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LUNAR ZONING: A PRAGMATIC EXPLORATION OF ZONING OPTIONS FOR THE MOON

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Introduction

The efficiency, productivity, and success of a permanent lunar settlement will depend significantly on the character of its land use tools and processes. This paper adapts land use and zoning best practices to lunar settlement planning for lunar development possibilities of the next 20 years. The paper poses policy recommendations intended to be comprehensive and integrable with broader city planning strategies, such as the creation of a functional grid on which to apply land use policies.

Land use and zoning policies regulate the built environment and frame the market for development and enterprise to operate predictably and productively. Assigning allowable activities to land and constructing a flexible development process can create this productive ecosystem and ensure the development outcomes align with the larger goals of the lunar settlement.

Zoning is a subset of land use planning that assigns specific regulations regarding form and bulk of structures, as well as placement of structures within lots. The larger land use plan of a city or region will assign categories of use, while more specific zones will dedicate use intensity as well as design and placement requirements of buildings within the lot and existing infrastructure [1].

The two appendices support the paper by offering bridging commentaries between the field of space policy and the field of urban planning. Appendix 1 contextualizes zoning within existing space law and establishes that zoning will be most comprehensive and productive through an international organization. Appendix 2 reconciles land use and zoning with space law principles and provides general legal guidance for future zoning regulation in space based on durable terrestrial land use law from the United States. These appendices are intended to be referred to throughout the paper as a source of background and foundational information for any reader who may be less familiar with either urban planning or space law.

Lunar Zoning Policy Possibilities

Institutional Capacity

The foremost desirable policy outcome is the development of institutional capacity for legislating zoning and land use policy. The power to effectuate impactful policy should not be confined to a single body or entity, but should be composed of transparent public meetings with open public comment, testimony from stakeholders, and consultations from experts. The goal should explicitly be an agreeable level of consensus: the effort required to comprehensively evaluate all possible policies and all foreseeable effects of every policy is an unrealistic endeavor in the face of limited resources and time-constrained policymakers. Priorities, technology, system inputs, and participants constantly change, so a "perfectly balanced policy" is unrealistic. Instead, the goal should be an *ongoing*, scientific, evidence-based legislative process with and for diverse stakeholders. Consensus as the ultimate goal for appointed or elected officials ultimately provides the durability and flexibility of legislative capacity to administer productive land use law [2].

Ongoing institutional capacity is critical to respond to changing science, technology, and stakeholders. As a result, the theme of an ongoing planning process, instead of a finished product, is central to these recommendations. For example, master planning is a medium to long-range planning effort that balances all elements of a site and prescribes a specific outcome; it is a costly, involved, wide-scope visioning process. For the objectives of master plans to be administered between the master planning intervals such as prioritizing annual spending on infrastructure, facilities, and personnel, an ongoing planning process should exist at much shorter intervals and lower cost. Institutional capacity should not be constrained to a site as master planning is; rather, the goal is comprehensive governance. Both master planning and institutional capacity for delivering master plan objectives should coexist for lunar settlements, although master planning alone will not suffice for delivering the wider planning objectives.

A pertinent case study of urban planning outcomes lacking ongoing institutional capacity would be McMurdo Station, Antarctica. McMurdo Station is the logistics hub and US "portal" to Antarctica through which the National Science Foundation and other entities conduct research [51]. McMurdo has expanded from a "primitive encampment" [22] to the largest Antarctic settlement. McMurdo was primarily initiated prior to the International Geophysical Year (IGY) of 1957, an international effort to conduct earth science studies at both poles that required substantial facilities for operations. McMurdo Station maintains numerous similarities to lunar settlements, such as an extreme environment and a long, costly supply chain [3].

McMurdo was the object of five master plans and two critical panel analyses since 1961. Unfortunately, the master planning efforts were not supported by a robust, ongoing process for administering the master plans' infrastructure and development objectives. Specifically, there was no distinct budget for delivering on the capital planning outlined in the master plans. Facilities development, maintenance, science, and logistics all competed for the same budget. As a result, McMurdo experienced incremental, incomplete facilities development over its history that resembled entirely unplanned development [4]. One master plan created different development zones for McMurdo, but the recommendations were not closely followed. McMurdo's ad hoc development demonstrates the need for ongoing planning strategies for settlements to adhere to master planning.

Institutional capacity for zoning and land use can take the form of a board of elected commissioners, a subcommittee with appointed professionals, or a legislative body, referred to as the "zoning authority" for the remainder of this paper. Exactly who should be elected or appointed is beyond the purview of this paper, but representation should be diverse and inclusive of stakeholders. For example, the Space Generation Advisory Council's approach to inclusivity is constructive [5]. The zoning authority will have several immediate and continuous priorities: evaluating which activities will require or benefit from zoning; involving stakeholders often; developing institutional tools for evaluating demands and needs of zoning; coordinating zoning with long-term visioning process such as master plans; and, producing and updating land use and zoning plans for sustainably guiding activities and development globally for the Moon.

Article I and II of the OST provide for free access to all areas of celestial bodies and prohibit national appropriation; these may seem at odds with the exclusionary nature of zoning. This paper assumes zoning administered through an international organization would resolve this possible conflict between zoning and the OST. See Appendix 1 for more detail on the matter.

To incentivize stakeholder buy-in to both an international organization and the policies of a zoning authority, the policies produced by the zoning authority must effectuate a productive, efficient, urban settlement through compact, co-location of development over a shared set of scaled infrastructure. **In other words, participation in the international organization and zoning authority should allow stakeholders to avoid developing their own base: the economic cost of independent, private infrastructure should be outweighed by the opportunity to specialize at lower cost.** The following set of policy recommendations will be useful for achieving this vision of the zoning authority's role.

Zoning an Urban Boundary

Urban boundaries produce a “ceiling” for growth and infrastructure development outside of the urban area, which encourages higher-density development within the urban boundary. Urban boundaries can be naturally-occurring or created through policy; both spur an accumulation of density around infrastructure and mitigate urban sprawl.

Economics of cities are often unfortunately inverted through the reverse of urban boundaries: cities in the US often regulate zoned height and density maximums which push development further from city centers, lowering the efficiency of infrastructure and increasing the cost of infrastructure per development as well as other costs such as travel time between different areas [6,7].

Naturally-occurring urban boundaries are usually rivers or bodies of water historically used for transportation during the formation of a city. Lunar settlements will likely be initiated adjacent to PSR, which will limit urban growth in at least one direction. The commonly-referenced example of a legislated urban boundary in the United States is Portland, Oregon. Portland enforces a relatively strict urban boundary, but regularly expands it to ensure enough availability of developable land to match the 20-year growth forecast [8]. Incremental expansions allow for new development along the border so that development does not lag behind population growth. This helps prevent inflation of housing prices from an artificially restricted housing supply that would result from a non-flexible urban boundary.

The lunar zoning authority should legislate a responsive urban boundary to maintain stakeholder buy-in and prevent disenfranchisement or detriment to reasonable expectation of economic activities. For example, the Portland urban boundary has been expanded about three dozen times since the late 1970’s. Too rigid of a boundary will encourage stakeholders to attack the policy or forgo participation entirely.

A principal lesson from Antarctic settlements would be to define space settlement types by their long-term or temporary use. Long-term Antarctic bases often have more extensive life support, from climate control to medical bays, as well as more complex infrastructure to support long-term residents. McMurdo Station and Scott Base share power from a wind farm, in one example of shared infrastructure. Permanent bases, especially McMurdo Station, are hubs for science and logistics activity that take place in part through visits to temporary-use field camps across the continent. These temporary-use field camps can vary from permanent structures to locations for tents [9].

For lunar settlements, longer-term-occupancy bases should be restricted to as few lunar urban areas as is practical without preventing necessary specialization of cities globally. There should not be arbitrary height or density maximums for the lunar urban

areas to maximize allowable density and productive activities across the shared infrastructure. An urban boundary should enforce a development maximum for field sites outside of the urban boundary: as field sites continue to be used, ad hoc development could lead to an unplanned evolution of the settlement into a more permanent base. **This should be prevented to mitigate a future of numerous, dispersed, semi-permanent bases with less-efficient, more costly operations globally.** Expansive proximity as well as independent infrastructure would increase cost of building, operating, and maintaining the higher volume of permanent base sites, as well as increasing the planning and coordination of activities across the surface of the Moon. Supplying numerous, dispersed, permanently or semi-permanently occupied bases is significantly less efficient than one or two centralized urban areas. Numerous, developed settlements could be a direct trade off with developing specialized activities.

Zoning for Preservation and Activity Management

Zoning should be used to preserve sites of high value and scientific importance, as well as manage the intensity of activities. Globally, restricting the uses and activities of targeted areas may have a marginal effect on lunar economics and development, but an outsized impact for specific stakeholders, especially scientists and future generations. This concept can be found in the discussion of historic preservation in *Penn Central Transportation Co. v. City of New York* (See Appendix 2) [38]. Restricting activities through zoning is likely possible through international cooperation, and is discussed more extensively in Appendix 1. The following are recommendations for restricting activities and managing activity intensity through zoning.

A planetary parks system, as discussed by Cockell and Horneck [10], would be useful for zoning specific areas for prohibiting all activities. Geologically unique and scarce lunar sites should be identified and preserved in perpetuity. Arguably, these could include specific PSR and Peaks of Eternal Light (PEL). This can be accomplished by the zoning authority by evaluating all PSR and PEL for unique features and determining a representative subset that should be preserved.

The zoning authority would need to construct a spatial analysis method with a Geographic Information System (GIS) for evaluating PSR and PEL. The selected sites should individually be of high value and scarce, but also a collectively representative sample of all PSR and PEL. Selecting specific areas from a diverse set through a GIS would likely take the form of a Multi-Criteria Decision Analysis (MCDA), where PSR and PEL qualities would be evaluated and compared to the whole set through spatial layering and composite scoring of the geologic features' attributes. For example, a PSR attribute layer would be its estimated quantity of volatiles. This attribute layer would compare all PSR, and be part of a composite score with all other layers. The highest scoring sites would be

reviewed, and a few final selected sites would be preserved for no activity. A useful set of visuals for MCDA methods can be found here [12].

Very few areas should be zoned for no activity; the vast majority of areas zoned for varying activity intensity management. Heritage sites, such as the Apollo landing sites, are suitable candidates for highly restricted activity. The zoning authority should institute historic preservation measures, a branch of urban planning with a suite of zoning tools. These include elements of institutional capacity that review sites for preservation, as well as policies determining the level of alteration that can take place [12]. Heritage sites should be zoned as landmarks, with accompanying activity management regulations for accommodating tourism without impacting the sites. As lunar settlements unfold, a comprehensive set of historic preservation criteria should be legislated by the zoning authority [13].

Special areas more generally, such as radio quiet zones, should be zoned to manage stakeholder activities. Activities in radio quiet zones should be staggered to create lengths of time with little or no activity to preserve the useful nature of this zone type. Intervals of no activity should be staggered for periods corresponding to the scientific needs specific to the radio quiet zone, as well as the activity needs that disrupt this zone. These varying forms of activity management reiterate the need for institutional capacity not only to legislate, but to administer these zoning policies. Regulating activities with specific rational connections to their purpose is discussed further in Appendix 2.

PEL could also be completely physically occupied by stakeholders in the long term. To prevent monopolizing PEL, the zoning authority should produce a permitting process that limits the total number of PEL permits any one stakeholder can maintain. This permit limit should be derived from a percentage of the total PEL area that can potentially be occupied, and should also be informed by best practices in monopoly prevention.

Zoning for Safety

Safety zones are a concept proposed within the Artemis Accords, and are an area-based deconfliction measure to prompt NASA and partner nations to notify and coordinate activities on the Moon and avoid harmful interference [14]. Safety zones are intended to be operational in nature and not amount to an appropriation of the lunar surface. In other words, Safety Zones may be better thought of as Rendezvous and Proximity Operations (RPO). Safety zones could be administered by the zoning authority, as zoning is heavily focused on the regulation of activities.

From an urban planning perspective, in order to pass strict legal scrutiny, safety zones should be strongly evidence-based and maintain a strict rational nexus between the deconfliction measures of OST (see Appendix 2, *Nollan v. California Coastal Commission)*

[15]. This will lead to multiple safety zone types created to manage issues of access to lunar settlements by vehicles, but also ground activities and their proximity to power stations, for example. Safety zones should maintain, to the extent practical, no physical barriers to continue their legal basis in operations and continue freedom of access otherwise.

Evidence-based Zoning

Lunar zoning should be scientific in its legislation and administration, only departing from terrestrial best practices with an abundance of evidence for doing so. One of zoning's longstanding best practices is mixing land uses. Urban core areas commonly feature mixed-use zoning for this reason: with no evidence for separating housing from commercial and office spaces, buildings are vertically integrated with both, and stand adjacent to other uses. Modern light-industrial uses can also coexist, with few or no externalities such as noise pollution. Mixed-use zoning allows for the efficient placement of compatible uses adjacent to their demand, either through planned or market-driven development. Workspace and crew residences coexist in the same structures, per many lunar base designs.

Terrestrial mixed-use zones are associated with human-scale design and coexist with more transit options. The coordination of land use and transit reduces both the volume of trips and their distances, easing transportation demand and subsequent transport infrastructure needs. Mixed-use zoning also cultivates a productive synergy of localized and specialized activities while reducing urban sprawl, preserving natural areas, improving resident quality of life and health, and increasing the value of the built environment [16]. As lunar settlements grow and stakeholder developments specialize, their coexistence near other specific uses will likely reduce necessary EVA time, for example. Single-purpose lunar settlements, such as bases built strictly for In-Situ Resource Utilization (ISRU) or science, may be entirely impractical at a large scale, and would work against the ability of enterprises to specialize across shared infrastructure. A wide scope of specialized activities would result in a more economically viable and resilient lunar settlement. [17].

The evidence for mixed-use zoning is derived from many types of scientific study. Two specific tools for gathering evidence will be demonstrated here: a GIS and parametric modeling with Rhino and Grasshopper [18, 19]. These tools help urban planners establish quantifiable metrics for planning and evaluation, and collaborate with other professions such as architects and engineers.

Parametric Modeling

The economic concept of opportunity cost applied to cities is simply “what could be here instead.” In mathematics, this range of potential outcomes could be described as an event space. To thoroughly explore an event space in a city, a parametric model can produce a large volume of plausible models while deploying a wide scope of architectural and urban planning analysis tools to answer complex questions with conflating variables. Parametric models are particularly helpful for identifying tradeoffs between development priorities and composite-scoring scenarios.

The parametric model below shows a grid of lots matching the common grid dimensions of US cities, including Portland, before the suburban boom in the mid 1900’s: 200 foot square blocks. This model compares average trip distances produced by four land use patterns composed of three hypothetical land uses: 50% residential (Purple); 25% scientific/laboratory (Aqua); 25% logistical/storage (Tan). The first model represents strict separation of uses, or the Euclidean (postwar suburban) model of land use. The next three apply randomness, subdivided lots, and density (five building floors) in that order. Trip distances between each use to the nearest three of the other two land uses are measured. The average of all of these plausible trips is displayed in the figures below.

This model demonstrates the importance of mixed-use zoning. **The average distance between each assigned use category dramatically decreases as lot sizes become more granular and denser, as well as randomly assigned (mixed-use) instead of strictly separated. Zoning for dense, mixed-use development allows for the random, stakeholder-driven co-location of activities, resulting in a plausible reduction of average trip distances by up to 88%.** This demonstrates the cost-savings of travel between each use, the potential EVA time savings, and the productive synergy of mixed-use zoning.

While it may seem like an argument against zoning and land use generally, this is because zoning is typically conceptualized as strictly separating uses, such as in the first model. Land use designates the uses and activities for land, while zoning regulates the form and function of the built environment. Together, these should include designated mixed-use, dense areas, where most activities are allowed. Varying public and private sector enterprises, including residential and business uses, can occupy these spaces in a mostly unplanned fashion represented by the “Granular Mixed-Use Density” model.

Trip Distances: Euclidean Zoning vs. Mixed-Use Density

Trip distances between one land use to nearest three of another are measured. Mixed-Use Density reduces average trip distance by 88%.

Euclidean Zoning — *Avg. Trip Distance: 138 m*

Mixed-Use Zoning — *Avg. Trip Distance: 96 m*

Granular Mixed-Use — *Avg. Trip Distance: 42 m*

Granular Mixed-Use Density — *Avg. Trip Distance: 16 m*

Parametric model created in Rhino & Grasshopper [Robert McNeel & Associates]

Geographic Information System (GIS)

GIS is a framework for gathering, managing, and analyzing spatial data. It's a common toolset for urban planners, and also exists as a standalone profession. A wide scope of spatial analyses can be conducted to draw observations of cities' development patterns, economic needs such as housing supply, and many others.

Analyzing the broad outcomes of different settlement types will be useful for estimating the needs of a Moon Village or other lunar settlement. This demonstration is a comparison of land use proportions between McMurdo Station, Antarctica, and Brooklyn, NYC analyzed in GQIS. McMurdo Station is akin to a future lunar settlement, while Brooklyn is a borough of NYC, a mixed-use, transit-rich environment. Both host shipping, industry, and housing at vastly different scales.

McMurdo Station

McMurdo's building uses can be broadly classified into seven different use types: Infrastructure; Service Facilities, Vehicles, and Maintenance; Administration and Office; Laboratory, Science, and Field Work; Storage and Warehousing; Residential and Community Spaces; and Mixed-Use. Mixed-use spaces are a combination of two or more of the first six building use classifications. The following displays data retrieved from a geodatabase publicly available from Klien et al [20]. The Building Use % column divides the total square meters of each building use type by the total square meters of the station. This provides a useful estimate of the space needed for various uses based on a town-sized extreme settlement.

McMurdo Building Use Area

Building Use Classification	Example	Total sq m	Building Use %
Infrastructure	Fuel Pump House	4,603	8%
Service Facilities, Vehicles, Maintenance	Helicopter Hanger	7,092	12%
Administration, Office	USAP Cargo Office	2,055	3%
Laboratory, Science, Field Work	Cosmic Ray Lab	8,748	15%
Storage, Warehousing	Flammable Storage	8,604	14%
Residential, Community Spaces	Dormitory	18,707	32%
Mixed-Use	Galley/Berthing/ Station Core Facility	9,516	16%
Total		59,325	100%

Data retrieved from Klein, et al (2008) [20].

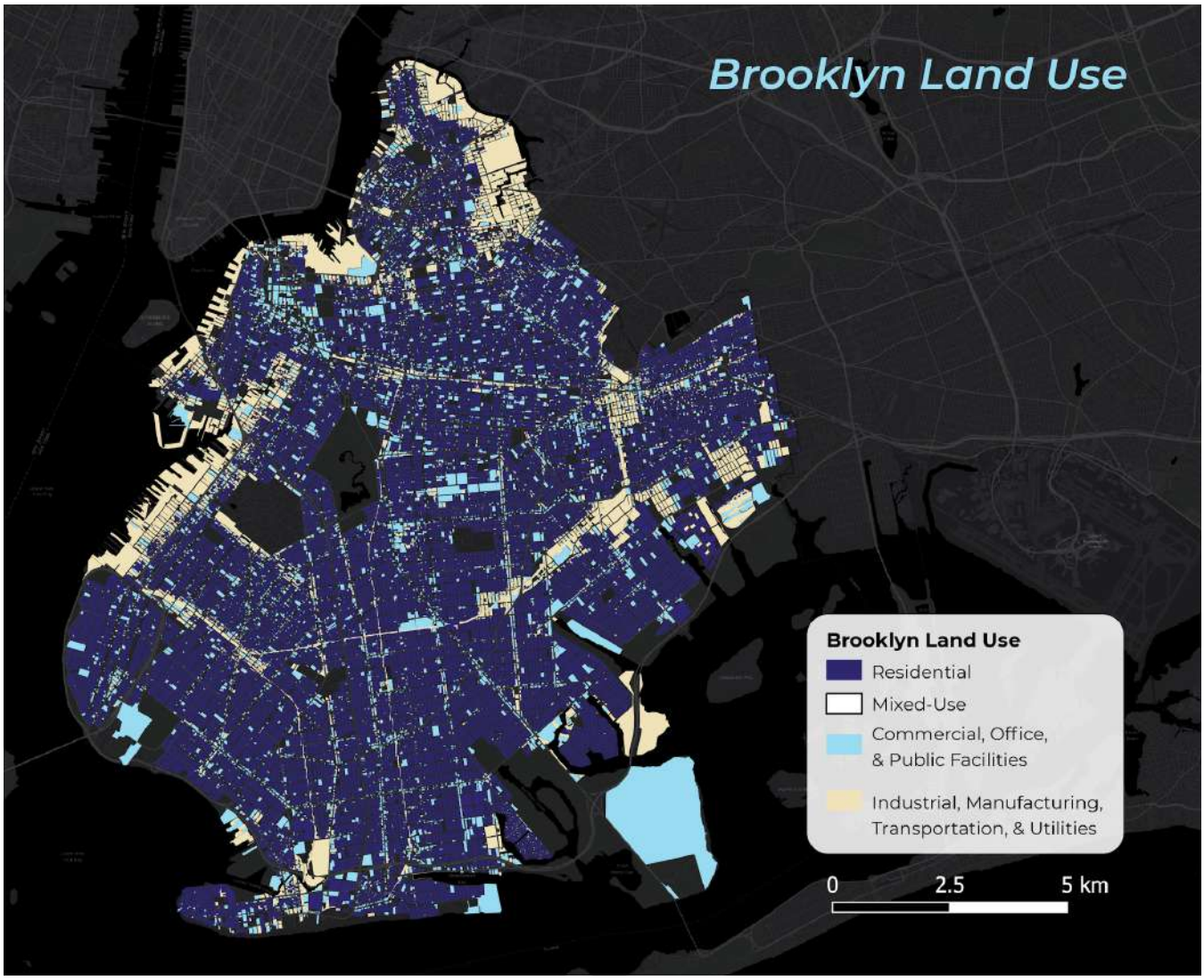
About one-third of McMurdo's total building area is dedicated to residential and community spaces. A consistent criticism of McMurdo Station is the inadequate amount of these spaces, especially the lack of individual private rooms. McMurdo residents cited the lack of individual private space as reportedly preventing their ability to de-stress after long hours of work [4, pp. 140-141].

Brooklyn Building Use Area

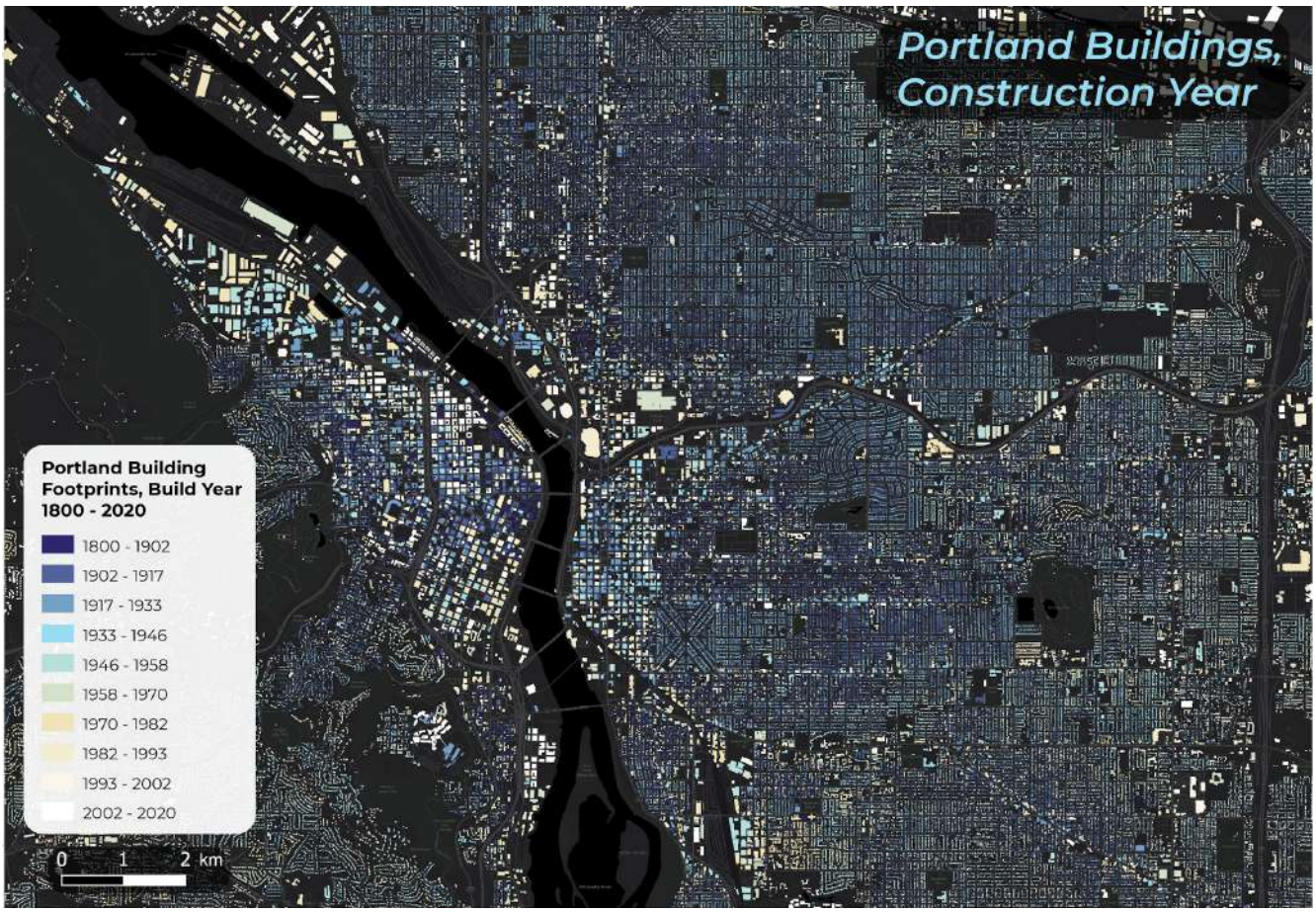
Use	Total sq m	Use %
Residential	84,326,567	61%
Mixed Residential & Commercial	20,213,463	15%
Commercial & Office Buildings	7,972,127	6%
Industrial & Manufacturing	6,792,844	5%
Transportation, Utility, & Parking	3,454,780	3%
Public Facilities & Institutions	14,410,184	10%
Open Space & Outdoor Recreation	423,717	0%
Total Building Area	137,691,536	100%

Data retrieved from NYC PLUTO [50].

In contrast to McMurdo Station, roughly two-thirds of Brooklyn's total building area is dedicated to housing. There is some conflation of mixed residential and office buildings, and a significant portion of Brooklyn residents commute into Manhattan daily. These both overrepresent Brooklyn's ratio of housing to other uses in this table. Brooklyn's housing stock includes housing that would be impractically large and costly for lunar settlements. Based on this brief survey of McMurdo and Brooklyn, the ideal building area dedicated to housing and shared spaces for lunar settlements may be between 40-50%, but should be based on additional evidence from stakeholder input and activity needs.

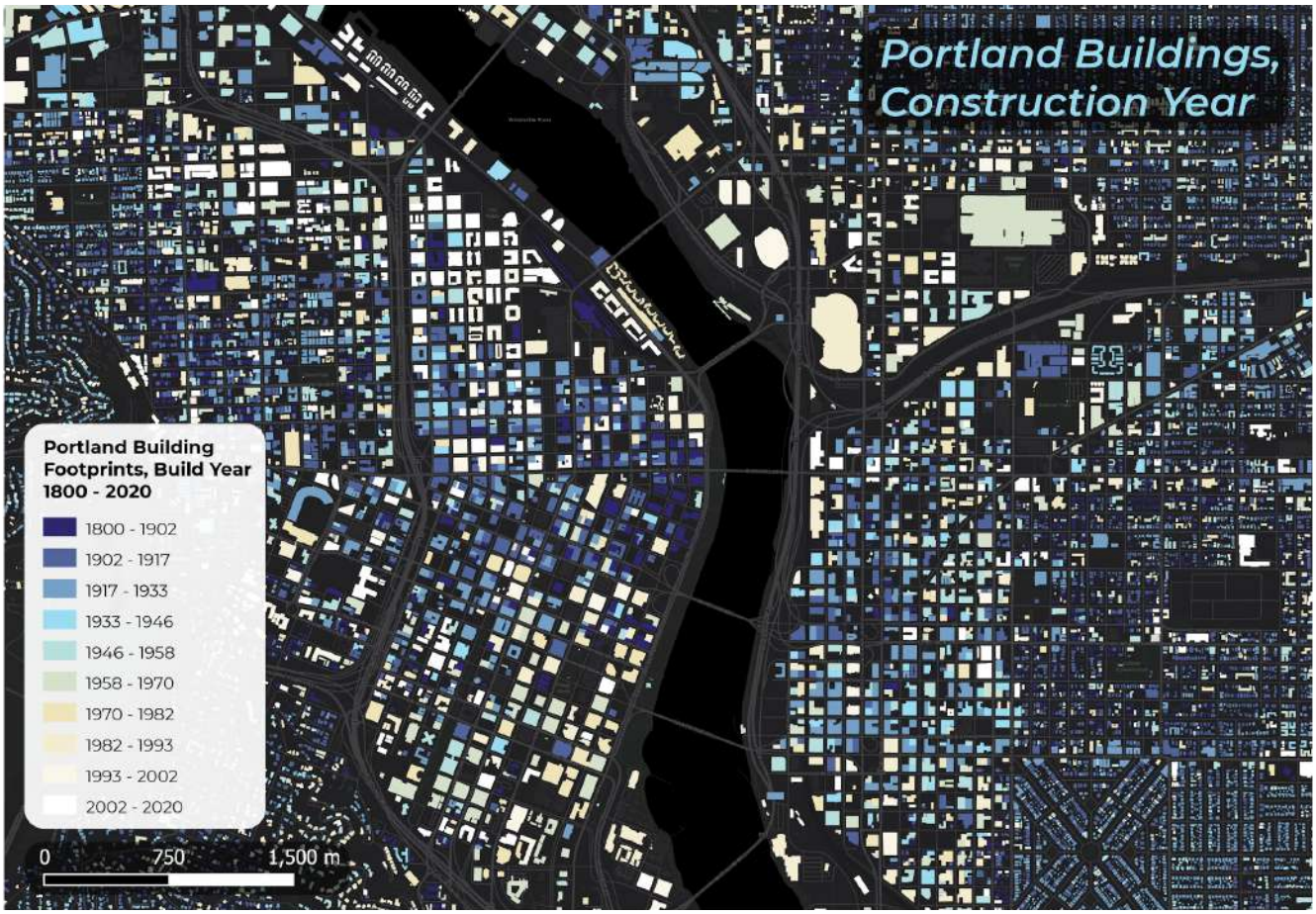

Brooklyn Land Use
Brooklyn Land Use
Residential
Mixed-Use
Commercial, Office, & Public Facilities
Industrial, Manufacturing, Transportation, & Utilities
0
2.5
5 km

Planning for Redevelopment



This is a map of Portland, Oregon, with building footprints symbolized by their age: purple buildings are the oldest, while white are the most recent developments. This is useful to demonstrate the concept of the city as a palimpsest: the story of a lot, and the resulting mosaic of a city, will be continually rewritten to an incomplete extent.

The largest buildings are downtown in the city center. This is by demand, but also by design. The interface of major infrastructure such as international shipping freight and rail, as well as an abundance of industry and warehousing, coexist adjacent to dense office and residential spaces.



This image shows the footprints of large, efficient buildings such as apartments, offices, and warehousing. Buildings are symbolized again by age from purple to white, oldest to most recent. These footprints correspond to denser buildings with higher Floor Area Ratios (FAR, see Appendix 2) and larger lots and lot coverage, but take place on a grid of the same size as housing outside of the downtown. Housing also takes place on smaller lots within the same grid blocks. Portland is lauded for its compact blocks of 200' x 200', and this image shows the range of possibilities that can coexist on the "canvas" that is the grid. **For the Moon, zoning policies should be similarly flexible to allow for a constant redevelopment and reinvesting. Zoning should not be constraining to the point that growth and redevelopment are hindered.**

Comprehensive Zoning

Zoning policy should be created with the context of the lunar environment in mind, but also in an effort to maximize the quality and productivity of resulting development. The following give an example of zoning with the OST in mind, as well as urban design creating highly granular zones that specify use of public space.

Zoning can enforce "free access to all areas" from Article 1 of the OST through design requirements. An example on Earth would be to prohibit gated communities in cities to keep neighborhoods accessible and integrated with the urban fabric. For the Moon, some master plans suggest a linear development pattern around crater rims; this is problematic as it may produce an access barrier to the crater over time [49]. Requiring some level of access throughout a settlement can be achieved through a baseline of roads and regularly-spaced open area connecting the craters to the other side of linear development.

Urban design, much more granular than land use, can require specific physical attributes of a site or building such as sidewalks of minimum width and location along the right of way (ROW, public area between buildings). Lunar facilities could require the implementation of connected, enclosed pathways to reduce the volume of EVA required between sites. Enclosed pathways would increase costs of development, but would also further incentivize compact, dense development, as arbitrary distance would add significantly more cost to connect to surrounding facilities. Enclosed pathways are a recommendation of McMurdo Station's first master plan of 1961 [22], and latest master plan of 2015 [23]. The Minneapolis Skyway System is a built example with 9.5 miles of enclosed, contiguous, second-level bridges connecting 80 city blocks [24].

Coordinating Zoning with Infrastructure

Urban planning best practices produce compounding benefits when enacted together. Zoning should not be deployed at an arbitrary scale, but coordinated with infrastructure development. This section describes the benefits of overlaying zoning on a grid.

A grid should be orthogonal (right-angle intersections) and cardinally-oriented to create a consistent and predictable development pattern resulting in an intuitive sense of place. For instance, NYC's gridiron generally features avenues running north to south, while streets run east to west. One can easily orient themselves by approaching an intersection. Additionally, orthogonal grids are the most efficient for producing useful divisible areas for lots, as well as easily-understood and enforceable boundaries. This efficiency is a physical expression of governance policy, in turn paving the way for sustainable enterprise.

Some examples of lunar master plans feature sparse habitats with no urban fabric, the essential connective tissue of a city that creates lot accessibility and accommodates mobility of all types. In addition, some master plans show habitats and base facilities at apparently arbitrary distances and arrangements [49]. This adds unnecessary cost to exchanges and interactions between base inhabitants, but also to infrastructure costs: arbitrary distances will still warrant infrastructure connections and add cost to development.

A grid should be sized to balance efficiency of all types of mobility, such as roads, EVA, ISRU robotics, rovers, as well as access to efficiently-sized facilities. Some of these priorities can produce tradeoffs, so parametric modeling and GIS, as well as reviewing urban planning studies can help determine the preferred balance of grid dimensions of block size and road size.

A grid can be continuously extended, allowing for ongoing investment and development. This coincides with the need for an ongoing planning process and institutional capacity: as enterprise develops, the grid will be routinely expanded to accommodate growth. Again, master planning on longer time intervals should not seek to achieve a “complete” settlement or replace ongoing, iterative, planning processes.

Land use and zoning tools should be oriented toward inclusive iteration instead of a finalized product. Zoning efforts should be coordinated with infrastructure development, especially the grid as the blank “canvas” on which development and activities will be planned.

Zoning for Investment

Zoning overlays can be financial: tax increment financing zones (TIF) are used to create a virtuous cycle of investment for specific areas. TIFs establish a baseline of assessed tax value, and earmark increases in assessed value from development for reinvestment in the specific TIF area. This can help revitalize underdeveloped or under-resourced areas, and is often administered in conjunction with an economic area plan [25]. Additionally, special economic zones can be created for applying specific regulations or market conditions to an area for a desired outcome.

Taxing space activities is a highly debated topic. Appendix 1 discusses the need for an international organization to administer zoning at the most useful capacity; the same international organization would likely be a prerequisite for administering a TIF zone.

Zoning for Accountability and Access

Land use and zoning processes should be developed in tandem with a flexible but accountable development review framework. Proposed development should be transparent in all facets, including design, production, and life cycle considerations.

Land use and zoning processes provide a consistent forum for public discussion concerning the administration of zoning regulations, but also regarding the overall effectiveness of the larger plans and procedures at work. For the Moon, the process of land use and zoning would also serve as a productive substrate for diplomacy around resource allocation; and in other words, could act as a Transparency and Confidence Building Measure [26]. An open and transparent public record or registry of activities would be part and parcel of zoning and development review efforts. This builds on the principles of the OST. Through these efforts, the collective goals of stakeholders can be pursued through a more productive and collaborative regulatory and development environment. This also corresponds to the identified need for a Multi Stakeholder Fora [27] to facilitate practical coordination. Land use and zoning processes would serve as an ongoing multi-stakeholder forum maintained by the zoning authority.

Conclusions

These policy recommendations are a non-exhaustive preview of what is possible through zoning. The immediate priority for legislating and administering zoning is the development of institutional capacity, or a zoning authority. An international governance framework will likely be needed for the zoning authority to be most effective. This will resolve issues pertaining to Article I and II of the OST for deploying zoning, managing activities, and guiding development, as well as create a flexible, accountable, and transparent process.

The zoning authority should aim to produce a global zoning plan for the Moon driven by evidence-based and consensus-driven policies. Administrative capacity will be critical for delivering on any site-specific master planning priorities. Evidence for this can be found with McMurdo Station, Antarctica.

Zoning policy should be closely tied to the goals of the settlement and should not implement arbitrary policies such as height restrictions without tying them to engineering constraints. These policies should be implemented within a legal framework constructed from durable terrestrial land use law that corresponds to the principles of the OST. Appendix 2 provides guidance for developing this legal framework.

The zoning authority should administer pragmatic policies to increase efficient and productive resource allocation. Terrestrial examples of best practices should be emulated and adjusted for the lunar environment. These should include an urban boundary to minimize the number of long-term-occupancy bases, spurring agglomeration around scaled infrastructure for cost savings and transport efficiency. Development should be coordinated with infrastructure: mixed-use zoning should be implemented on an orthogonal grid. These policies will cultivate stakeholder buy-in by creating a productive ecosystem for enterprises to immediately specialize instead of developing their own base.

Zones should be administered for activity management around various sites. These will range from complete preservation of selected geological features to managing tourism activities around heritage sites. In each case, the regulations should be closely tied to a rational, specific goal grounded in principles of the OST.

Zoning comprises a subset of city planning methods and tools for administering a vision of the built environment. Parametric modeling and GIS specifically provide robust evidence for policy, such as estimating the volume of residential space needed for a settlement or the impact of mixed-use as opposed to strictly separating uses. Broadly, city planning methods and tools should be further explored and implemented to ensure a productive, efficient, and sustainable lunar built environment.

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Appendix 1:
Primer on Legal Context and Evolution of Space Law

The next two decades of space exploration will likely see permanent, ongoing development on the Moon, and perhaps beyond. This is good news for space governance: the stakeholders driving the development of celestial bodies may push an advancement of the *corpus juris spatialis* through international law, customary law, national law, and bilateral agreements. The maturation of the body of space law, combined with expanded case law, will help solidify which stakeholder activities can take place.

A prominent example is the Artemis Accords, which respects the principles of the Outer Space Treaty, and puts forward the concept of Safety Zones [28]. These 'zones', effectively a perimeter defined by the possibility of harmful interference or anomalous events occurring during nominal operations, are intended to be flexible, temporary, and operational in nature. The Artemis Accords derived Safety Zones from Articles IX, XI, and XII of the OST, but are debated as a possible erosion of freedom of access and prohibition on national appropriation established by Article I and II of the OST.

The OST, the foundation of space law, has held many interpretations by legal experts and scholars, but there have been no rulings. In the United States, the OST is executed by state practice and municipal regulations, such as the US FAA's regulation of commercial spaceflight. Uncertainty remains in the detail of precisely which activities are legal, including factors of how they are conducted. This uncertainty in international space law has spurred some countries to develop their own legal solutions. For example, the US, UAE, and Luxembourg have adopted space law of varying scope, and notably assert that space resources can be extracted and utilized [29]. Positions such as these are debated, but prototype a way forward. Waiting for interpretations of the OST in international courts may be too extensive of a timeline for the current pace of space exploration, especially since most cases are solved through arbitration or diplomatically. The Moon will serve as a competitive laboratory for settlement technology and design, and as such, deploying and iterating resource management policies and stakeholder governance structures should occur at a similar pace [30].

The evolution of space law coincides with a growing consensus that space resources and activities will need to be managed. This movement will likely impact international law and norms for space activities, creating momentum toward an international governance framework that would allow for the conception of zoning and other viable, sustainable governance tools. The institutional capacity for monitoring and discussing legal issues arising from space activities exists within the UNCOPUOS; their meetings and committees acting as an essential forum in this ongoing process [31].

Ultimately, this article assumes an international governance structure will be adopted for governing space resources and activities. With multinational stakeholders opting into a shared framework, coordinated activities resolve issues of freedom of access and national appropriation per Article I and II of the OST, as no one nation is claiming area through use or occupation. Deploying multinational personnel and developing facilities for specific areas would be considered the allocation of human, financial, and built capital by the organization proportional to mission plans, not the designation of exclusive areas to individual or national stakeholders.

Assuming an international organization will manage space resources and activities is not without pitfalls: some nations may not buy into an international organization as a prerequisite for space activities; some nations may contest governance structures with their own operations; an international framework may produce equity and access issues for member buy-in and participation. Additionally, the body of space law may not necessarily evolve toward supporting an international governance structure. Acknowledging potential shortcomings, participation in the international organization should be as accessible as possible. To spur stakeholder buy-in, sensible, pragmatic policies should be adopted and communicated. The production of shared infrastructure through a functional governance framework for enterprise will encourage accumulation of capital with coordinated and specialized investments at lower cost.

Foundational to land use and zoning law is the widely litigated principle that a governing body can reduce the “bundle of rights'' associated with a parcel. A property’s bundle of rights is derived from property law, and the bundle is not always complete for any given parcel on Earth, varying depending on the state and municipality [32]. While property rights do not currently exist for celestial bodies, an argument can be applied for an incompleteness of activities for specific areas of the Moon. Freedom of use and access to all areas are pillars of the OST in similar capacity to American constitutional property rights. Excluding some activities from some areas may not abridge the freedom of access and use clauses of the OST, as long as the exclusions land equally among states and their parties. For example, a unique crater and its water ice could be preserved exclusively for scientific use for future generations. Taken globally, prohibiting ISRU in that specific crater may only marginally impact lunar operations, if at all, and would be congruent with the spirit of the OST. Exclusions of specific activities should result from a codified, global land use plan.

In the absence of proactive institution development, zoning and land use policies will be the *de facto* result of industry-led resource allocation. Promisingly, site-specific terrestrial best practices can serve as the starting point for developing lunar-based land use and zoning policies regardless of the governance mechanism through which they are delivered.

Appendix 2: Primer on Reconciling Land Use and Zoning Policies with Space Law Principles

Zoning Fundamentals and Police Power

Zoning and land use regulations are administered to accomplish a high-quality built and natural environment for the health, wellbeing, and productivity of citizens. The absence of land use planning, or the presence of ineffective or deficient land use planning, can result in a built environment that does not meet basic health and safety standards, such as access to potable water. Specific goals of land use planning include the separation of incompatible uses, the governance of externalities from land and subsequent use activities, the efficient and productive coordination of transportation and land use, the production of public parks and preserves, environmental stewardship, equity and housing goals, and many others.

While evidence of planned cities exists in ancient ruins, the Industrial Revolution precipitated the professionalization of Urban Planning. Rapid industrial development and population growth within cities, as well as unmitigated effects of density, traffic, pollution, and public health issues led to legislation to manage the effects of industrialization [33]. The specificity of land use and zoning policies we observe today are a result of more than a century of international policy implementation, revision, and litigation through and adjacent to urban planning. In the United States, NYC's 1916 Zoning Resolution served as the pioneering citywide zoning code spurred from the development of the largest building at the time, the Equitable Building, which coincidentally hosts the central office of the NYC Department of City Planning today [34].

Zoning is often referred to interchangeably with *Land Use*. Land use is more general and assigns broad use and activities for land, while zoning applies subsequent classifications, density and intensity of activities, and specific physical regulations to the larger land use categories. Both work together to govern the use of land, create markets, and enforce law at varying scales.

For example, in New York City a "Residential" land use designation would be specifically governed by one of several zoning categories such as R3-2 [35]. This zoning classification structures the real estate market by specifying development rights: the R3-2 zoning category corresponds to an allowance of .5 Floor Area Ratio [36]. FAR is a measure of the density of development on any given lot, and is calculated by dividing the Gross Floor Area (GFA) of all buildings on a lot by the area of that lot. The GFA is further regulated by the maximum height and bulk regulations, which confine the building envelope within a specific space and form. This granular application of land use regulations creates an orderly, stable, predictable pattern of development. At the same time, the wide range of

zones allow for the development of a variety of housing, commercial, office, and other development types that allow for diverse functional and architectural developments to take place.

Land use and zoning enforcement power is derived from municipal and state police power and are delivered in large part through subsidiarity in the United States [37]. Courts decide the level of intrusiveness and viability acceptable for legislation within the bounds of their government's law, as well as the administration of the law. The most foundational land use law cases for the United States can be found here [38]. Internationally, police power law is most often attributed to state sovereignty: the state legislates and administers a wide breadth of policy that encompasses safety, wellbeing, and health of the public [39, 40]

Bedrock Land Use Law in the United States

Land use and zoning policies for the Moon should be guided by durable terrestrial land use law that agrees acceptably with the principles of space law. Several bedrock land use law cases in the US are helpful for outlining a workable legal framework. This survey of land use law is not advocating for a similar governance framework based in property law, but does advocate for similarly impactful policies through an international governance framework.

A prominent case is *Village of Euclid v. Ambler Realty Co.* Decided in 1926, *Euclid v. Ambler* established that zoning is a valid exercise of police power. This case found that for zoning to be declared unconstitutional, it must be obviously arbitrary and unreasonable, and divorced from any legitimate goal of police power such as public health, safety, morals, and general welfare [38]. Ambler Realty Co. was challenging the general constitutional validity of zoning, which was found to be a valid exercise of police power. Zoning for celestial bodies should also not be conducted as an arbitrary restriction of activities.

Unfortunately, *Euclid v. Ambler* led to a widely-adopted type of zoning, aptly named Euclidean zoning, that featured low-density autocentric (car-centric) development with an excessive separation of land uses. An abundance of evidence exists within urban planning and other professions that Euclidean zoning produces a myriad of negative consequences as a result of grafting land use against its natural tendency to be closely mixed. These include: excessive, unnecessary trip volumes and distances for routine needs such as commuting; low-density urban sprawl, which lowers the efficiency of infrastructure investments and tax ROI; artificial restrictions on housing supply and increased housing costs; exacerbated segregation issues; costly dependency on individual vehicles; stunted population density inhibiting viable transit; increased pollution and destruction of the natural environment; and negative consequences for mental health and community

development [41]. The communities in which Euclidean zoning continues to be legally administered are often burdened by some or all of these issues.

Although this is a prominent issue in US urban planning, zoning as a framework does not imply any particular zoning policy. An equal profusion of evidence exists for urban planning best practices [42] through evidence-based land use policy. Major policy groupings include Smart Growth [16], New Urbanism [43], Transit-Oriented Development [44], and walkability [45]. Zoning and land use are legislative policy tools; wielding these tools responsibly and scientifically can ensure more productive and cost-effective developments take place.

Despite extreme environments, settlements off Earth will provide similar functions and needs of those we are accustomed to, such as housing, transportation, health, and economic needs. As a result, lunar settlements will be subject to the same issues and risks, and should be viewed with a lens of urban planning. Best practices for allocating resources, planning systems of infrastructure, building transportation networks, and numerous other priorities encompassing the full range of city-related policy should be the starting point. Departure from city planning best-practices should only be done with an abundance of evidence for doing so [46,47].

Additional seminal land use law cases should be considered when developing a framework for lunar land use and zoning policy. While these cases are based in US constitutional property rights, the effect of these cases provide useful direction for future space settlements [38]. The following cases resulted in particular outcomes that may be instructive for outlining a legal framework for lunar land use and zoning.

In depth stakeholder engagement ensures valued activities are not substantially inhibited through zoning policy outcomes. These processes will be critical for creating the productive ecosystem of lunar enterprises and ensuring predictable investment outcomes. This concept is derived from *Pennsylvania Coal Co. v. Mahon* found that regulation of land use that destroys the economic value of a property might constitute a taking [38]. In legislating the specific land use laws for celestial bodies, policy should not be so heavy-handed as to make impractical any of the expected activities or economic benefits of those activities.

Additionally, connecting private funding to infrastructure development is a worthwhile endeavor (see Zoning For Investment above). The private sector should be closely involved in development planning and could contribute to public sector infrastructure financing. In the case of *Golden v. Planning Board of Ramapo,* growth phasing within the city was found to be a valid exercise of police power. Development timelines were extended, and developments forestalled, to allow the city to match infrastructure development and grow at a slower pace in the interest of the public [38]. Ad hoc development should not be the

goal for future lunar settlements; a coordinated development of infrastructure and facilities to support settlement growth should be mapped, and agreed in advance of major investment.

Any lunar governance framework should consider the formation of flexible and collaborative tools for guiding development, such as land use and zoning policies, but ensure these do not arbitrarily condition stakeholder developments further than their justifications. *Nollan v. California Coastal Commission* [38] is a natural continuation of the above discussion: in this case, the California Coastal Commission required a public easement across a private property as a condition for redevelopment. This requirement was found to be unrelated to its justification, that public visual access of the beach should be continued for the public interest. This case established that public sector exactions can take the form of a taking requiring compensation, if the exaction is not directly related, or maintains no "rational nexus," to the problem in which the exaction is intended to remedy. Caution should be exercised when justifying public exactions from economic activities. For the Moon, the anticipated iterative regulations of activities will each need a strong connection to a rational objective. For example, safety zones are debated as an erosion of Article I and II of the OST. For safety zones to pass strict legal scrutiny, they must be specific and closely tied to the activities taking place.

The ongoing conversation on coloniality compels a discussion of seminal land use cases establishing criteria for protecting human rights. Future lunar settlements should exercise caution and awareness toward the impacts of land use and zoning tools on specific stakeholders and communities that develop. The following is a non-exhaustive set of legal cases fundamental to land use and zoning that work to protect against disenfranchisement.

Lunar settlement planning should be proactive in its inclusivity through legislation. Terrestrial land use and zoning actions have been invalidated by courts for discrimination toward minority or disadvantaged communities. *Village of Arlington Heights v. Metropolitan Housing Development Corp*. established that discriminatory intent must be found in order to invalidate such zoning regulations [38].

Lunar settlements should proactively avoid exclusionary policies via stakeholder engagement, and policy that does not explicitly or implicitly prohibit certain groups participation in the settlement. *Southern Burlington County NAACP v. Township of Mount Laurel [Mount Laurel I]* established a regional fair share of housing burden: a city "cannot foreclose the opportunity of the classes of people mentioned for low and moderate income housing and in its regulations must affirmatively afford that opportunity, at least to the extent of the municipality's fair share of the present and prospective regional need therefore." *Southern Burlington County NAACP v. Township of Mt. Laurel [Mount Laurel II]* established the model fair housing remedy for exclusionary zoning in the US, including

that municipalities should not only eliminate obstacles to affordable housing, but actively pursue an affordable housing supply commensurate with regional needs through zoning provisions such as density bonuses and mandatory set-asides. Land use and zoning policies have been wielded to exclude people of specific race, ethnicity, and income level with precision [38].

Broadly, land use cases establish fundamental principles that are useful for developing governance frameworks for future space settlements. Specific means-ends balancing tests for evaluating regulatory takings are established in *Penn Central Transportation Co. v. City of New York*. Other cases establish that new regulation cannot deprive property owners from expected economic use of their property without compensation.

While these bedrock land use law cases are not necessarily fundamental to all nations, some aspects of land use law are gradually and significantly moving toward international cohesion. Citizens across the globe are urging local officials to promote sustainable land use systems and development patterns with accessible, cohesive governance institutions for example [48]. Future lunar settlements should adopt a set of internationally accessible, evidence-based, and effective land use policies to achieve a robust, high-quality built environment. The development of accessible, effective institutional capacity for administering these policies will be critical.