ЕКОНОМІКА. ЗЕМЕЛЬНІ ВІДНОСИНИ ТА АКТУАЛЬНІ ПРОБЛЕМИ ЗЕМЕЛЬНОЇ РЕФОРМИ

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ONTOLOGY OF BOUNDARIES IN THE SYSTEM OF MODERN LAND MANAGEMENT: FROM GEOMETRY TO THE REGIME OF RIGHTS AND VALUES

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Abstract. *The article conceptualizes the notion of a boundary in modern land management as an institutional-regime category that transcends the geometric interpretation of a dividing line. Based on comparative-historical and institutional analysis, norm-oriented modeling, and formal ontologization (LADM), it substantiates the transition from a material-geometric to a regime-based ontology of space, where the boundary functions as an event-relation that constitutes rights, restrictions, responsibilities, and rent flows. Four structural levels of the boundary-material, legal, informational, and ecological-are identified, and their supervenient relations and the causal influence of procedural data validity on the legitimacy of regimes are demonstrated. The principles of ontological boundary design are formulated (procedural*

constitutiveness, multimodality, adaptability, quality metricity, compatibility and priorities, value transparency), which enable the integration of legal norms, spatial data, and mechanisms of land value management. The practical significance lies in the transition from a "register of lines" to a dynamic regime-based model of space for cadastral and planning systems, improving decision quality, minimizing conflicts, and ensuring transparent benefit distribution. The work is positioned as a contribution to the development of modern land management theory as a fundamental discipline; further publications are announced concerning regime formalization, GeoBIM integration, and legitimacy assessment procedures.

Keywords: *boundary; spatial ontology; land management; LADM; institutional regimes; rights and restrictions; 3D/4D cadastre; interoperability; value capture; spatial governance.*

Problem Statement

The modern system of land management is undergoing a profound theoretical and methodological shift. Historically, its foundation was the geometric paradigm, within which the boundary was regarded as a linear representation of territorial division. Such reduction ensured technical precision but failed to reflect the complex nature of space as a bearer of rights, restrictions, land-use regimes, ecosystem services, and socio-economic values. As a result, a key ontological gap has emerged in the scientific theory of land management—the absence of a holistic understanding of the boundary's nature as a phenomenon irreducible to a physical line or coordinate geometry.

In the contemporary context, a boundary is not merely a material marker but the result of a complex interaction among legal, economic, environmental, and informational processes. It represents the spatial form of legal titles and restrictions, a concentration of social relations of ownership, access, control, and responsibility. In the conditions of cadastral digitalization, the formation of multidimensional (3D and 4D) models of land use, the development of spatial planning systems, and automated management, the classical notion of a boundary as a static geometric line loses its heuristic value. Instead, there emerges a need for a new ontology of boundaries – one that explains them as procedural, multilevel, and relational structures combining materiality, legal status, informational representation, and social legitimacy.

Theoretical indeterminacy in understanding boundaries generates systemic problems: inconsistency of legal regimes, land-use conflicts, difficulty of integrating cadastral, environmental, and urban-planning data, and imperfections in assessing spatial value and constraints. The lack of a comprehensive ontology of the boundary leads to fragmentation in state land policy, legal instability, and discrepancies between physical space and legal reality.

Thus, the scientific problem lies in the need to reconceptualize the essence of boundaries in the modern land management system – to move from a geometric toward an ontological-legal and regime-based understanding of space. This involves the development of a theoretical model in which the boundary appears not only as the result of measurement but as a process of constituting

rights, generating value, reconciling interests, and maintaining spatial justice. The development of such an ontology of boundaries is a necessary condition for building a modern scientific theory of land management capable of integrating spatial, legal, economic, and ecological dimensions of land governance.

The purpose of this article is to develop the theoretical and methodological foundations of the ontology of boundaries in the system of modern land management as a fundamental basis for the transition from a geometric to a legal-value-based understanding of space. The research aims to conceptualize the boundary as a multidimensional phenomenon – a procedural, legal, informational, and socio-ecological structure that constitutes regimes of ownership, use, restriction, and management of land resources.

To achieve this purpose, the following objectives are set:

– to substantiate the philosophical and ontological nature of boundaries as a category of modern land management theory;

– to determine the regularities in the evolution of boundary concepts from material-geometric to institutional-regime models;

– to identify the key structural levels of a boundary (material, legal, informational, ecological) and the interrelations among them;

– to formulate the principles for constructing an updated ontology of boundaries capable of integrating spatial data, legal norms, and land value management mechanisms;

– to define the theoretical conditions for further formalization and practical implementation of this ontology in modern land management systems.

The realization of this goal allows the boundary to be reinterpreted not as a technical abstraction but as a key institutional and legal element of spatial organization, determining the efficiency, justice, and sustainability of land relations in contemporary society.

Materials and Methods

The empirical base comprised three classes of materials:

(1) historical and legal corpora and sources concerning the establishment of boundaries and titles from the earliest periods (Ancient Eastern boundary markers such as kudurru; the Roman Corpus Agrimensorum Romanorum; medieval fiscal surveys like the Domesday Book; parliamentary enclosure acts; the Napoleonic cadastre; the Torrens system, etc.);

(2) contemporary normative and standard documents that formalize the ontology of boundaries in data and law (UNECE Land Administration Guidelines, FAO Voluntary Guidelines on the Responsible Governance of Tenure (VGGT), ISO 19152 Land Administration Domain Model (LADM), FIG documents, and national legislation on cadastre and planning, including the provisions of the Law of Ukraine “On the State Land Cadastre”);

(3) spatial and registry data relevant to the regime-based interpretation of boundaries (cadastral maps, urban zoning data, property rights registries, and remote sensing datasets based on programs such as Landsat and Copernicus).

The methodology combines multilevel conceptual-institutional analysis with formal data-based procedures. The comparative-historical method was applied to identify invariants of boundaries across legal systems; institutional analysis and property rights theory

were used to interpret the boundary as a bearer of regimes of access, exclusion, and responsibility; deontic logic and norm-oriented modeling were employed to describe permitted, prohibited, and obligatory spatial relations; formal ontologization was carried out within the LADM framework by mapping the concepts "object – right/restriction/responsibility – event" onto entities of cadastral and planning databases; systems analysis was used to establish relationships among the material, legal, informational, and ecological levels, among others.

Analysis of Recent Studies and Publications

The ontology of boundaries in land management has developed at the intersection of legal history, the economics of property rights, and cadastral information standards. Ancient Eastern artifacts such as the kudurru demonstrate an early understanding of the boundary as a legal fact: these were monumental royal grants inscribed with sanctions for encroachment, meaning that the boundary functioned as a performative act rather than a purely physical marker [1]. Modern Assyriological studies clarify that the kudurru should be interpreted primarily as legal monuments recording titles and boundary agreements, not as "boundary stones" in the literal sense [1].

The Roman tradition codified the boundary as a synthesis of law, procedure, and technique: the Corpus Agrimensorum Romanorum systematized methods of delimitation, emphasizing that the legal validity of boundary establishment is ensured by a public act and its textual documentation [2].

Medieval fiscal surveys, notably the Domesday Book (1086), illustrate the boundary as a basic unit of taxation, jurisdiction, and proof of title. Historiography consistently interprets the Domesday as an instrument of land value accounting and of legal immunities, granting the boundary the status of an administrative-legal constant [3–4].

Early modern transformations–the parliamentary enclosures in England–shifted the boundary from a mode of "common use" to a regime of private exclusivity. Parliamentary records and academic reviews document thousands of acts and millions of acres restructured under enclosure laws, reflected in detailed plans and a new rent-based logic of the boundary [5-6].

In the nineteenth century, institutions emerged that still define the ontology of the boundary. The Napoleonic Cadastre (1807) established the duality of "plan-register" and the unified parcel as the vehicle of fiscal equity; recent empirical studies confirm the scale and objectives of this reform [7-8]. In parallel, the Torrens system (South Australia, 1858) introduced the principle of indefeasibility of title, whereby the authenticity of boundary and title is guaranteed by the state register [9].

During the twentieth century, cadastral systems transitioned from a "narrow fiscal" to a multifunctional model. Classical works on cadastral evolution showed that these systems transcended fiscal functions to become information infrastructures serving markets, planning, taxation, and environmental protection [10-11]. Simultaneously, GIS and remote sensing emerged: Roger Tomlinson's CGIS project for the Canada Land Inventory inaugurated operational GIS and revealed the potential of thematic layering as a new mode of "seeing" boundaries, as documented in his original publications and subsequent

reviews [12-14]. The Landsat program, launched in 1972, provided a continuous record of terrestrial imagery, institutionalizing data as evidence of spatial change and forming a foundational layer for cadastral and planning decision-making [15-16].

In the twenty-first century, the ontology of the boundary was formalized through international guidelines and standards. The UNECE Land Administration Guidelines defined the target functions of land administration systems and emphasized the role of basic spatial units, including those "above and below surface" [17-18]. The FAO Voluntary Guidelines on the Responsible Governance of Tenure (VGGT, 2012) anchored human rights and legitimacy of tenure regimes as criteria of proper land governance, thereby expanding the boundary's scope from geometry to ethics and inclusion [19-20]. The key framework is ISO 19152 (Land Administration Domain Model, LADM): the 2012 edition and the forthcoming 2024–2025 revision unify the "people–land–rights/restrictions/responsibilities" model, transforming the boundary into a formal data entity with explicit semantics and interoperability [21-23]. Parallel to this, the 3D/4D cadastre program conceptualized the boundary as a volume in space–time: FIG publications, thematic reports, and national roadmaps (notably those of the Netherlands) describe models of legal objects, BIM/CityGML integration, and progressive implementation [24-26].

The theoretical foundation of the "regime-based" understanding of boundaries was provided by the economics of property rights and the institutional theory of collective action. The classical works of R. Coase on externalities and transaction costs, H. Demsetz on the evolution of property rights, and E. Ostrom on rules and boundaries in common-pool resources explain why boundaries constitute rents, conflicts, and mechanisms of their resolution; these ideas have been repeatedly incorporated into land policy and cadastral design [27-29].

Synthesis of these research directions yields three robust conclusions from prior studies: 1) the boundary has historically evolved from a sacred-legal act to a digital institution with a verifiable data chain [1-3, 7-9, 21-23]; 2) the market-economic and public-legal functions of the boundary have expanded from fiscal accounting to multifunctional regimes of value and restriction [10–11, 17–20]; 3) 3D/4D cadastral models and interoperability standards have established a foundation for the formal description of boundaries as volumetric-temporal carriers of rights and restrictions [21–26].

This defines the current theoretical gap: the absence of an integrated ontology that unites legal, economic, and data-based interpretations of the boundary into a single regime model.

Presentation of the Main Research Material

In global practice, several types of boundaries are distinguished according to their ontological status and legal effect:

1) Jurisdictional: state borders, administrative divisions, municipal and special districts (water management, forestry, port zones);

2) Cadastral: parcel boundaries, sub-parcels, servitude strips, infrastructure corridors, rights-of-way and access, including 3D rights (surface, subsurface, building volume) and temporal limits of rights;

Table 1. Principles of Ontological Design of Boundaries in Land Management

Principle Name	Essence of the Principle	Example of Application
Procedural Constitutiveness	A boundary exists only insofar as it is created and confirmed by a valid procedure (act, registry, public notice).	A fence placed "by sight" between two plots does not constitute a valid boundary until coordinates are recorded in the cadastre and ownership rights are registered.
Multimodality	A boundary integrates five layers: material, legal, informational, social, and ecological. Failure in any layer reduces legitimacy.	For a coastal protection zone: physical signs (material), council resolution (legal), GIS layer (informational), public hearings (social), and shoreline ecosystem regime (ecological). Only together do they function.
Adaptivity	The boundary regime changes in accordance with predefined risk and data triggers.	For a flood-prone area: if the water level exceeds X cm once every 10 years, new construction is automatically prohibited and/or mandatory land filling is required.
Metric Quality	Boundary quality is measured by open metrics: coordinate accuracy, data provenance, procedural legitimacy.	For example, land management documentation states: boundary point accuracy ±0.10 m; source–survey of 2024; protocol of neighbor agreement. This allows the owner to understand the boundary's reliability.
Compatibility and Priorities	Predetermined rules define overlaps of jurisdictions and special regimes and their hierarchy of precedence.	A power line crosses an area zoned as residential. The rule applies: the power line protection zone takes precedence, so housing cannot be built directly under the wires even if the master plan allows it.
Value Transparency	Gains and losses from boundary or regime changes are disclosed and fairly distributed under value capture/sharing rules.	After construction of a new metro line, nearby land values increase. Part of the gain, through property taxes or infrastructure contributions, returns to the city for public facilities, while the remainder stays with owners.

Note: Author's elaboration.

3) Planning: functional zoning boundaries, protective belts, coastal buffer zones, sanitary and noise buffers, risk zones (flood, landslide), and urban growth boundaries;

4) Environmental and heritage: protected areas, biocorridors, buffer zones of World Heritage sites, archaeological areas;

5) Resource and agrarian: agricultural land masses, reclamation networks and their components, irrigation/drainage zones, shelterbelts;

6) Sectoral and special-purpose: right-of-way and protection zones for power lines, pipelines, transport routes, aerodrome restriction surfaces, military zones, coastal and maritime limits (shoreline, baselines, water areas).

All these boundaries function as regime generators: they define permissible, prohibited, and conditionally permitted uses of space, shaping rents and externalities. Thus, in land management theory, the boundary is neither an object nor merely a "line on the ground" but a category that fixes the mode of existence of space as an ordered field of rights, restrictions, and values. Its ontological type is that of a relation and event, not a substance. The boundary constitutes the difference between spatial regimes and introduces this difference into the institutional order through rules, procedures, and representational artifacts. Ontologically, it is an operational entity–it exists only insofar as it is maintained through procedures of establishment, confirma-

tion, public visibility, and enforcement (see Table 1).

The boundary has a tripartite structure. As an event, it arises through constitutive acts-establishment, agreement, and registration. As a relation, it links at least two regime domains, setting correlatives of permissions and prohibitions. As a rule, it operates as a norm of spatial behavior, organizing expectations, sanctions, and rent flows. Thus, the boundary is not reducible to geometry; its geometry is derivative of its normative form.

In the modal sense, the boundary defines what is possible, permitted, forbidden, and obligatory in space. It is a deontic object: one that structures rights (ownership, use, exclusion), duties (maintenance, access, tolerance of impacts), and responsibilities (compensation, restitution, insurance). A deontic ontology explains why one and the same material plot acquires different values depending on the regime established by its boundary.

The boundary exists simultaneously in several modes:

• material (marker, fence, natural barrier),

• legal (title, restriction, servitude),

• informational (cartographic record, database topology, change log),

• social (agreement, legitimacy, participatory procedure),

• ecological (environmental gradients, impact buffers).

Its ontological stability is a function of supervenience: failure of any mode diminishes the evidential validity and legitimacy of the entire construct.

The boundary may have "thickness" (as a buffer) and volumetric form. It not only separates but also creates transitional spaces with their own regimes of compatibility. Mereologically, it represents a special case of partially overlapping regions, where components may be continuous in law yet discrete in materiality. Topologically, the boundary is a morphism between regime spaces, defining rules of intersection, precedence, and hierarchy.

The legal consequences of a boundary are not confined to the surface. A boundary projects vertically (to subsurface, underground structures, aquifers, air corridors) and temporally (terms of validity, phases, conditional transitions). Its identity lies in persistence through change: it endures not through geometric invariance but through procedural continuity and the version chain of data.

Every boundary representation is, necessarily, an interpretation with uncertainty. Therefore, the ontology of boundaries includes epistemic attributes: accuracy, evidentiality, traceability, stability, and interoperability. A boundary acquires causal power through institutions that guarantee record verifiability, contestability, and enforceability.

The boundary is an operator of spatial value. It endogenizes rents through access scarcity, regulatory rarity, compatibility or incompatibility of uses, network effects, and ecosystem services. Value is not an intrinsic property of "the land itself" but an emergent property of the regime generated by boundary rules.

The normal state of a boundary is tension of interests. Ontologically, conflict is not an anomaly but a mechanism of regime renewal. The legitimacy of a boundary derives from procedural justice, proportionality of restrictions, and fairness in benefit-burden distribution. Without these, the boundary degenerates into a fact of domination, losing its status as a publicly justified norm.

In the digital age, the boundary possesses informational-legal autonomy: a

registry entry conforming to semantic and quality standards acquires ontic validity. Algorithmic zoning, control, and monitoring procedures become part of its ontology; hence, transparency, reproducibility, and auditability are not matters of programming ethics but conditions of existence for the boundary as a public fact.

Philosophically and ontologically, therefore, the boundary is an institutionally sustained event-relation that structures space into regime domains, endowing them with deontic, value-based, and spatio-temporal dimensions. Its truth is ensured not by geometry itself but by the linkage rule → representation → procedure → enforceability. Within this framework, the boundary functions as a basic operator transforming territory into an ordered space of rights and values, which constitutes the subject matter of the modern scientific theory of land management.

The evolution of boundary concepts within land management reflects a deep transformation of spatial rationality-from material-geometric to institutional-regime. In the initial model, the boundary was a static spatial marker recording ownership or territorial division, its ontological status determined by physical attributes such as embankment, river, fence, or boundary stone. Geometry, measurement, and physical localization dominated this paradigm. Later, the boundary acquired legal meaning–as a form of securing rights and titles, an element of proof of possession. Gradually, the transition occurred toward an institutional model in which the boundary not only divides space but structures social relations, creates regimes of permission and prohibition, and defines rules of access, responsibility, and value distribution.

In the digital era, this evolution enters the phase of a regime ontology, where the boundary functions as an infrastructure of data, norms, and procedures-a spatial-legal infrastructure rather than a measurement object.

The modern boundary has a multilevel structure integrating four interrelated levels: material, legal, informational, and ecological. The material level defines the physical parameters of space (relief, features, boundary markers). The legal level determines titles, servitudes, restriction zones, and usage norms. The informational level provides representation within cadastral and planning systems, including metadata, accuracy, traceability, and digital signatures. The ecological level reflects the boundary's interaction with natural processes-landscape stability, buffering, and ecosystem functionality.

These levels interact systemically: legal regimes shape the informational structure; informational precision affects ecological adequacy; and physical stability of space constrains the scope of legal norms. This multilevel integration is summarized in Table 2.

From the standpoint of systems analysis, the formation of an updated ontology of boundaries requires three interrelated blocks of principles. The first is integrative: the combination of geospatial data, legal norms, and mechanisms of land value management into a unified ontological model. This involves the unification of the concepts "object," "regime," and "event" in terms of ISO 19152 (LADM) and harmonization with INSPIRE spatial standards. The second is procedural: the creation of procedural logic for the automated determination, verification, and updating of boundaries based on sensor data, governmental decisions, and transactions in registries. The third is val-

Table 2. Levels of Boundaries in Land Management

Boundary Level	Core Content	Function in the Land Management System
Material	Physical representation of space, natural or artificial boundary elements	Ensures localization and topographic determinacy
Legal	System of titles, restrictions, servitudes, and land-use regimes	Establishes the legal regime of space
Informational	Data, models, coordinates, LADM/ INSPIRE standards	Represents boundaries in digital cadastral systems
Ecological	Natural linkages, buffering, influence on landscapes	Maintains ecosystem stability and zonal balance

Note: Author's elaboration.

ue-regulatory: the introduction of mechanisms for transparent assessment of the effects of boundary changes, the consideration of ecological and social value, and the distribution of benefits according to the principle of public justice.

The theoretical conditions for the formalization of this ontology are: 1) recognition of the boundary as a complex event-based entity that possesses modes of material, legal, informational, and ecological existence; 2) use of a data metamodelling framework capable of representing multilayered objects (LADM 2.0, GeoBIM); 3) establishment of unified criteria for accuracy, reliability, and procedural legitimacy; 4) integration of cadastral and planning systems in a mode of semantic interoperability; 5) normative consolidation of the principles of adaptability, compatibility, and value transparency.

The implementation of these conditions will ensure the transition from a "register of lines" to a dynamic regime model of space, where the boundary functions as a systemic interface between law, data, and the environment.

Conclusions from the conducted research

The problem of the ontology of boundaries is a key link in the development of the modern theory of land management as an independent fundamental scientific discipline. It has been determined that under current conditions, the boundary ceases to be merely a geometric attribute of territory and acquires the status of a complex institutional–regime category that integrates the material, legal, informational, and ecological levels of spatial organization. Its existence is defined not by physical localization but by procedural validity, legal legitimacy, informational coherence, and ecological rationality. Thus, the boundary emerges as an active instrument of space construction, not merely its description.

The evolution of boundary concepts-from a material-geometric to an institutional-regime model-demonstrates a regular transition from a descriptive to a normative-procedural type of spatial reasoning. This determines the need to create a new ontology of boundaries based on the principles of procedural constitutiveness, multimodality, adaptability, metric quality, regime compatibility, and value transparency. Such a vision enables the integration of legal norms, spatial data, and land value management mechanisms into a single coherent theoretical system. This integration forms the foundation for the transition from a cadastral-technical to an intellectual-ontological level of land management.

The results of the study represent an attempt to form a theoretical framework for the further development of modern land management theory as a fundamental discipline combining legal philosophy, spatial ontology, information sciences, and ecological economics. The proposed approach outlines prospects for the formalization of the regime model of boundaries in digital cadastres, the improvement of spatial governance systems, and the advancement of the normative and value basis of public geospatial policy.

Furthermore, the research results can be applied in the development of sustainable land-use policies, public rent management, and ecosystem service monitoring. The proposed ontological structure of boundaries provides a foundation for building digital "territorial models" that reflect not only physical but also legal, socio-economic, and ecological interrelations. This enables more accurate assessment of land value, equitable distribution of benefits and risks among stakeholders, and the development of value capture/value sharing instruments in public policy. Therefore, the study has practical significance both for the scientific substantiation of spatial development strategies and for applied fields such as land management, cadastre, territorial governance, and ecological planning.

The authors regard the obtained results as the first step toward creating an integrated scientific theory of modern land management. Subsequent publications will focus on the development of a methodology for ontological spatial modeling, the formation of a categorical framework for contemporary land management science, and theoretical aspects of managing regimes of value, risk, and justice within the land management system.

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ОНТОЛОГІЯ МЕЖ У СИСТЕМІ СУЧАСНОГО ЗЕМЛЕУСТРОЮ: ВІД ГЕОМЕТРІЇ ДО РЕЖИМУ ПРАВ І ЦІННОСТЕЙ

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Анотація. *Стаття концептуалізує поняття «межа» в сучасному землеустрої як інституційно-режимну категорію, що перевищує геометричне трактування лінії поділу. На основі порівняльно-історичного та інституційного аналізу, нормоорієнтованого моделювання і формальної онтологізації (LADM) обґрунтовано перехід від матеріально-геометричної до режимної онтології простору, де межа функціонує як подія-відношення, що конституює права, обмеження, відповідальності та рентні потоки. Ідентифіковано чотири структурні рівні межі – матеріальний, правовий, інформаційний, екологічний – і показано їх супервенійні зв'язки та причинний вплив процедурної валідності даних на легітимність режимів. Сформульовано принципи онтологічного дизайну меж (конститутивність процедури, багатомодусність, адаптивність, метричність якості, сумісність і пріоритети, ціннісна прозорість), що уможливлюють інтеграцію правових норм, просторових даних та механізмів управління цінністю землі. Практична корисність полягає у переході від «реєстру ліній» до динамічної режимної моделі простору для кадастрових і планувальних систем, підвищенні якості рішень, мінімізації конфліктів і прозорому розподілі вигод. Робота позиціонується як внесок у становлення теорії сучасного землеустрою як фундаментальної дисципліни; анонсовано подальші публікації щодо формалізації режимів, GeoBIM-інтеграції та процедур оцінки легітимності.*

Ключові слова: *межа; онтологія простору; землеустрій; LADM; інституційні режими; права й обмеження; 3D/4D-кадастр; інтероперабельність; value capture; просторове врядування.*