Landscape Architecture

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Agro-Urban Coupling Efficiency in Gandhinagar District, Gujarat: Agricultural Retention, Settlement Absorption and Transition Exposure

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Abstract

Planned capital districts are normally characterized using the growth rate of the administrative city, but the persistence of their land system can be determined based on the reaction of surrounding villages, industrial fringes, cultivated lands, scrublands and water channels. Gandhinagar district of Gujarat State is studied using the Agro-Urban Coupling Efficiency Audit framework to test if low urban growth comes with efficient agricultural retention. Land cover accounting uses nine classes of data in 1995, 2003, 2010, 2016 and 2025 with accuracy of classification of data for 2016, 2016-2025 transition probabilities and driver association coefficients. Built up urban, built up rural and other built up land categories are considered together in the settlement absorption category and compared to agriculture, bare land and semi natural water. Agricultural land area decreases from 1825.36 km^2 in 1995 to 1730.49 km^2 in 2016 and to 1676.70 km^2 in 2025. The constructed land increases from 120.13 km^2 to 218.99 km^2 between 1995-2016 and grows to 255.68 km^2 in 2025. The cost of agriculture retention increases drastically because 0.96 km^2 of agricultural land change to every 1 square kilometre of constructed land gain between 1995-2016 and 1.47 km^2 during 2016-2025. The transitions occur mainly in agriculture and scrublands with 53.99 km^2 and 20.71 km^2 expected to leave their 2016 class designation. Driver analysis reveals that proximity to urban centre is first and elevation, river/canal distance and slope still highly correlated. Gandhinagar low urban growth implies that the district is undergoing transformation at an earlier stage and agricultural retention needs intervention.

Keywords: agricultural retention; planned capital district; Gandhinagar; land-cover transition; settlement absorption; scrub exposure; urban management

1. Introduction

First, urbanization influences land-cover through rearranging household settlement, institution presence, service provision, industry and infrastructure placement. The outcome of this process is visible from growth in the built-up class, but the hidden result is pressure reassignment between fields, village margins, scrub lands, water surfaces and ecological corridors. Land-cover transition is known to affect energy balance, hydrology, biodiversity, climatology and resource availability depending on changes in agricultural and semi-natural land to impervious and/or intensive land use [17, 34, 40]. In other words, the urban growth process is not solely demographic and engineering; it

Received: 20 Janaury 2022; Revised: 11 April 2022; Accepted: 14 August 2022; Published: 30 September 2022.

doi: 10.70517/la20221123-05

is also a land-class allocation process, whose results determine whether future growth will be dense, dispersed, agriculturally expensive or ecologically intrusive.

Urban expansion in India occurs at metropolitan, planned capital, state corridor, town, estate and village levels. Advanced remote sensing and GIS capabilities allow regular monitoring of land-cover changes and comparison between observed and allocated land-cover categories based on medium-resolution imagery [25, 27, 32, 39, 48]. However, land-cover mapping does not automatically imply efficient land use, even though some cities grow slowly while imposing heavy agricultural cost. A city can maintain slow land-cover expansion but consume much cultivated space. Alternatively, a land class can remain stable as a percentage but exhibit considerable exposed area if it covers the larger share of a district. Similarly, vegetative or scrub gain cannot offset loss of agricultural land if it is limited, patchy or ecologically different.

In addition, land-change science has indicated that urban expansion is rarely a process involving direct transformation between two particular land classes. It is a function of infrastructure placement decisions, land-regulation policies, agricultural returns, water resources, speculative processes and settlement hierarchy [12, 13, 15]. The interpretation of urban land class change in an Indian planned capital city district requires distinguishing between the observed land change and underlying mechanisms driving the observed result. The change may look like a map transition from one category to another, but it is actually a combination of urban and regional processes influencing settlement and institution formation.

Secondly, literature relevant to land cover predictions emphasizes that model output accuracy and class area need to be supplemented by a planning language. Accuracy establishes the confidence level of the map, transition probability indicates the extent of class persistence, and future area describes allocation. However, no single value describes whether the agricultural efficiency of urban expansion is acceptable or a large class with high persistence exhibits substantial exposed area. Validation studies indicate that comparing maps should account for class disagreement even if the total agreement is relatively good, because class errors may occur despite overall excellent aggregate performance [14]. This paper expands the planning relevance of validation results by linking class area, persistence and accuracy in the same audit.

Literature on peri-urban regions emphasizes that rural and urban classes are often hard to distinguish near major cities and development corridors. Village development, service centers, junctions, education campuses, government buildings and industrial estates can occupy locations outside the legally established boundary of a city but still compete with agriculture for resources and drive the need for additional infrastructure. Such peri-urban growth is less visually dramatic than metropolitan expansion, but it contributes to fragmentation of cultivable land and prevents formation of compact urban regions [16, 32]. A planned capital city district with a metropolitan effect offers a useful context for analyzing such dynamics.

Finally, existing approaches to detecting and allocating land change are solid technical bases for the current investigation. Markov chains, cellular automata, SLEUTH, CLUE-type models and MLPNN have been used for modelling future urban growth and land-cover changes worldwide [1, 6, 21, 22, 31, 33, 45]. These methods are effective because land cover change is determined not by a single factor but rather by distance to urban centers, distance to road network, topography, slope, proximity to river, land policy, industrial sector and population [23, 24, 29]. However, an open issue remains: policy analysis of land use tends to rely on aggregate measures of accuracy, class size or visual impact of model results. Such indicators are necessary but insufficient to evaluate agricultural costs and exposed class area.

As mentioned above, the unique character of planned capital districts implies that land cover change must be evaluated using both class area and persistence. A planned state capital and administrative center with a relatively small population, Gandhinagar is surrounded by an extensive agricultural interior, affected by a neighboring metropolitan region, and characterized by river-canal ecological corridors [4, 5, 7, 8]. Therefore, Gandhinagar is not a typical saturated metropolitan urban agglomeration. Instead, it is an Indian district where planned urban development, agricultural landscape, peri-urban growth and green cover co-exist.

Previous literature has indicated that the urban growth rate of Gandhinagar is lower than rates estimated for other metropolitan cities in India, including Jaipur, Chandigarh, Pune and Delhi. Comparing the growth rate with other urban centers is informative, but the current study addresses a related yet distinct question: whether the agricultural cost of land conversion and peri-urban pressure at the district scale is manageable or needs to be addressed by policymakers. Answering this question is crucial because the district is far from fully developed and still able to retain its agricultural identity.

The novel aspect of the analysis is a developed set of metrics for measuring Agro-Urban Coupling Efficiency. They include indicators of settlement absorption, agricultural cost, semi-natural adjustment, urban-rural balance, class transition exposure and class transition exposure sensitive to reliability. Importantly, the analysis does not rely on an imaginary urbanization scenario but calculates metrics for the real land change based on the existing class area, transition probability and class reliability record. The paper aims at providing evidence-based recommendations to policy analysts: land use efficiency should be assessed at the Gandhinagar district scale.

2. Study area and land-cover record

Located in Gujarat, India, Gandhinagar district comprises a state capital and a surrounding agricultural district established in 1970. It encompasses 2140 km^2 and constitutes 1.09% of the area of Gujarat state. Gandhinagar district is composed of the Gandhinagar, Kalol, Dehgam and Mansa talukas, featuring town and village clusters, planned sectors, industrial influence and extensive agriculture. The population of Gandhinagar district recorded by the 2011 census was 1,391,753 inhabitants, with 16% urban population and 15 towns and 252 villages [20]. The district largely belongs to the Sabarmati River basin. The principal streams in this region are the Sabarmati, Khari and Meshwo rivers, though they run dry throughout most of the year except monsoon seasons. Annual precipitation is approximately 823 mm, and the district is predominantly alluvial plain with sandy loam to alkaline sandy loam soil.

The spatial context of the analysis is very important since the study area is not an isolated district but part of the larger geographic setting. First, there are close ties with its southern neighbor Ahmedabad, a major metropolitan city that exerts significant metropolitan effect on the planned capital core through employment, transportation and market interaction. Second, Kalol, lying to the west of Gandhinagar, is associated with industrial activities and non-agricultural employment. Third, Gandhinagar district has a planned sector in the form of a capital and surrounding urbanized area, a vast agricultural landscape, and peri-urban growth. The spatial context of the analysis is presented in the setting map in Figure 1.

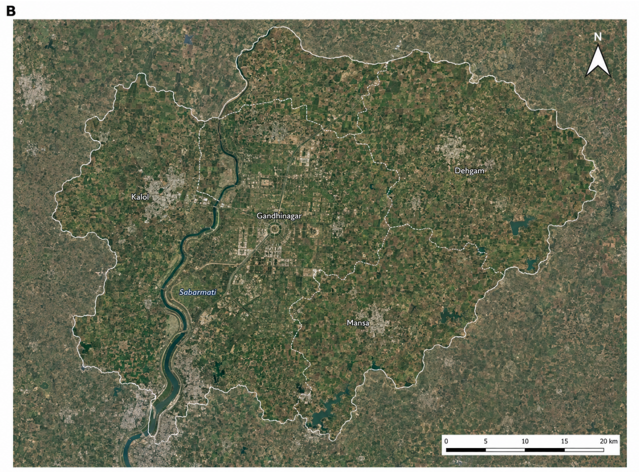
The sequence of maps highlights the importance of taking the entire district into consideration when setting the unit of analysis. The India-Gujarat locator identifies Gandhinagar as being part of Gujarat, the district surface panel illustrates how agricultural land cover, built up land cover and rivers/canals exist together, and the pressure zones panel divides the region along its southern part adjoining Ahmedabad, western part connecting Kalol and the rest of the agricultural district. This makes clear the geographic context of the subsequent tables where settlement growth will not necessarily occur in concentric circles around the planned capital.

The Gandhinagar land cover includes class areas, class percentages, accuracies, transition probabilities, driver-association measures and urban growth comparison figures for Gandhinagar district and some cases of Indian city-regions. The classification is based on nine land cover classes of which there are: agriculture, barren land, rural built up, urban built up, other constructed land, rivers/canals, scrubland, vegetated area and water bodies. The class-area statistics span the years 1995, 2003, 2010, 2016 and an allocated year of 2025. Data sources used in this classification include: landsat TM, ETM+ and OLI satellite data, SRTM elevation data, district-level census data, groundwater data and roads.

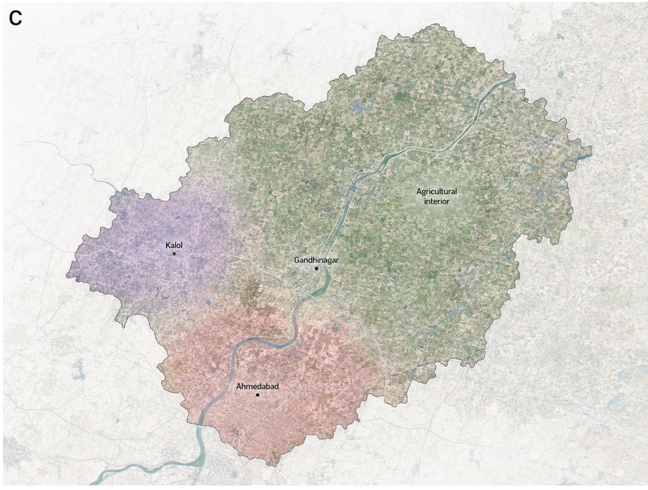
The area record also presents the constant total district mapped area of 2142.96 km^2 that ensures the possibility of a class substitution observation. Although agriculture is the leading class in every period, it is decreasing overall by 148.66 km^2 within the entire period under analysis. Both rural built-up and urban built-up lands nearly double within the given period, whereas the increase in other constructed lands is smaller. The change of small waterbody and barren classes is small by absolute value due to a tiny size of these categories, although the percentage changes are rather significant. Thus, the record requires a combined reading of both absolute and proportional figures.

 doi: 10.70517/la20221123-05

(a) Regional position.



(b) District surface.



(c) Pressure zones.

Figure 1. Study-area setting.

Table 1. Land-cover areas.

Class	1995	2003	2010	2016	2025
Agriculture	1825.36	1815.50	1754.49	1730.49	1676.70
Barren land	3.42	3.18	4.99	7.80	13.98
Built-up rural	48.07	56.61	76.60	86.77	102.85
Built-up urban	62.33	67.03	102.30	111.11	128.46
Other constructed land	9.73	9.74	17.26	21.11	24.37
River-canal	35.28	35.29	37.53	37.55	37.70
Scrub	134.29	132.80	121.89	118.53	126.07
Vegetation	21.30	19.78	22.99	24.52	27.06
Waterbody	3.17	3.03	4.91	5.08	5.77
Total	2142.96	2142.96	2142.96	2142.96	2142.96

The analysis of the land account is performed at the level of district as a whole and not just the city. In the allocation of 2025, agriculture makes up 78.24% of the district area. However, the decrease of 148.66 km^2 over the 1995–2025 period is larger than the 2025 area of urban built-up. This means that the agricultural shift is the leading land balance event.

Nine classes of land-cover also imply different types of planning considerations. Agriculture affects food production, rural life and groundwater resources. The category of rural built-up lands implies village expansion, construction of access roads and fragmentation of land. Urban built-up lands reflect formally the city growth, including density and infrastructure requirements. Other constructed lands include industrial sites, resorts, office premises and various institutional zones. The scrub, vegetation, river-canal and waterbody categories relate to ecological issues and landscape continuity. Considering all classes together as the reserve open spaces will lead to ignoring their individual planning significance.

3. Methods

An Agro-Urban Coupling Efficiency Audit aims to solve one practical problem: does Gandhinagar develop effectively by absorbing population settlement while preserving the agricultural land? This audit considers the district as a closed land account. The total mapped area remains constant, meaning that changes within one category have to be considered in connection with those within others. This analysis goes beyond the mere listing of land cover classes in terms of areas because it measures agro-urban coupling. In particular, it analyses the growth of settlements with regard to agricultural and other land types' change.

Constructed land includes rural built-up, urban built-up and other constructed land. All these types are considered together in Gandhinagar because village expansion, industrial enterprises, institution complexes and urban development contribute to land change. Let us consider the constructed portfolio of the year t as

$$C_t = A_{BR,t} + A_{BU,t} + A_{O,t}, \tag{1}$$

where $A_{BR,t}$ is rural built-up area, $A_{BU,t}$ is urban built-up area and $A_{O,t}$ is other constructed land. This formula seems to be quite simple, but it needs careful explanation from the planning perspective. In particular, some districts might seem to have rather restricted urban development considering solely urban built-up land. In contrast, rural built-up and other constructed lands may quietly absorb the growth pressure of settlements.

Secondly, let us consider the semi-natural and water-associated portfolio that includes scrub, vegetation, river-canal and water body as follows:

$$N_t = A_{S,t} + A_{V,t} + A_{R,t} + A_{W,t}. \tag{2}$$

Although this group does not mean that the listed land cover classes are ecologically equivalent, it allows tracking whether there is contraction or recovery of non-constructed, non-agricultural land alongside the decrease in agricultural lands. In Gandhinagar's case, it is necessary because the reputation of the city is determined not only by the number of trees within the urban limits but also by the presence of continuous landscape, riparian areas and the preservation of semi-natural land.

Finally, the agricultural conversion cost ratio estimates the efficiency of retention of agricultural lands by dividing the area lost to constructed land:

$$ACCR_{t_1,t_2} = \frac{A_{A,t_1} - A_{A,t_2}}{C_{t_2} - C_{t_1}}. \tag{3}$$

Here ACCR means the cost of agricultural land lost per square kilometre of constructed land gained during the period t_1 to t_2. If the cost ratio equals or is smaller than one, then the growth of constructed lands is greater than the loss of agricultural land. Conversely, an index above one implies less efficient land retention. This indicator does not trace all transitions from agricultural lands to other categories. However, it estimates the costs of growth with regard to the agricultural land balance.

doi: 10.70517/la20221123-05

The semi-natural adjustment indicator estimates whether the semi-natural and water land portfolio increases with the decrease of agricultural area:

$$SNAR_{t_1,t_2} = \frac{N_{t_2} - N_{t_1}}{A_{A,t_1} - A_{A,t_2}}. \tag{4}$$

Negative values mean that agricultural and semi-natural land portfolios shrink simultaneously. Positive values indicate the opposite trend. SNAR ratio is significant because it distinguishes land conversion that is accompanied by additional degradation of open spaces from those cases when semi-natural lands recover during the conversion process.

The urban-to-rural ratio measures whether the part of constructed lands is more urban or rural. Thus, it estimates the share of urban built-up lands relative to rural built-up lands:

$$URB_t = \frac{A_{BU,t}}{A_{BR,t}}. \tag{5}$$

High or growing URB value means that urban sector prevails while a lower and falling ratio implies the predominance of rural sector. Gandhinagar is concerned with this ratio because even though the formal city grows slowly, rural lands may fragment and degrade agricultural lands around settlements.

Next, transition exposure is estimated based on the transition table data. Exposure of land-cover class i is defined as follows:

$$TCE_i = A_{i,2016}\left(1 - \frac{p_{ii}}{100}\right), \tag{6}$$

where p_{ii} is the persistence value for land cover class i. This calculation may cause confusion because a highly persistent large class may imply more exposed land than a less persistent but smaller one. TCE thus provides the area-based estimation of exposure to transitions.

Finally, reliability-sensitive exposure adjusts TCE with respect to accuracy of classification:

$$RSE_i = TCE_i\left(1 + \frac{100 - Q_i}{100}\right), \tag{7}$$

where Q_i is producer-user accuracy mean. RSE cannot be treated as a direct correction of land use allocation but a planning alert. Land cover classes that demonstrate considerable exposure and somewhat lower separability deserve closer attention than those with higher separability.

Cramer's V values are used to determine the importance of each driving factor. Every value is normalized as follows:

$$DW_j = \frac{V_j}{\sum_{j=1}^{m} V_j}, \tag{8}$$

where V_j is driver j. DW does not reflect causality but gives a quick overview whether one driver explains land cover structure better than the rest. This weight may be used in combination with spatial information to make the decision about land use planning.

The audit presented here does not include any sophisticated formulas, parameters and algorithms. The aim was to provide the quantities that could be calculated from the tabular record without any need for parameterization or assumptions related to hidden routines of allocation. Every quantity presented above has its meaning in land use planning. Constructed land measures settlement growth. Agricultural cost measures the efficiency of agro-retention.

Semi-natural adjustment reveals the openness of the land account. The urban-to-rural ratio characterizes settlement type. Transition exposure indicates the area that undergoes the transition. Reliability-sensitive exposure suggests where exposure is combined with less accurate classification and thus deserves additional attention. This is important for local planning organizations that need to repeat this process whenever the next land-use record becomes available.

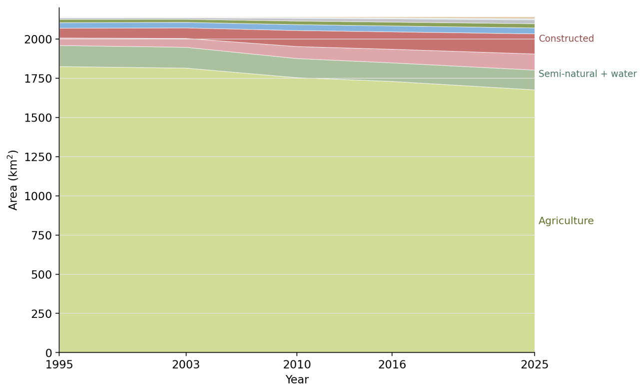
Another important feature of the audit is a clear distinction between assessment of land use structure and land use regulation. This audit does not declare the required growth of urban sector or suggest specific areas to preserve. Instead, it simply measures the current status of the land account with regard to urban settlement development. Such a separation is necessary to avoid confusion and misunderstanding of the methods by scholars. However, this feature gives much value for land use planning in terms of revealing trade-offs: what is the cost of a certain volume of settlement growth in terms of agricultural and semi-natural land?

4. Results

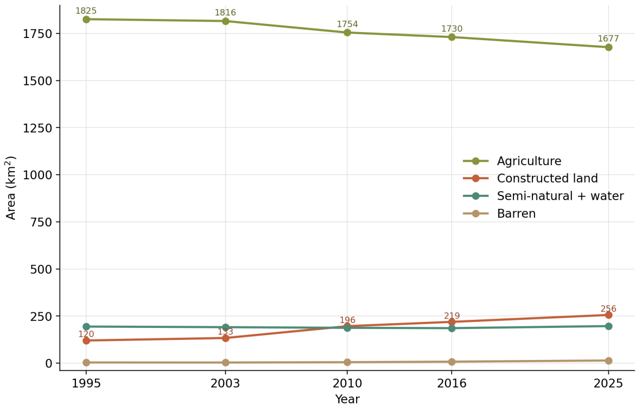
4.1. Land use structure and trends in Gandhinagar

First, agriculture is the leading land-use category in the studied area. At the same time, this class is shrinking during all periods. The area of this category decreases from 1825.36 km^2 in 1995 to 1815.50 km^2 in 2003, 1754.49 km^2 in 2010, 1730.49 km^2 in 2016 and 1676.70 km^2 in 2025. The decline is not strong in the first two intervals, however, the rate becomes higher later and continues until 2025. The district has lost 94.87 km^2 of agriculture during 1995–2016, and 53.79 km^2 during 2016–2025.

(a) Class columns.



(b) Portfolio stream.

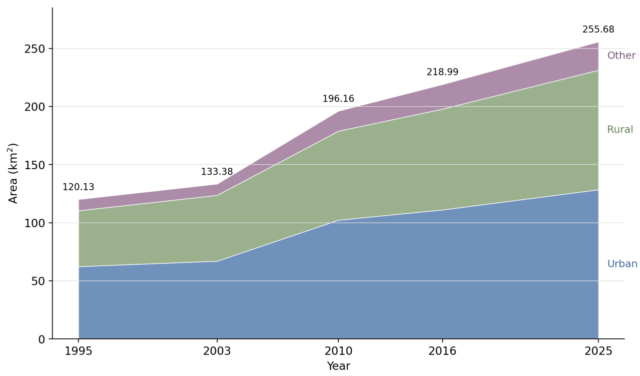


(c) Portfolio paths.

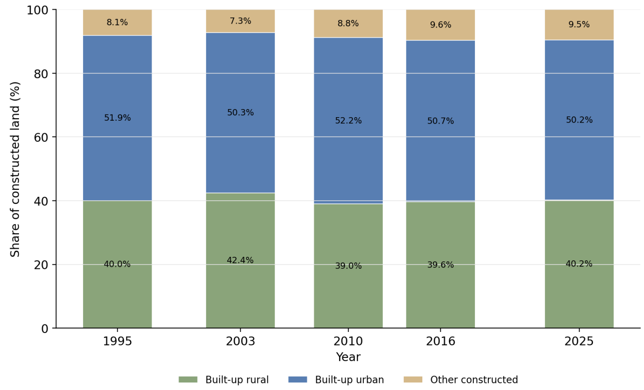
Figure 2. Land-cover portfolio.

The visual of the portfolio in Figure 2 juxtaposes the decrease in agricultural land against the small but increasing constructed and open land portfolios. The similarity in the height of the bars shows that the sum of the district is constant and what is important here is its rearrangement. The visualization of the stream plots and lines reveals that constructed land increases continuously, while the semi-natural/water portfolio initially decreases and then goes back up to 2025. These facts imply that the district does not undergo urbanization in just one way, but reorganizes several categories of open lands at once.

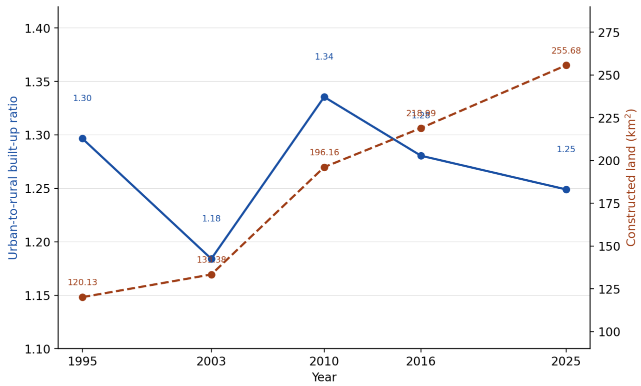
All categories of constructed land increase in each period. Built-up rural land increases from 48.07 km^2 to 102.85 km^2 between 1995 and 2025. Built-up urban land grows from 62.33 km^2 to 128.46 km^2. Other constructed land increases from 9.73 km^2 to 24.37 km^2. Thus, the sum of constructed land rises from 120.13 km^2 in 1995 to 255.68 km^2 in 2025. It can be seen that the amount of constructed land doubles between 1995 and 2025 and becomes just 11.93% of the total area in the latter year. It must be noted, however, that this share of the portfolio does not mean that there is less.



(a) Constructed area.



(b) Class share.



(c) Settlement balance.

Figure 3. Settlement absorption.

It can be seen from the Figure 3 that the expansion of settlement in the district is not solely driven by the urban group. Despite the fact that urban built-up constitutes the largest category of construction, rural built-up and other construction represent 40.2% and 9.5%, respectively, of the constructed land in 2025. While the urban-rural ratio is 1.30 in 1995, it drops to 1.25 in 2025 after a temporary increase in 2010. Therefore, one can say that village and peri-urban development continue to play an essential role.

The derived values presented in Table 2 make it clear how different absolute dominance is from a trend toward expansion. The district still consists of 78.24% agriculture in 2025, yet the only class to undergo significant reduction is agriculture. The constructed land achieves 255.68 km^2 and the semi-natural/water portfolio regains its lost share of 196.60 km^2 after the 1995 to 2016 interval in which it shrank.

Table 2. Derived portfolio values.

Indicator	1995	2003	2010	2016	2025
Constructed land	120.13	133.38	196.16	218.99	255.68
Semi-natural/water land	194.04	190.90	187.32	185.68	196.60
Agriculture	1825.36	1815.50	1754.49	1730.49	1676.70
Barren land	3.42	3.18	4.99	7.80	13.98
Urban-to-rural built-up ratio	1.30	1.18	1.34	1.28	1.25
Constructed share (%)	5.61	6.22	9.15	10.22	11.93
Agricultural share (%)	85.18	84.72	81.87	80.75	78.24

4.2. Settlement absorption and agricultural conversion cost

The Agricultural Conversion Cost Ratio is clearly defined by the audit results. In the interval 1995 to 2003, the constructed land gains 13.25 km^2 and agriculture loses 9.86 km^2, thus achieving the cost ratio of 0.74. For 2003 to 2010, constructed land gains 62.78 km^2 and agriculture loses 61.01 km^2 (cost ratio 0.97). The 2010 to 2016 interval features gains for constructed land of 22.83 km^2 and losses in agriculture of 24.00 km^2 (cost ratio 1.05). For the entire historical period of 1995 to 2016, the ratio equals 0.96. However, in the future interval 2016 to 2025, the gains of constructed land become smaller (36.69 km^2), whereas the losses of agriculture become bigger (53.79 km^2); the cost ratio increases significantly, reaching 1.47.

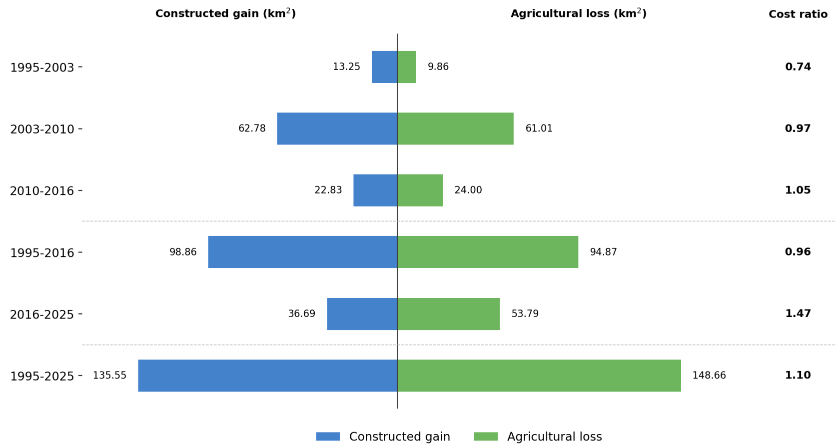


Figure 4. Agricultural retention cost.

Figure 4 explains the difference between the future and historical intervals: the gain in constructed land decreases relative to the strong interval of 2003 to 2010, while the agricultural loss increases significantly. As a consequence, the district therefore becomes less efficient at retaining agriculture for each unit of construction. This result changes the interpretation of Gandhinagar's future allocation: the issue is not only how much new settlement appears, but how expensive that settlement becomes in agricultural terms.

Values of the intervals in Table 3 indicate two interlinked transitions. Firstly, agricultural loss is relatively higher than constructed gain since 2016. Secondly, the semi-natural ratio shifts from negative during 1995–2016 to positive during 2016–2025. This means that the positive ratio of 0.20 translates to semi-natural/water land increasing by approximately 0.20 km^2 per square kilometre of agricultural loss in future allocation. While this partial recovery is welcome, it does not eliminate agricultural loss and includes scrub, vegetation, river-canal and waterbody, which are different ecologically and hence cannot be considered substitutes for farmland.

Based on the change history, 2003–2010 can be termed as the highest intensity period of settlement absorption. During this interval, the urban built-up grew by 35.27 km^2, rural built-up by 19.99 km^2 and other constructed land by 7.52 km^2. Meanwhile, agriculture reduced by 61.01 km^2. Post-2010, the rate of constructed growth slowed down while agricultural reduction kept occurring. What is critical here is that the lower rate of constructed growth did not imply any alleviation of agricultural pressure. Land can transit through intermediate categories like scrub or barren land and continue undergoing net agricultural reduction irrespective of low construction gains.

Table 3. Interval conversion audit.

Interval	Constructed gain	Agricultural loss	Cost ratio	Semi-natural ratio
1995–2003	13.25	9.86	0.74	-0.32
2003–2010	62.78	61.01	0.97	-0.06
2010–2016	22.83	24.00	1.05	-0.07
1995–2016	98.86	94.87	0.96	-0.09
2016–2025	36.69	53.79	1.47	0.20
1995–2025	135.55	148.66	1.10	0.02

Direct transition matrices confirm that agriculture is the primary source of supply for rural built-up, urban built-up and other constructed land. From the net transition matrix of 1995–2016, it is evident that agriculture provided roughly 91.88 km^2 directly for the construction of these three categories. Scrub contributed roughly 6.97 km^2 to the same. Therefore, the agricultural contribution was over 13 times higher than the scrub contribution. This further validates the fact that agricultural block protection is central, not secondary, to settlement absorption planning in Gandhinagar.

It is also worth considering the implications of the change in interval on the interpretation of the 2025 allocation. If a lower annual growth rate of urban land is seen, it would mean that pressure is declining. The reverse, however, occurs when considering the cost ratio. The critical difference lies in the speed of urban area expansion and land composition of the expansion. The slower mapping of built-up land might have less efficiency of construction if the rate of agricultural loss increases. It is for this reason that auditing prioritizes the relationship between classes than the rate of growth.

4.3. Transition exposure and classification reliability

Persistence percentages in the 2016–2025 transition table are high in some classes: river-canal at 99.52%, rural built-up at 98.93%, agriculture at 96.88%, urban built-up at 96.91%, other constructed land at 96.93% and vegetation at 95.24%. Classes exhibiting low persistence are barren land at 55.48%, scrub at 82.53% and waterbody at 86.86%. Persistence percentage itself cannot identify planning exposure. High persistence is noted in agriculture but it has an extent of 1730.49 km^2 in 2016. This results in 53.99 km^2 exposed agriculture.

The tile display in Figure 5 makes the difference between class size and percentage persistence visible. Agriculture dominates the district surface and therefore produces the largest exposed area despite a high persistence percentage. Scrub is much smaller but more unstable. Barren land has the lowest persistence, but its small 2016 area limits its absolute exposure to 3.47 km^2. The figure supports a planning hierarchy in which agriculture and scrub require the most attention, while barren land should be interpreted as a localized transition signal rather than as the dominant land-pressure class.

The exposure table confirms that agriculture and scrub dominate transition sensitivity. Together they account for 74.70 km^2 of class exposure, far exceeding all other classes combined. The reliability-sensitive values do not change this ordering. Agriculture rises to 56.66 km^2 after adjustment and scrub to 21.84 km^2. This stability is important because it shows that the central result is not an artefact of small differences in class accuracy. The total accuracy of the predicted 2016 image is about 96%, yet large exposed areas remain because exposure is driven by area and persistence, not by accuracy alone. In the chart of reliability shown in Figure 6, producer's and user's accuracies appear alongside exposure. For instance, agriculture has a producer's accuracy of 96.00% and user's accuracy of 94.12%, while scrub has 95.56% and 93.48%. While these values are good, it is important to highlight that their transition exposure markers are quite high. On the other hand, built-up rural has a lower producer's

 doi: 10.70517/la20221123-05

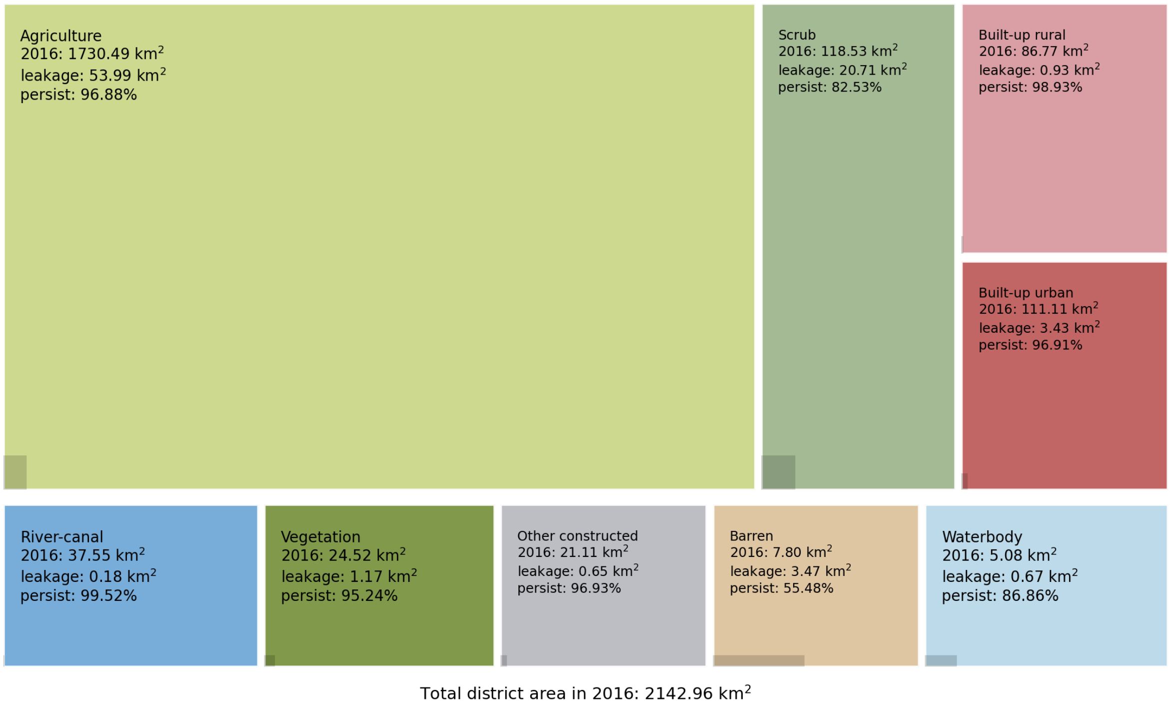


Figure 5. Transition exposure.

Table 4. Exposure and reliability.

Class	2016 area	Persistence	Exposure	Mean accuracy	Adjusted exposure
Agriculture	1730.49	96.88	53.99	95.06	56.66
Barren land	7.80	55.48	3.47	96.98	3.58
Built-up rural	86.77	98.93	0.93	94.94	0.98
Built-up urban	111.11	96.91	3.43	96.92	3.54
Other constructed land	21.11	96.93	0.65	94.64	0.68
River-canal	37.55	99.52	0.18	96.85	0.19
Scrub	118.53	82.53	20.71	94.52	21.84
Vegetation	24.52	95.24	1.17	96.08	1.21
Waterbody	5.08	86.86	0.67	98.84	0.68

accuracy of 92.00% but maintains low transition exposure since it has high persistence and low area in comparison to agriculture. Thus, the results confirm that caution is required even when validation quality is high – the focus of planning should remain within highly exposed land types.

This measure will be very helpful when discussing the classification and validation process with the planners who might otherwise interpret high overall accuracy as an incentive for reducing caution. High overall accuracy shows that the data is trustworthy, and yet does not imply that all classes are equally stable. Agriculture and scrub are considered to have large exposure areas since their land accounts and persistence lead to significant transition areas. Meanwhile, other classes like built-up rural, other constructed land and river-canal have relatively low exposure areas despite being present in large quantities in the 2016-2025 table.

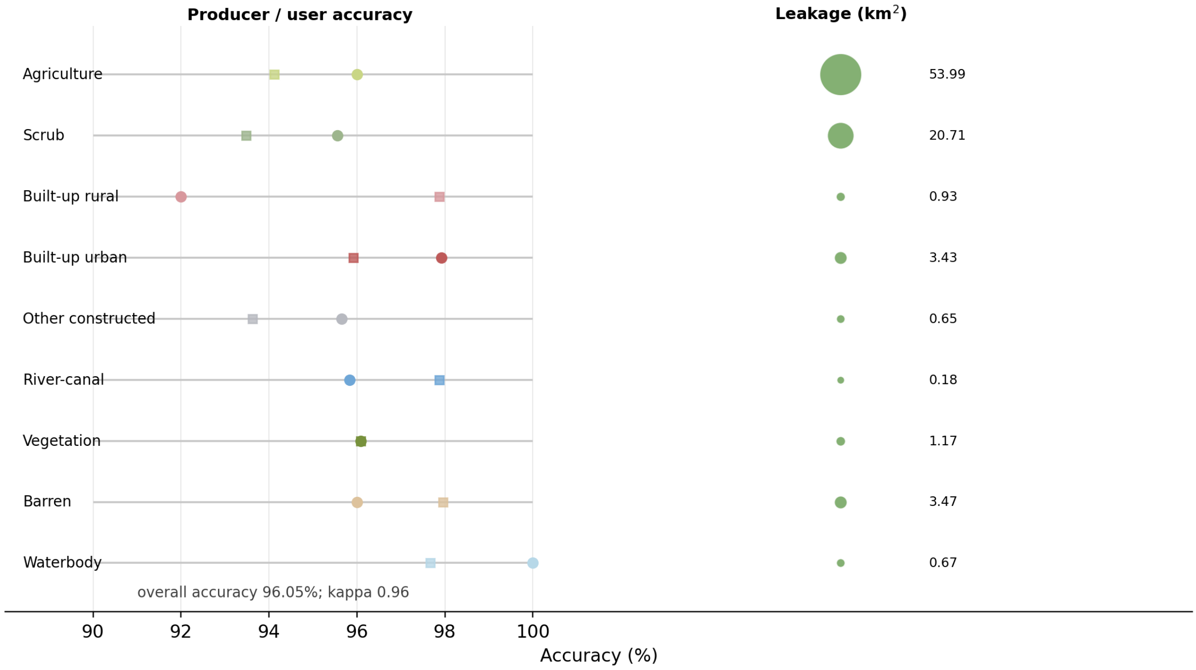


Figure 6. Accuracy and exposure.

4.4. Spatial controls on land-cover change

None of the measures of accessibility can explain the transition pattern independently of each other. The highest Cramer's V score belongs to the variable "distance to urban centre" at 0.3481. Other variables that score high are "elevation" (0.3400), "distance to river-canal" (0.3333) and "slope" (0.3320). "Distance to roads" scores lower at 0.2654. Normalized weights are as follows: distance to urban centre – 0.215, elevation – 0.210, distance to river-canal – 0.206, slope – 0.205 and distance to roads – 0.164. Since there is little separation between the weights of first four factors, they should be viewed together.

The driver compass shown in Figure 7 is the most efficient way to visualize these findings. The proximity of urban centres has become the strongest factor in the transition since it has an impact related to Gandhinagar, Ahmedabad-oriented development and Kalol-related expansion. The proximity of elevation, slope and distance to river-canal demonstrates the importance of modifying land conversions due to topographical and hydrological aspects. Finally, despite being important, "road distance" scores lower and cannot explain land transition in the district independently of other accessibility variables.

Table 5. Driver weights.

Driver	Cramer's V	Normalized weight
Distance to urban centre	0.3481	0.215
Distance to roads	0.2654	0.164
Distance to river-canal	0.3333	0.206
Elevation	0.3400	0.210
Slope	0.3320	0.205

The drivers with the greatest weightings (Table 5) demonstrate that agriculture cannot be effectively controlled within the district via road-front management. Urban-centre distance represents the strongest weighting, followed by elevation, river/canal distance and slope. This means that agricultural land close to the urban centre, river/canals, or with physically-suitable surface may face conversion pressure even more intense than when being closer to a road. It appears that the driver data confirms the need for spatially differentiated protection of agriculture rather

 doi: 10.70517/la20221123-05

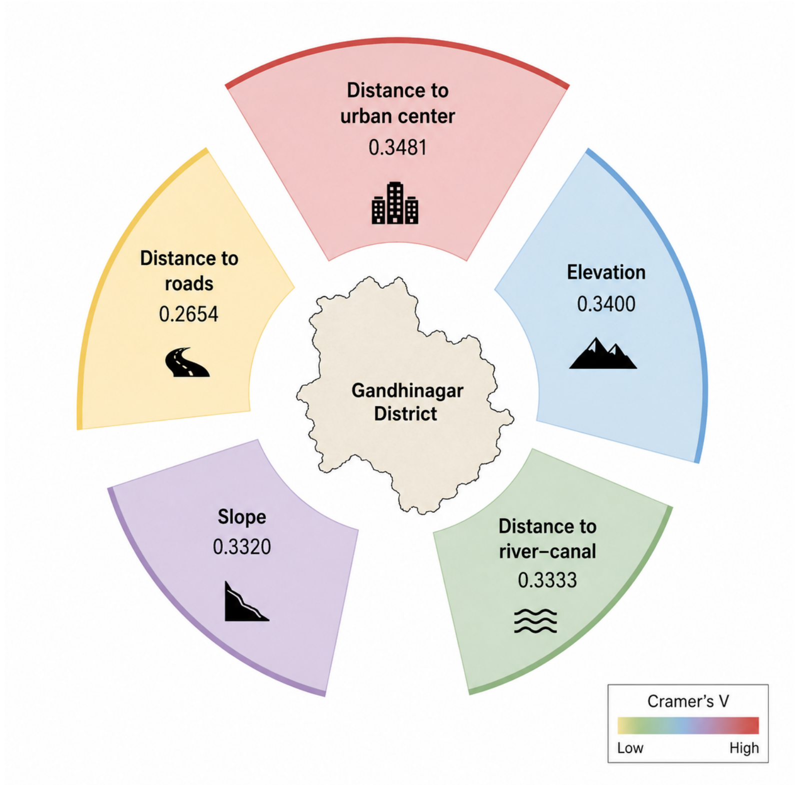


Figure 7. Driver association.

than its general restriction over the whole district.

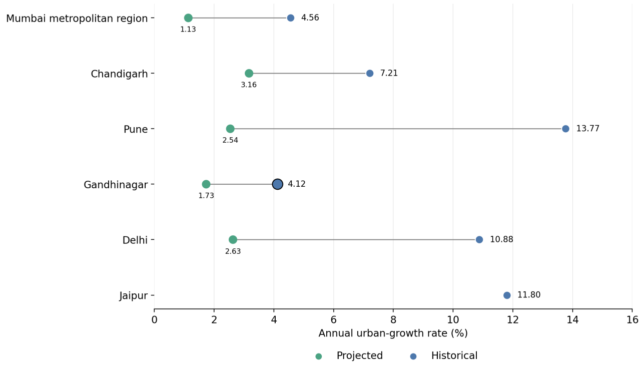
Given that all the four physical variables have very similar weightings, conversion pressure should also be examined in light of local terrain and hydrology. The area has an alluvial and semi-arid climate with seasonal river channels in the non-monsoon period. This indicates that parcels suitable for both agriculture and conversion are those near river/canals and with physically favourable characteristics. Instead of converting Cramer's V results into a rigid zoning approach, therefore, a district plan needs to use the driver evidence together with on-the-ground information about irrigation potential, land condition, drainage and settlement demand.

4.5. Comparative urban-growth context

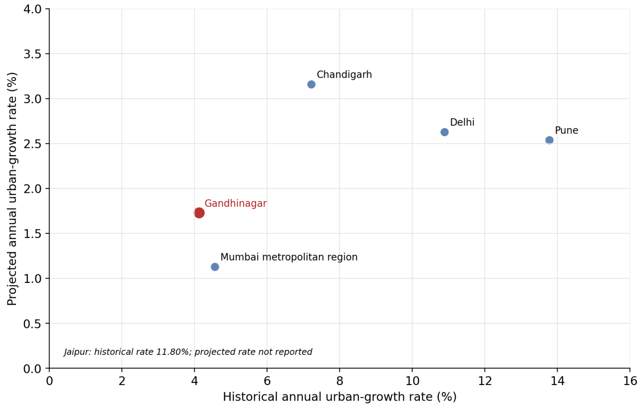
Urban growth per year of Gandhinagar District is slower than for the following cities: Jaipur (historically 11.80%), Chandigarh (7.21% historically and 3.16% predicted), Pune (13.77% historically and 2.54% predicted), Delhi (10.88% historically and 2.63% predicted) and the Mumbai metropolitan region (4.56% historically and 1.13% predicted). This places Gandhinagar below the average, although the audit shows that low urban growth does not mean less land retention risks.

As can be seen from Figure 8, Gandhinagar is not a high-growth exception. The significance of the graph can be understood through the difference with the case of agricultural cost. It is possible for an urban region to exert great pressure on agricultural lands even when its growth rate is lower, provided that the available land is primarily agricultural and the process of growth involves gains in rural built-up and rural periphery.

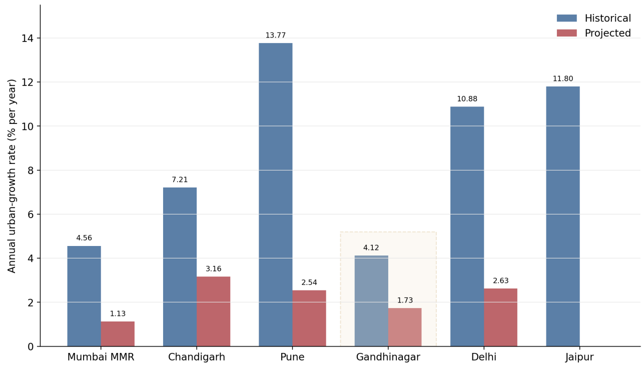
In fact, the comparison reveals that there is some discrepancy between growth speed and land-use efficiency. The historical annual urban-growth rate of Gandhinagar is close to that of Mumbai metropolitan region but much slower than the annual rates observed in Pune, Jaipur and Delhi. At the same time, Gandhinagar's current land situation differs greatly from those city-regions due to a significantly higher proportion of agriculture in its district area. While agricultural proportion declined in other city-regions, Gandhinagar continues to depend on large agricultural blocks. In addition, the fact that agriculture comprises 80.75% of the district territory in 2016 and 78.24% in 2025 makes current decision making crucially important for land-use efficiency.



(a) Rate pairs.



(b) Two-rate position.



(c) City-region bars.

Figure 8. Urban-growth comparison.

Table 6. Urban-growth comparison.

City region	Historical annual rate	Predicted annual rate	Model type
Jaipur	11.80	–	Not reported
Mumbai metropolitan region	4.56	1.13	MLPNN
Chandigarh	7.21	3.16	SLEUTH
Pune	13.77	2.54	MC-CA
Gandhinagar	4.12	1.73	MLPNN
Delhi	10.88	2.63	MC-CA

Thus, the comparison highlights how urban-growth rate alone fails to describe land-use efficiency. As the analysis revealed, the district faces the increasing difficulty of retaining its agricultural land in the face of growing demand from settlement and institutional activities. Such inefficiencies in land absorption cannot be detected from a traditional city-region ranking table and require a separate analysis. This result is a key contribution of the paper because it allows to convert the relatively mild growth case into an important land-use problem.

5. Discussion

As demonstrated above, the audit shows that it is impossible to evaluate Gandhinagar's land change based on its urban-growth rate alone. Indeed, despite the relatively modest annual rate compared to other Indian city-regions, agricultural cost rises in the 2016–2025 allocation. This is the key contribution of the paper because this result transforms an ordinary land growth story into a problem of inefficient absorption. Indeed, the question is not whether Gandhinagar is growing faster than other cities and capitals. The question is whether the district is capable of protecting its agricultural base against the pressure created by growing settlement and institutional areas.

This interpretation agrees well with the existing land-change literature that treats the class-loss social cost rather than class gain as an important criterion in the evaluation of urban development [42]. Numerous studies demonstrate that cultivated and peri-urban open land can disappear rapidly despite the fact that metropolitan regions are yet to become spatially saturated [27, 30]. This is exactly what happens in Gandhinagar – the metropolitan saturation is yet to come but the absorption efficiency starts declining.

An important reason for such inefficiency consists in the fact that urban growth involves more than simple increase of urban built-up land. In fact, during 1995–2025, rural built-up land grows from 48.07 km^2 to 102.85 km^2, while other constructed land expands from 2.74 km^2 to 112.77 km^2. The resulting constructed area of 127.22 km^2 becomes close to the 128.46 km^2 of urban built-up land in 2025. Therefore, this finding implies that the planning geography of the paper should be reconsidered to exclude from consideration rural settlements, industrial areas and other constructed complexes.

A high share of agriculture in the total area is a double-edged sword for Gandhinagar because of a few reasons. First of all, there is plenty of agricultural land that can serve as a basis for development plans. However, it is also a source of potential pressure because agriculture is easy and fast to transform. As the net transition record shows, in 1995–2016, agriculture lost the most amount of land to the three constructed classes. Namely, out of 98.03 km^2 of net losses, 91.88 km^2 was transformed to urban and rural built-up lands and other constructed classes.

The increase in agriculture cost in 2016–2025 allocation becomes even more significant because of its implication. When comparing cost ratio in the historical and future periods, it becomes evident that agriculture is more costly in 2016–2025 than in 1995–2016 when cost ratio was 0.96. In 2016–2025 allocation, it becomes 1.47 indicating that agriculture costs more than constructions. From a planning perspective, this ratio can be caused by the fact that agricultural losses are accompanied by gains in barren, scrub, vegetation and water-related classes, or by contributions of other non-agricultural classes.

This situation implies that future development strategies should address directly the issue of agricultural land transformation rather than expect it to be absorbed by marginal or less efficient land categories. Otherwise, the agricultural cost would continue growing in the face of future constructions. The fact that the district is losing agriculture faster than it gains constructions means that future strategies will only be effective if they track agricultural land transformation into other categories.

As for the semi-natural/water portfolio, the recovery in 2025 compared to the historical level (see Fig. **??**) is rather encouraging since it suggests increases in the area of scrub, vegetation and water-related classes. This interpretation should be handled with caution because it assumes that each subcategory in the portfolio serves a different ecological purpose and plays a different role in maintaining environmental balance. Therefore, scrub, vegetation, river-canal and waterbody classes are not interchangeable, implying that their gains are to be considered individually.

The gain in the area of vegetation (27.06 km^2 against 24.52 km^2 in 2016) may appear promising until it is considered against 53.79 km^2 of agriculture loss predicted in the same period. Thus, although it seems like a compensation for land used for development, vegetation gain should be considered on the condition that agriculture is continuously protected and not converted to other classes.

Similarly to vegetation, scrub should be viewed independently of other classes despite the fact that it becomes increasingly important after 1995. Although its share in the total area is lower than that of other classes, scrub exposure (20.71 km^2) becomes quite large due to its relatively low persistence (82.53%). Indeed, in 1995–2016 period, it expanded from 97.51 km^2 to 118.53 km^2. However, in 2016–2025 period, scrub becomes less stable receiving 3.53 km^2 from river/canal but losing 11.48 km^2 to agricultural land. In semi-arid and alluvial contexts, scrub can be instrumental in hydrological functioning of land.

Driver values confirm that there are multiple factors driving land transformations in Gandhinagar district. Among them, the strongest driver is the distance to urban centre, as expected in light of the district's proximity to Gandhinagar, Ahmedabad and Kalol urban regions. On the other hand, similar driver values for elevation, distance to river/canal and slope imply that the physical context also matters in the land transition process. In turn, the relatively low driver value for distance to roads does not mean that roads are insignificant but implies that they are less influential than other listed drivers. Land policies should therefore focus on the issue of the position of agricultural land in relation to urban areas, river canals, elevations and slopes.

Governance can also affect the land transformation processes. Despite being a planned capital under state governance, Gandhinagar district is characterized by a complex combination of institutional jurisdictions and planning authorities [7, 8]. This can create opportunities for fragmented agricultural development and transformation of rural settlements, industrial areas and various kinds of land into agricultural and constructed land. In fact, the audit results suggest that such fragmented approach can lead to negative consequences.

The audit results emphasize that agricultural protection, rural built-up growth, urban expansion, green-cover management and river-canal governance issues cannot be solved separately. Rather, they should be viewed in the common frame of a district land account. Without the creation of such common account, each agency tends to optimize its own area. The need for a joint assessment of land classes is therefore increased by the fact that land pressures in Gandhinagar district cannot be confined to its borders.

This point is important to highlight because Ahmedabad-facing growth and Kalol-induced industrial development do not depend on district boundaries. Similarly, village expansions depend on the logic of economic opportunities that goes beyond the limits of the administrative district. For this reason, although a district audit cannot solve the governance problems, it can provide the necessary common numerical language that can be useful for each planning authority. After all, it is always easier to find common ground starting from numbers.

The audit also provides valuable information that can be used for monitoring temporal thresholds. The identification of two intervals during which the land change process occurred in different ways can be instrumental for solving distinct issues related to the growth process. Namely, it should be emphasized that 2003–2010 is the period during which the district gained the maximum amount of constructed land, including the urban built-up category and other constructed land types. On the other hand, 2016–2025 is characterized by the highest agricultural conversion cost per square kilometre of new construction. These two facts indicate two different development issues that should be analyzed separately.

For example, one question concerns why the district faced a rapid growth of constructed land. The other question concerns why an increase in the amount of constructed land leads to such a high agricultural loss per unit of construction. Treating both periods as a result of equally efficient urbanization would mean ignoring these shifts and differences in efficiency of land absorption and use.

The results should be considered carefully in the context of the comparison with other Indian city regions. High urban-growth rates in Pune, Jaipur and Delhi imply rapid constructed growth pressure. However, in case of Gandhinagar, the slow growth rate implies a planning opportunity because the district still has enough agricultural land for careful land planning. That is why the concluding remark in the paper does not seem too pessimistic. Increasing agricultural cost ratio is just a warning but not a sign of structural lock of the district in inefficient land use.

Therefore, the district can still manage to implement efficient agricultural growth through compact land extension, development of constructed land, clearly defined edges of villages and rural service-centers, retention of contiguous agricultural land areas, and maintenance of green corridors. The challenge, however, cannot be ignored because of its increasing intensity and urgency in the coming years. Moreover, the audit results indicate that there are several areas where this challenge is currently most pronounced.

Despite the usefulness of the audit, it has certain limitations. Firstly, it is based on tables of land-cover areas, transition probabilities and accuracies. Although this approach helps to detect the key issues in the land development process, it does not replace spatial models or local policy assessments. Secondly, maps and plots can be helpful to interpret land transitions, but for each specific area of interest, planners still need detailed cadastral, demographic and land market data. Nevertheless, audit results prove to be rather useful because they translate land evidence into specific numbers.

6. Implications for district-scale land management

The first implication is that planning should include constructed growth together with agricultural cost ratio. A development document stating only urban growth will understate the land use issue if it predicts a greater agricultural loss than constructed gain. Since the cost ratio in 2016–2025 period reaches 1.47, it should be interpreted as a warning threshold. Therefore, future plans should include the information on the agricultural area lost for each square kilometre of construction gain.

The second implication concerns management of rural built-up expansion. The fact that in 1995–2025 period, rural built-up area increased by 54.78 km^2 indicates that rural settlements are capable of expanding and transforming agricultural land into construction land even without rapid urban-core expansion. Therefore, the issues of village-edge management and protection of high-continuity agricultural land blocks become urgent.

The third implication concerns the need for management of scrub and green cover. In 2016–2025, scrub exposure amounts to 20.71 km^2. In view of the fact that the scrub class is less stable than others, it should be carefully examined in relation to its soil, habitat and hydrological functions before any land transformation decisions are made. Vegetation should also be considered in the framework of its survival and continuity.

The fourth implication is that driver values should be interpreted differently. In Gandhinagar, the urban-centre proximity, elevation, river-canal distance and slope are important factors in relation to agricultural retention. For this reason, agricultural protection should be prioritized in the proximity of the Ahmedabad facing southern edge, Kalol connected western edge and river canal corridors.

The fifth implication concerns the necessity of supplementing future land-cover studies with the data on cost ratios, class exposure and driver values. The former will help researchers and policy-makers to compare agriculture, rural built-up land, constructed land and green cover. The latter will prevent large classes from being underestimated because of high persistence.

The final synthesis plot reflects the main planning values in one cartographic illustration. Agricultural class remains the largest area in 2025 (1676.70 km^2), constructed land is 255.68 km^2, while semi-natural/water land reaches 196.60 km^2. What is more important is that the 2016–2025 cost ratio of 1.47 should draw special attention of planners because it shows that agricultural loss is higher than constructed gain per unit of area. In this regard, the geographic focus on the agricultural interior, the Kalol connected western edge and the Ahmedabad facing southern edge will facilitate the planning process.

7. Conclusions

Overall, the paper's main idea was that it was necessary to check whether or not low urban-growth rate in Gandhinagar could be considered efficient agricultural land retention. The findings show that the answer to this question is negative because the cost of retaining agriculture increases sharply in 2016–2025 allocation despite low urban growth rate. In fact, constructed land increases from 120.13 km^2 in 1995 to 255.68 km^2 in 2025, whereas agriculture decreases from 1825.36 km^2 to 1676.70 km^2. As a result, the cost ratio increases from 0.96 to 1.47 indicating agricultural losses that are higher than constructed gains.

As for the key issue raised by the audit, there are two leading classes that are important in the process of land use management – agriculture and scrub. In general, agriculture is characterized by a high percentage persistence, but due to the fact that its area is large (see Tables 1 and 3), its exposure reaches 53.99 km^2. On the other hand, scrub becomes less stable, although the absolute difference from agriculture is relatively smaller. Its exposure also amounts to 20.71 km^2. The reliability-sensitive adjustment maintains the same order of priorities, confirming that agriculture and scrub deserve attention in the district's planning process.

Finally, driver values show that land conversion is influenced by such variables as urban-centre proximity, terrain parameters and distance to river canals rather than distance to roads. For this reason, the overall conclusion drawn from this study is straightforward. Gandhinagar shows signs of low land-use efficiency that become apparent as a result of a rapid increase in cost ratio (0.96 to 1.47). In 2016–2025 allocation, Gandhinagar becomes characterized by 74.70 km^2 of exposure in agriculture and scrub.

From a practical perspective, it is necessary for Gandhinagar to be managed as an agro-urban planned-capital district with regard to its agricultural land, constructed land, rural built-up land, green cover and industrial edges. It is also important to note that the lack of metropolitan saturation creates the unique opportunity to act immediately. Therefore, the conclusion is that Gandhinagar district needs to become managed efficiently, and it should not let the moment pass.

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