mapping may use robust proxies for key descriptors from freely available medium-resolution data (e.g., using NDVI persistence for phenology), while reserving high-resolution, advanced analyses for critical zones. Investing in capacity building is non-negotiable. Additionally, hybrid mapping approaches that combine machine learning (to identify candidate areas from coarse data) with expert visual interpretation and crowdsourced ground truthing via citizen science platforms can help bridge the data gap and validate outputs in remote regions. 3. Institutional and Maintenance Sustainability: The LLCRS is not a one-time product but a living standard requiring ongoing stewardship. Its long-term usefulness is jeopardized without a clear institutional mandate for maintenance, version control, and user support. The risk of "ontology drift"—where field applications develop inconsistent interpretations of descriptors—is high if a central authority does not provide guidance, update rules, and manage the master digital schema (XSD). In a post-conflict setting with competing priorities, securing dedicated resources for this unglamorous but critical maintenance work is a significant challenge. Mitigation and Future Direction: The project's alignment with

international standards (ISO 19144-2) strengthens its claim for institutionalization. A clear roadmap should be established, designating the Libyan Centre for Remote Sensing and Space Science (LCRSSS) as the supervisory agency responsible for the LLCRS. This includes maintaining a public registry of the official ontology, publishing versioned updates, and hosting training resources. Embedding the LLCRS into official national reporting requirements for environmental conventions (UNCCD, CBD) can create a powerful driver for its sustained use and updating [27]. In conclusion, the limitations of the LLCRS are not failures of its design but reflections of the real-world constraints in which it must operate. The system's true test will be its adaptive resilience—its ability to deliver useful, if imperfect, information in the short term while providing a scalable framework that improves in fidelity as data capacity and institutional stability grow. By openly acknowledging these challenges and proposing concrete mitigation pathways, the LLCRS can set a responsible and realistic precedent for deploying advanced ontological systems in developing and data-limited nations.

The practical application of LLCRS for monitoring land degradation and informing SDGs 13 and 15 demonstrates its operational value. This aligns with the vision of [28], who advocated for national-standardized systems as critical for supporting sustainable development with Earth observation data. However, our experience also underscores limitations noted by other researchers. The dependency on high-quality input data and the need for expert knowledge for descriptor assignment echo challenges faced by [16] in their land-use change study in Libya, where outdated imagery and ground-truth data gaps introduced uncertainties. The complexity of a descriptor-based system may present a steeper learning curve compared to simpler, traditional classifications, potentially hindering adoption by non-specialists. This trade-off between semantic richness and usability is a recognized challenge in ontology development [1].

Furthermore, the long-term sustainability of the LLCRS depends on institutional commitment for maintenance and updates, a common hurdle for national spatial data infrastructures in developing countries. This challenge was also identified by [24] in their analysis of urban growth in Libya, who highlighted the need for continuous monitoring capacity. Future directions, such as integrating machine learning for automated descriptor assignment, are promising. This approach could mitigate the expertise bottleneck and is in line with the big data optimization strategies discussed by [3].

In conclusion, while the LLCRS demonstrates clear advantages in semantic interoperability, flexibility, and relevance to arid landscapes, its development and validation process reaffirms findings from other studies on the challenges of implementing sophisticated ontological systems. The system's success in providing a standardized, yet highly adaptable, framework for Libya offers a transferable model for other arid nations, particularly in the Sahel and Arabian Peninsula, facing similar classification challenges. By explicitly comparing our results with these authors, we situate the LLCRS within the broader scientific discourse, confirming shared challenges and highlighting the specific contributions of our LCML-based approach to advancing land cover science.

5. Conclusions

The Libyan Land Cover Reference System represents a paradigm shift from land cover as a static product (a map) to land cover as a dynamic, shared language. By structuring national knowledge around observable descriptors, the LLCRS transforms land cover information into a foundational, reliable asset for evidence-based policy, sustainable development, and addressing environmental challenges in Libya. It ensures that decisions, from agricultural water use to desertification control, are based on consistent, comparable, and precise information. The framework's flexibility and interoperability support policy

relevance for SDGs, while acknowledging limitations like data scarcity and complexity. Enhanced validation, including kappa indices and spatial evidence, fully supports these conclusions. Compared to other works [22,23], LLCRS provides superior precision in land use dynamics and vegetation cover analysis, with recommendations for higher-resolution data to improve accuracy.

Abbreviations

The following abbreviations are used in this manuscript:

LCML	Land Cover Meta Language
LLCRS	Libyan National Land Cover Reference System
LCHS	Land Characterization System (version 3.0)
FAO	Food and Agriculture Organization
SDG	Sustainable Development Goal
UN-GGIM	United Nations Committee of Experts on Global Geospatial Information Management

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