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Forest cover and land use change trajectories within gazetted forest reserves in Nasarawa State, North Central Nigeria (1966–2020)

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ABSTRACT

The rapid losses of Protected Areas (PAs) and forest reserves has led to negative environmental, social, and economic impacts globally. This study examines land use and land cover change (LULCC) in Nasarawa State, North Central Nigeria, focusing on the timing and patterns of change in three gazetted forest reserves since 1966. Systematic and purposive techniques were used to select three forest reserves for the study, one in each of the state's geopolitical zones. Polygon maps of the three reserves from 1966 provided a baseline, against which a temporal sequence of Landsat remote sensing imagery was used to analyse historical trends of LULCC from 1986 to 2020. The analysis showed substantial degradation across all the reserves. Risha Forest Reserve experienced the highest loss, with 88 % of its forest cleared, largely due to cropland expansion (87 %). Doma Forest Reserve lost 83 % of its forest, with cropland covering 65 % of the area. Odu Forest Reserve had the lowest loss (55 %) and maintained 45 % forest cover by 2020. These significant losses pose severe threats to local biodiversity, increase greenhouse gas emissions, and exacerbate climate change impacts in the region. This study recommends the urgent assessment of current tree cover in gazetted forest areas, especially due to shifting agriculture. The government and forest communities should take steps for immediate and long-term sustainable forest management, monitoring reserves to preserve what remains and maintain conservation potential. Implementation of the 2020 National Forest Policy is needed to reduce rapid deforestation in north-central Nigeria so the development potential of managed reserves can be realised. Overall, the findings contribute to the understanding of deforestation trends in protected areas in Nigeria and West Africa more broadly, providing a valuable baseline for future research and policy development.

1. Introduction

Evaluating natural resources requires a comprehensive approach (Chunwate et al., 2019; Nesha et al., 2021). Land-use and land-cover mapping play a vital role in providing information to support sustainable environmental management (Nyengere et al., 2025; Appiah et al., 2021; Phiri and Nyirenda, 2022). Land use and land cover change (LULCC) encompasses human-induced alterations with ecological, hydrological, and socioeconomic impacts, including biodiversity loss, habitat fragmentation, and economic shifts (Mgalula et al., 2024; Jew et al., 2019; Chunwate et al., 2019; Capitani et al., 2019).

Nigeria's rapidly expanding population, which grew from 208 million in 2020 to an estimated 223 million in 2023, is projected to reach approximately 375 million by 2050, significantly intensifying pressure on the country's finite land and forest resources (Salisu et al., 2024; NPC and ICF, 2019). Despite this large population, Nigeria's total land area is only marginally larger than the U.S. state of Texas, resulting in heavy dependence on forests for fuelwood, timber, and agricultural expansion (Ankomah et al., 2020; Olaniyi et al., 2019). >70 % of Nigerians are currently engaged in farming, a proportion that is

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projected to increase in absolute terms due to population growth, placing additional pressure on biodiversity conservation efforts (Ekpo and Mba, 2020; Eludoyin and Iyanda, 2019).

According to Global Forest Watch (2024), Nigeria currently has approximately 20 million hectares of forest area, yet nearly 200,000 hectares are lost annually due to deforestation. Alarmingly, the country has lost an estimated 95 % of its original forest cover, largely attributable to aggressive deforestation occurring at rates as high as 5 % per annum between 2010 and 2015 (FAO, 2020).

LULCC insights are critical for environmental planning, particularly in forest conservation and PA management (Aziz et al., 2024; Fogang et al., 2023; Gong et al., 2020). For instance, in Falgore Game Reserve in Kano, Nigeria, spatio-temporal analysis revealed a significant decrease in dense and moderate woodland between 1985 and 2015, with open woodland becoming the dominant land cover type by 2015 (Suleiman et al., 2017). The main drivers of forest resource degradation in that area were identified as excessive fuelwood collection, overgrazing, agricultural expansion, and forest fires. Forest reserves, managed by Nigeria's State Forestry Department, face challenges of weak enforcement and degradation, despite official forest demarcation (Anwadike, 2020; Federal Ministry of Environment, 2006; 2015). The 2018 IPCC report underscores the importance of preserving these areas for climate regulation and other ecosystem services (IPBES, 2018; Ahrens et al., 2025). However, from 2000 to 2016, Nigeria's protected forest cover declined by over 33 %, significantly impacting the country's overall forest resources (FAO, 2017; Scheren et al., 2021). As a result, the depletion of both protected and unprotected forests led to a severe shortage of locally available lumber, forcing Nigeria to import 75 % of its wood supply (FAO, 2017; Scheren et al., 2021).

Gazetted forest reserves, established during the colonial and post-colonial periods in Nigeria, are legally designated areas aimed at regulating timber extraction, land use, and conserving biodiversity (Federal Department of Forestry, Nigeria, 2019; Ujor, 2018). Introduced under British colonial rule in the early 20th century, these reserves formed a core part of Nigeria's conservation strategy, with over 1000 reserves covering about 10 % of the country's land area by the 1960s (Areola, 1987; Abdulaziz et al., 2015). They were officially recognized and managed to ensure the long-term preservation of nature, ecosystem services, and cultural values (Chiaka et al., 2024; Ujor, 2018; Abdulaziz et al., 2015). However, many reserves are poorly managed (Alao, 2009; Moussa, 2015; Soul, 2016) and their effectiveness often hinges on meaningful local community engagement. Absence of such engagement can lead to degradation, thus impacting forest cover (Fogang, 2023; Ellis et al., 2013). While the primary aim of protected areas is to conserve forests, it is noteworthy that their effectiveness in achieving this goal varies, highlighting the complexity of conservation outcomes and the need for context-specific management strategies. For example, in Ghana's Kakum National Park, a fully protected reserve, minimal forest cover change was experienced in contrast to less protected reserves, which showed greater levels of deforestation (Tsai et al., 2019). However, the same study also found that reduced forest cover was more prevalent near reserve boundaries, suggesting degradation at the edges of protected areas. This highlights the complex relationship between forest cover, land use change, and protected area management.

The instability of Nigeria's forests particularly in the north-central regions reflects a significant knowledge gap concerning their historical transformations and current status. Developing an accurate land cover database is essential for monitoring landscape changes (Ahrens et al., 2025; Gong et al., 2020; Sittadewi et al., 2025). This study examines historical spatial changes in three gazetted forest reserves in Nasarawa State, a hotspot for deforestation, by analyzing transformations since their original demarcation in 1966 (Alao, 2009; Abdulaziz et al., 2015). It explores the timing, character, and extent of these changes, comparing patterns across the study area. Understanding these patterns and their drivers is crucial for developing effective conservation strategies and sustainable land and forest management practices to achieve sustainable development (Chiaka et al., 2024).

2. Methodology

This section details the geographical setting of the research area, the procedures employed, and the techniques used to gather and analyse data.

2.1. The study area

This study was carried out in Nasarawa State, Nigeria (Fig. 1).

The decision to conduct this research in Nigeria (Fig. 1) was driven by its strategic position in the West African Guinea savanna region, which is renowned for its economy based on natural resources and rich biodiversity (Inuwa et al., 2022). Nasarawa State, located in North Central Nigeria within the Guinea savanna zone, was selected because it is a known hotspot of land cover change. Migration caused by insurgency as well as conflicts between farmers and herders in other parts of Nigeria has prompted people to seek safety and livelihoods in Nasarawa State (Atim and Gbamwuan, 2022; Chunwate et al., 2021; Madu and Nwankwo, 2021; Ogu, 2020). This influx has enhanced Nasarawa's reputation as a significant national food producer, supporting a variety of food and cash crops (Ihemezie and Dallimer, 2021; Okoli and Atelhe, 2014). The state exhibits characteristics of both Southern and Northern Guinea, with Northern Guinea grass species resembling those of the southern region, featuring grasslands and woody shrubs (Atim and Gbamwuan, 2022; Chunwate et al., 2021. This vegetation is subject to annual fires caused by human activity (Buba, 2015), with species such as *Parkia biglobosa* (African locust bean tree), *Vitellaria paradoxa* (Shea butter tree), *Milicia excelsa* (Iroko tree), *Burkea africana* (Wild syringa), *Anogeisses leiocarpa* (African, birch satin wood), *Afromosia* (African teak) resistant to fire (Fabolude et al., 2023; Federal Department of Forestry Nigeria, 2019; Buba, 2015). The vegetation of the area has evolved over centuries owing to selective tree harvesting based on utility to the local populations and ongoing fire damage, with trees developing long taproots and thick bark for survival (Ahungwa et al., 2013).

Nasarawa State receives between 1100 and 2000 mm of annual rainfall, with moderate to heavy precipitation during the wet season, supporting agriculture and vegetation (Agidi et al., 2018; Saidu and Yahaya, 2020; Fabolude et al., 2023). The dry season, spanning from November to March, results in lower humidity, higher temperatures, and Harmattan winds, which affect temperature and visibility (Saidu andYahaya, 2020). Agriculture is the primary economic activity, and land is allocated to crops and livestock (Ihemezie and Dallimer, 2021; Okoli and Atelhe, 2014). Communities engage in subsistence farming, reliant on seasonal rainfall (Saidu andYahaya, 2020; Chunwate et al., 2019). The state's fertile soils and climate support crops such as yams, maize, rice, and cassava, even within designated forest reserves (Soule et al., 2016; Abdulaziz et al., 2015). Fig. 2 illustrates the 1966 forest boundaries distribution for the state.

Nasarawa State has 41 officially acknowledged forest reserves, established and documented legally in 1966, although some were proposed without full legal backing (Benue Plateau State Government, 1972; Chunwate et al., 2025). Due to the different years of official recognition, not all were mapped. These reserves are spread across the Nasarawa North, South, and West Senatorial Districts (Figs. 1 and 2), with most situated in the southern region, followed by the northern and western areas. They were officially recognized under the Benue Plateau State of Nigeria, as per the gazetted supplement part B to Northern Region gazetted No.8, vol. 2, 1966. This recognition prohibited local residents from clearing vegetation, yet forest communities retained rights to access resources while maintaining the forest cover. They were permitted to use the forest to collect water, thatching grass, dead wood, stones, fruits and medicinal plants significant to their culture. However, resource extraction is only permitted for personal domestic use and not

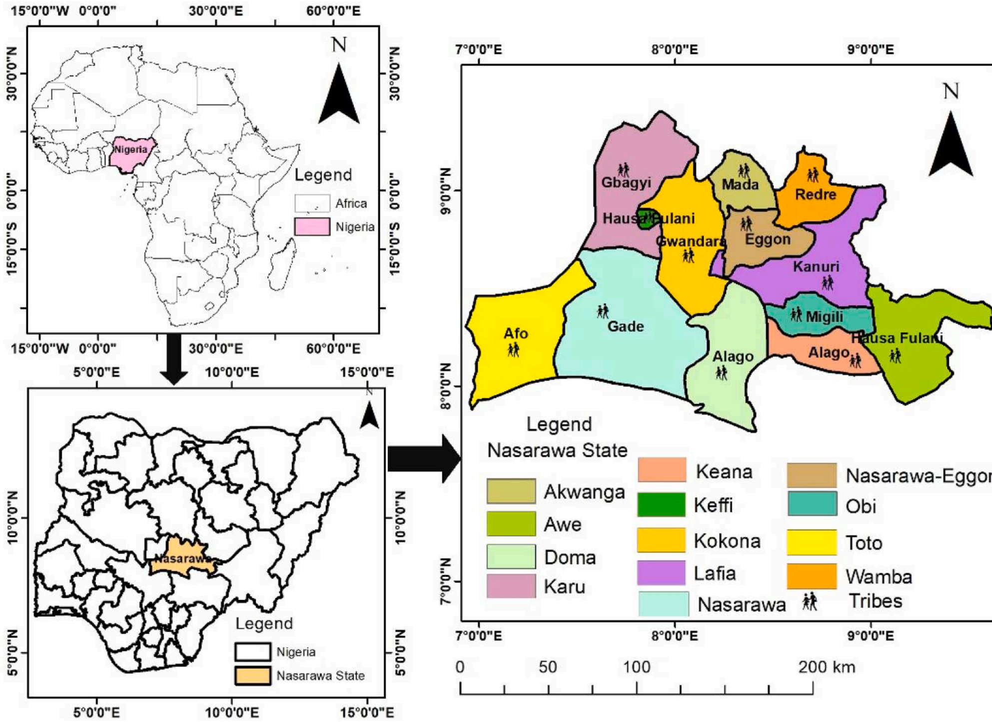

Fig. 1. Location of Nasarawa State within Nigeria, showing administrative subdivisions and major tribes.

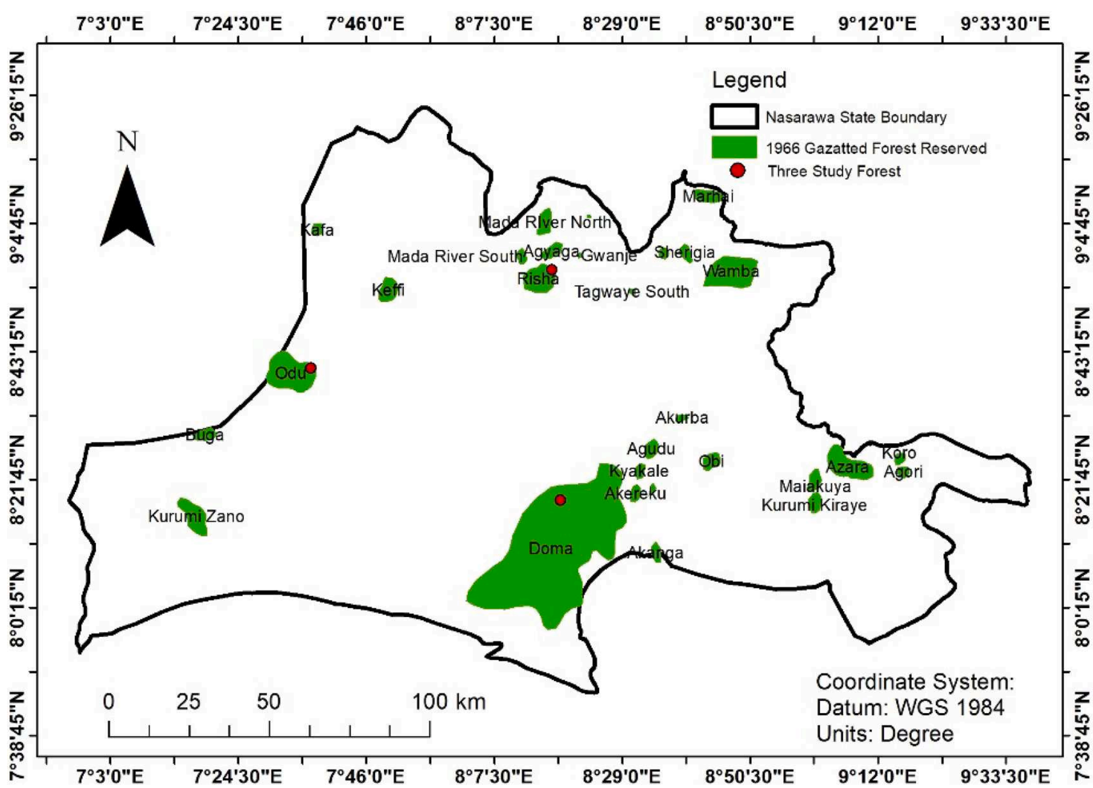

Fig. 2. Nasarawa state map showing the distribution gazetted forest reserves for 1966.
Source: Authors' extraction from the shapefile, Ministry of Environment Abuja and Nasarawa Geographic Information Service, 2020).

for commercial purposes to ensure the vegetation cover is not damaged (Benue Plateau State Government, 1972). Three forests, Doma (south), Risha (north), and Odu (west) (Fig. 2), were selected to represent each geopolitical zone. This selection ensured a comprehensive approach, considering ecological similarity, cultural importance, and geographic distribution, representing various ecological zones and forest types of different sizes with comparable biodiversity (Abdulaziz et al., 2015). The selection of forest sites also aimed to avoid areas known for security threats such as kidnappings, farmer–herdsmen conflicts, inter-community crises, and cultural barriers. Before field visits to the area for ground truthing data collection for the selection sites, consultations took place with Nigerian security services to gather the latest security information.

2.2. Data sources and methods

This study adopted a mixed-method approach in which quantitative and fieldwork (ground truthing) data were integrated (Fig. 3).

The extracted gazetted forest map boundaries of 1966 (Fig. 2) were overlaid on the classified maps to understand the proportions and patterns of changes of land use and forest cover over time. Doma, Risha and Odu reserves were officially gazetted in 1966 and at that time were intact according to the Federal Ministry of Environment, Nigeria and Nasarawa Geographic Information Service, Nigeria (2020), suggesting that the gazetted forest boundaries indicated complete forest cover for all three forests under study in 1966. However, the accuracy of these boundaries might be questionable due to potential issues in their definition or in the mapping by the Federal Ministry of Environment, Nigeria. This raises concerns about the accuracy of the 1966 data for this study, as it may not accurately represent the true forest boundaries at that time. Furthermore, the absence of remote sensing data from 1966 limits the ability to verify or analyse these boundaries comprehensively for this first epoch. Despite these limitations, the survey boundaries of the gazetted forest provide a crucial baseline for understanding the initial forest cover within the gazetted forest reserves. This baseline is essential for assessing subsequent changes in forest cover and for managing and conserving these forest areas over time. The historical context established by the 1966 boundaries allows for a more informed analysis of deforestation, forest degradation, or other land-use changes that have occurred since then.

2.2.1. Landsat imagery

The study used the surveyed reserve boundaries map for 1966 (Fig. 2) and Landsat imagery covering the study area for the years 1986, 2000, 2010, and 2020. Landsat imagery was downloaded from the USGS Global Visualization Viewer (GloVis) for Nasarawa State, Nigeria (https://glovis.usgs.gov/) and used to analyse and generate image maps of LULCC from 1986 to 2020 (Appendix A, Table 1; Fig. 3).

Five scenes were downloaded yearly to cover Nasarawa State. Imagery was from the dry season, with cloud-free images from December, November, and January. This approach minimised variations from phenological changes and maximised stability in spectral measurements of forest reserve land cover changes (Gong et al., 2020; Amini et al., 2022). The years 1986, 2000, 2010, and 2020 were selected as these had good quality imagery with minimal cloud cover (Gong et al., 2020; Phiri and Nyirenda, 2022). For inclusion in the study the images required <10 % cloud cover. The study years were thus chosen based on data quality and availability, considering also that early 1990s' satellite data had some gaps due to Landsat 6′s failed launch in 1993. The intervals (1986–2000, 2000–2010, and 2010–2020) effectively capture long-term trends despite their slight variations in length.

2.3.3. Development of a classification scheme for LULCC of the study area

A reconnaissance survey was conducted across the study site from December 2020 to January 2021, during the dry season, to inform the land cover classification. This timing ensured ground conditions matched remote sensing data, minimizing seasonal variations that could affect land features. The survey identified existing land use features and coordinates of land classes to inform pattern, shape, and association, providing background knowledge of the study area. Farmland was associated with bare surface, riverine areas with shrubs and forests, while built-up areas were typically near cultivation lands.

The classification system was based on Anderson (1976) and the national land use classification scheme developed in Nigeria in 1995 (Federal Ministry of Environment, 2015). Additional insights from the Federal Department of Forestry Nigeria (2019) and Gong et al. (2020), covering classifications applicable to African regions, were considered. When combined with ground-truthed data, remotely sensed data helps validate classification accuracy, allowing researchers to group land features with similar characteristics into classes. The research consolidated classes distinguishable on satellite imagery (Hansen, 2013; Onilude and Vaz, 2020; Gong et al., 2020). Six classes were developed based on the study area LULCC categories around the reserve, such as shrublands, croplands, built-up land, grasslands, bare surface, wetlands, and forests (Table 1).

While these categories were considered suitable for the level of analysis conducted in this study, it is somewhat limited in scope. Some important subcategories, such as different types of forests (e.g., primary

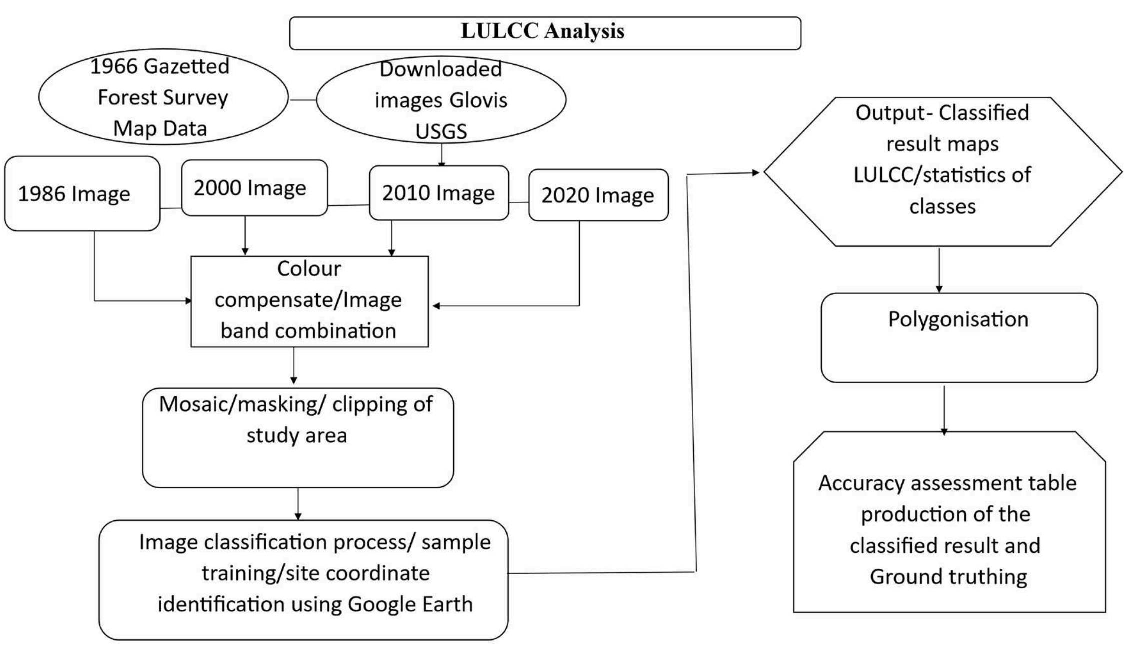

Fig. 3. Flow chart showing the workflow and steps involved in the LULCC mapping.

Table 1
Description of the classification scheme for the study.

Categories of land use/ cover type	Description
Shrublands	Mix of plants or woody shrubs, smaller than trees generally <5 m tall dispersed across the landscape with exposed soil or rock. Scrub-filled clearings within an area with multiple permanent stems branching from the near ground: moderate to sparse cover of bushes, shrubs and tufts of grass, savannas with very sparse woody or other plants.
Cropland	Area covered with crops, farmlands, and cultivation of arable and non-arable land, irrigated and non-irrigated agricultural farming. Planted cereals, and crops such as maize, wheat, beans, soya beans, yams, cassava, and fallow plots.
Built up area	Areas covered by human made structures, major road and rail networks, large homogenous impervious surfaces including parking structures, office buildings and residential housing; examples being houses, dense villages / towns / cities, paved roads, asphalt in both rural and urban areas.
Grasslands	Open areas covered in homogenous grasses with little to no taller vegetation; and grasses with no obvious human agent; examples include natural meadows and fields with sparse to no tree cover, open savanna with few to no trees, parks/golf courses/lawns, pastures.
Wetlands	Areas covered by water bodies such as dams, ponds, streams, rivers, swamps, and marshes. Areas where water is predominantly present throughout the year. Contains little to no sparse vegetation.
Bare surface	Areas of land covered mainly with bare land, including untarred roads. Areas covered by all different types of rocks including hilly areas, with very sparse to no vegetation for the entire year; examples include exposed rock or soil and sand, lake beds and mines.
Forest	Land area spanning >0.5 hectares with trees higher than 5 m and a canopy cover of >10 to 20 %, or trees able to reach these thresholds in *situ*. Any significant clustering of tall (15 m or higher) dense vegetation, typically with a closed or dense canopy. This area of land is covered with trees close together, including all natural and artificial forests with tree crown density (crown closure percentage) of 10 % or more and are stocked with trees. >75 % of the tree species shed their leaves in response to seasonal change.

Sources: Authors' description of the classification scheme for the study, based on FAO (2020).

vs. secondary forests) or variations within built-up areas (e.g., infrastructure development industrial vs. residential), are not explicitly distinguished. Additionally, transitional land covers, mixed-use areas, or degraded landscapes may not fit effectively into these categories.

2.2.4. Land use land cover classification use and analysis

ArcGIS Pro software version 3.x with a valid license for the proprietary software was obtained by the University of York, UK and used in accordance with ethical and legal standards for mapping and overlay analysis.

A supervised maximum likelihood classification was most suitable for this study in line with Gong et al. (2020) and Radwan (2021), as it is widely adopted for Landsat images and considers that each spectral class can be explained by a multivariate normal distribution. The supervised classification identifies spectrally similar areas by using 'training' sites of cluster features and extrapolating spectral signatures to the feature class (Hansen et al., 2013; Ahmed et al., 2020; Radwan et al., 2021). The classification provides training data to help the computer recognize similar patterns (Radwan et al., 2021; Mousivand and Arsanjani, 2019; Keenan et al., 2015). The process involves creating and managing signatures (Mousivand and Arsanjani, 2019; Radwan, et al., 2021), giving training classes homogeneous appearances through decision rules (Geidam, et al., 2020; Phiri and Nyirenda, 2022). For class quality, images were composed with bands 1–7 of ETM+, TM images and bands 2–7 of OLI images. Training data was based on field visits, researcher knowledge spanning 30 years, and coordinate points of land use classes around gazetted forests (Chunwate et al., 2019; Appiah et al., 2021).

The classification aimed to select multiple reflectance areas for each land cover type to provide quantitative descriptions of thematic land use classes. The supervised classification uses sample pixels from multiple areas rather than just one or two (Radwan et al., 2021). At least ten times the number of spectral bands were selected for training (Chunwate et al., 2019; Appiah et al., 2021). According to USGS, tier 1 images show high quality due to geometric and radiometric corrections, enabling time-series analyses without additional processing (USGS, 2021). However, Nasarawa State images showed scan line cover artefacts, which were removed using ArcGIS Pro software, improving image visualization and land class discrimination.

To visualise classification, small training areas were used to help the algorithm identify land cover classes from spectral signatures in imagery data. Google Maps (Sentinel) helped verify coordinate sites to confirm land use types (Amini et al., 2022; Das et al., 2021; Capitani et al., 2019). Training areas for each land cover class were created by selecting image pixels and converting them to KML files for verification in Google Earth imagery (Gbedzi et al., 2022; Gong et al., 2020). The classified dataset was polygonised to calculate class areas (Fasona and Sobanke, 2020; Owusu and Essandoh-yeddu, 2018; Mousivand and Arsanjani, 2019). Areas were calculated using the geometry of the attribute table in ArcGIS Pro software version 3.x (Phiri and Nyirenda, 2022; Fasona et al., 2020). Challenges included differentiating between land use classes, particularly cropland and grassland. Using remote sensing/GIS experience, ground truthing data was incorporated into training sets to reclassify Landsat images for accurate land use maps from 1986 to 2020. Areas not aligned with ground conditions were reclassified to improve accuracy. The classified Landsat images were assessed using 90 geographically referenced points from the gazetted forest, as detailed in the next section

2.2.5. Accuracy assessment of LULCC classes

The accuracy of the land use and land cover classification for 1986, 2000, 2010, and 2020 was assessed using ArcGIS, following the approach by Adedeji et al. (2015) and Dibaba & Miegel (2020). The assessment involved generating an error matrix, accuracy totals, and a Kappa statistic (Table 2). Reference data from the supervised classification module in ArcGIS were used to create the error matrix, based on methods used by Khawaldah (2016), and Fasona et al. (2020).

2.2.6. Field ground truthing

Ground-truthing was conducted on selected gazetted forest reserves to verify land use classification results and understand ongoing activities (Appendix B). Field validation improved the quality and accuracy of classified maps (Dibaba, et al., 2020) by obtaining ground truth data to verify the classified maps of gazetted forest reserves. Ground truth points were sampled with GPS using random sampling techniques considering security and accessibility, following Oliphant et al. (2019), Phiri & Nyirenda (2022). To maintain consistency and allow for direct comparison between the three forest reserves, a sample size of 30 points was selected for each site (Appendix A, Table 2). The choice of 30 sample points aligns with recommendations from established remote sensing accuracy assessment guidelines (e.g., Foody, 2009; Congalton and Green, 2019; Kraatz et al., 2023), which suggest that a minimum of 30–50 points per class is sufficient to provide a reliable estimate of classification accuracy when resources are limited. This threshold balances the need for robust accuracy assessment with practical constraints such as field accessibility, time, and cost. Although Doma Forest Reserve is larger than the others, the decision to use an equal number of sampling points (30) across all three reserves was made to ensure uniform sampling intensity and to prevent sampling bias. 30 ground truth points for each forest were geographically referenced using GPS (Appendix A, Table 2). In this study, only accessible areas without significant known

Table 2
ArcGIS generated accuracy (%) of the classified image analysis result assessments of 1986, 2000, 2010, and 2020 images using an error matrix.

LULCC Class	1986 Producers' accuracy (%)	Users' accuracy (%)	2000 Producers' accuracy (%)	Users' accuracy (%)	2010 Producers' accuracy (%)	Users' accuracy (%)	2020 Producers' accuracy (%)	Users' accuracy (%)
Croplands	84.2	88.1	85.6	92.2	93.2	94.6	94.1	95.2
Shrublands	89.9	92.4	88.7	93.4	90.3	91.7	91.2	94.1
Forest lands	89.6	94.2	87.5	89.4	88.2	93.5	90.1	96.4
Grasslands	80.2	84.7	85.6	93.6	87.6	94.2	88.5	93.8
Wetlands	86.5	87.2	82.8	86.3	90.1	90.5	90.1	90.7
Built-up land	86.8	88.3	88.4	90.7	89.4	92.8	91.4	94.2
Bare surface	87	88.2	88.6	90.7	83.3	91.2	81.8	92.9
Overall Accuracy assessment	**86.90 %**		**87.50 %**		**90.48 %**		**93.33 %**	
Kappa coefficient	**0.85**		**0.87**		**0.89**		**0.98**	

risks like rough terrain, terrorism, cultural restrictions or dangerous wildlife were included. The selection of 30 points balanced spatial coverage with fieldwork safety, time, and resource constraints. Sampling covered different types of land use and forest covers, including farms, forests, shrublands, grasslands, built-up areas, and water bodies (Appendix A, Table 2). Previous studies in similar ecological and geographical contexts have successfully applied comparable sampling intensities to validate classified land cover maps (Kraatz et al., 2023; Foody, 2009). The distribution of sample points across different land cover classes also ensures proportional representation of both dominant and minor classes, thereby enhancing the reliability of the accuracy metrics derived. This approach improves confidence in the final land use and land cover change (LULCC) assessment presented in this study. Photographs evidence validating land cover classes (Appendix B). The points were imported into ArcGIS, georeferenced using UTM zone 32, and superimposed onto the classified image map, providing visual representation of classification accuracy and allowing authentication of real-world conditions within forest boundaries (Fig. 4). Nonetheless, it is important to acknowledge that the number of sample plots used for accuracy measurement may still appear insufficient and could introduce bias into the analysis; therefore, the sample size should be further justified or expanded where feasible to ensure robust and reliable results.

3. Results

The findings overall reveal trends in land use and land cover around the gazetted forest reserves in the study area.

3.1. Accuracy assessment of land cover classification result

The field ground-truthing results are presented in Fig. 4, providing validated or verified information on the classified results for land cover maps. The sampled points of the classes of the LULCC generated on the

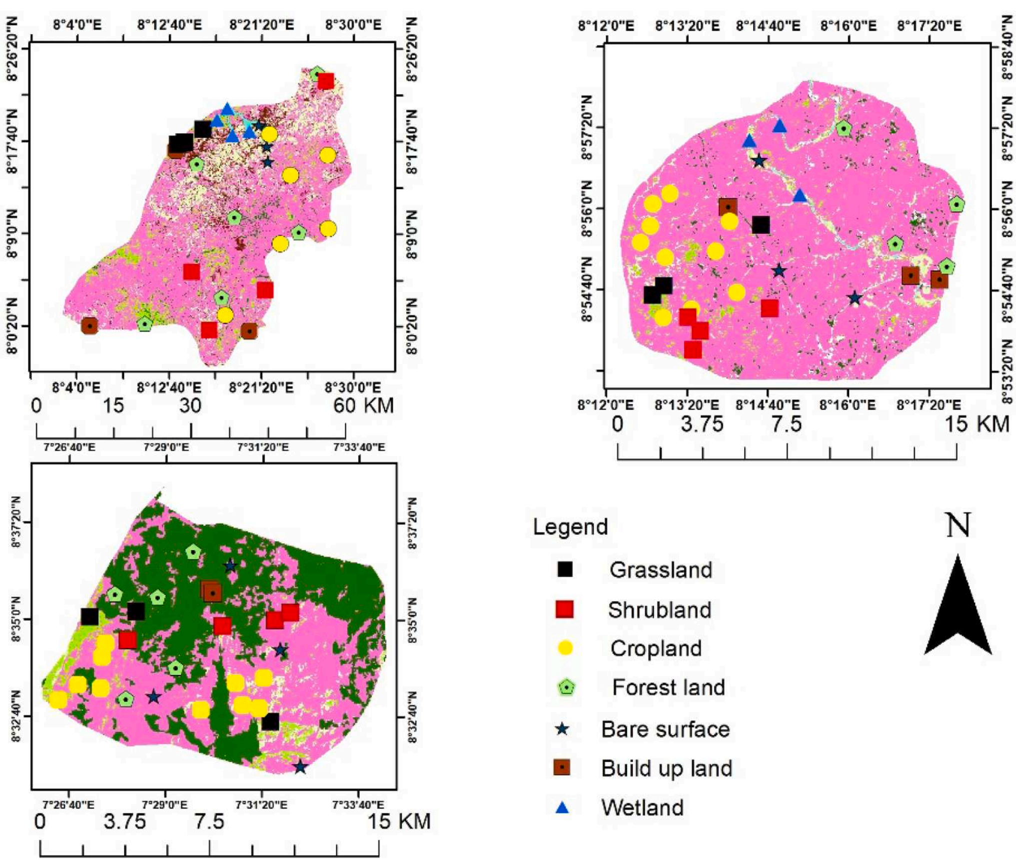

Fig. 4. Spatial overlay ground truthing points corresponding to LULCC classes from the fieldwork on the classified image map of the three forest reserves.

classified maps of the study area forests (Appendix A Table 2) showed 30 points for each of the forest reserves; the cropland class had 10 sample points in each reserve, while other classes such as forestland, bare surface, shrublands, built-up land, and wetland had three to seven sample points. These points were overlaid on the overall classification maps to ascertain accuracy for 2020 (Fig. 4). Table 2 also presents the accuracy for the classified maps. The accuracy of the user refers to the certainty that a pixel categorised on the map accurately depicts the corresponding ground feature, while the producer accuracy relates to the probability of correctly classifying a reference sample (Ding et al., 2021). The ArcGIS analysis showed a classification map accuracy of 93.33 % for 2020, with a Kappa coefficient of 0.98 implying a very strong agreement between

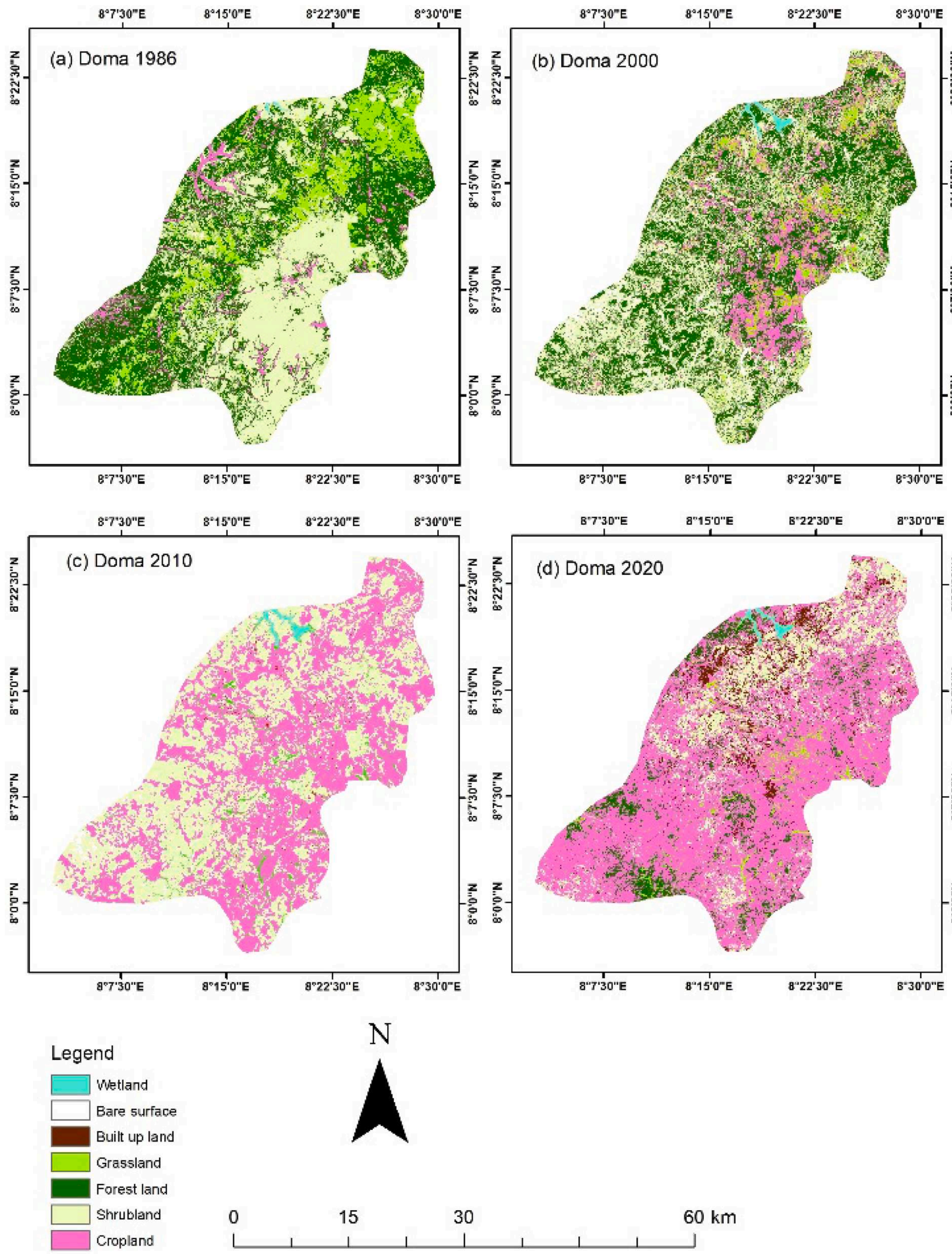

Fig. 5. Classified image map of LULCC for the Doma gazetted forest area from 1986 to 2020.

the predicted and actual classifications. These results are presented in Table 2 and the classified maps are shown in Figs. 4–10.

3.2. Trends of LULCC around Doma gazetted forest reserve

Figs. 5 and 6 show the analysed image and results of the LULCC for the years 1986, 2000, 2010, and 2020 for Doma. These figures demonstrate that the forest cover experienced a substantial decline up to 2020. In 1986, forests dominated the region, covering a significant portion of the area. There was minimal presence of croplands and built-up lands, indicating a natural landscape with limited anthropogenic intervention. A notable decline in forests was observed, with increasing croplands in 2000. The year 2000 also witnessed an expansion of built-up lands and bare surfaces (Figs. 5, 6). The major transformation was that croplands became the dominant land cover, covering the larger portion of the region. Substantial loss of forest and grasslands was evident, indicating high deforestation rates. Further expansion of built-up areas and bare surfaces was observed, demonstrating settlement expansion and land degradation. Shrublands and natural vegetation were substantially reduced. In 2010, trends revealed a further reduction in forest cover, which had become highly fragmented. Substantial expansion of croplands continued to dominate the landscape with marginal increases in built-up areas and bare surfaces, reflecting continued forest cover loss and land degradation. Wetlands were observed predominantly in the northern part of the region with other minor occurrences across the areas. From 1986 to 2020, the extent of wetlands fluctuated erratically (Figs. 5, 6), appearing minimal in 1986, increasing between 2000 and 2010, and decreasing towards 2020. In summary, the progression from 1986 to 2020 highlights a steady decline in natural vegetation, particularly forests and grasslands, as croplands and built-up areas expanded, with permanent fields being established in the reserve and becoming the dominant land use by 2020, and the expansion of human activities. Built-up lands, though relatively small, have gradually expanded over time, and wetlands are dispersed, mainly concentrated toward the northern and southern parts fluctuating over the study years (Fig. 8). Bare surfaces and forests have limited coverage, particularly in 2020.

3.3. Trends of LULCC around Risha gazetted forest reserve

Figs. 7 and 8 show the classified maps of land use and land cover results for the years 1986, 2000, 2010, and 2020 for Risha. It is evident from these figures that the forest cover experienced a substantial decline. Forests were the most prominent feature in 1986. Grasslands and shrublands were also widespread, with minimal presence of croplands, built-up areas, and bare surfaces. This is similar to that of the Doma reserve map for 1986, whereby the landscape in 1986 reflected a natural forest cover with limited anthropogenic interference. However, the 2000 map for Risha demonstrated a dramatic reduction in forest cover, being replaced largely by shrublands and croplands. An increase in bare surfaces was observed, indicating deforestation or land degradation, as well as expansion of built-up lands, although these are still relatively small compared to other categories (Fig. 8). This period marked the onset of intensified human activity, such as agriculture and infrastructure development, evidenced by cropland expansion and shrubland around the reserve. The deforestation trends suggested a growing demand for farmland and forest resources.

In 2010, trends indicated a continued reduction in forests, with remaining forest areas being severely fragmented. Further expansion of croplands spread across the reserve, with this becoming the dominant land cover type. Furthermore, there was a slight increase in built-up areas and bare surfaces, indicating settlement increases, and an increase in land degradation. In 2020, croplands dominated the landscape. Only small, isolated patches of forest remained. There was a further increase in bare surfaces and built-up areas. The year 2020 reflected the culmination of decades of deforestation and agricultural expansion; the dominance of croplands indicated that subsistence or commercial agriculture had become the primary land use. Wetlands, which were significant in 1986 with a river feature observed across the forest area, experienced a decrease in extent between 1986 and 2000, increased in 2000 and 2010, and were observed to have decreased substantially by 2020 (Fig. 8). This change suggests environmental impacts of deforestation, such as reduced biodiversity and ecosystem disruption from this reserve.

Overall, forest cover experienced a dramatic decline over the 34-year

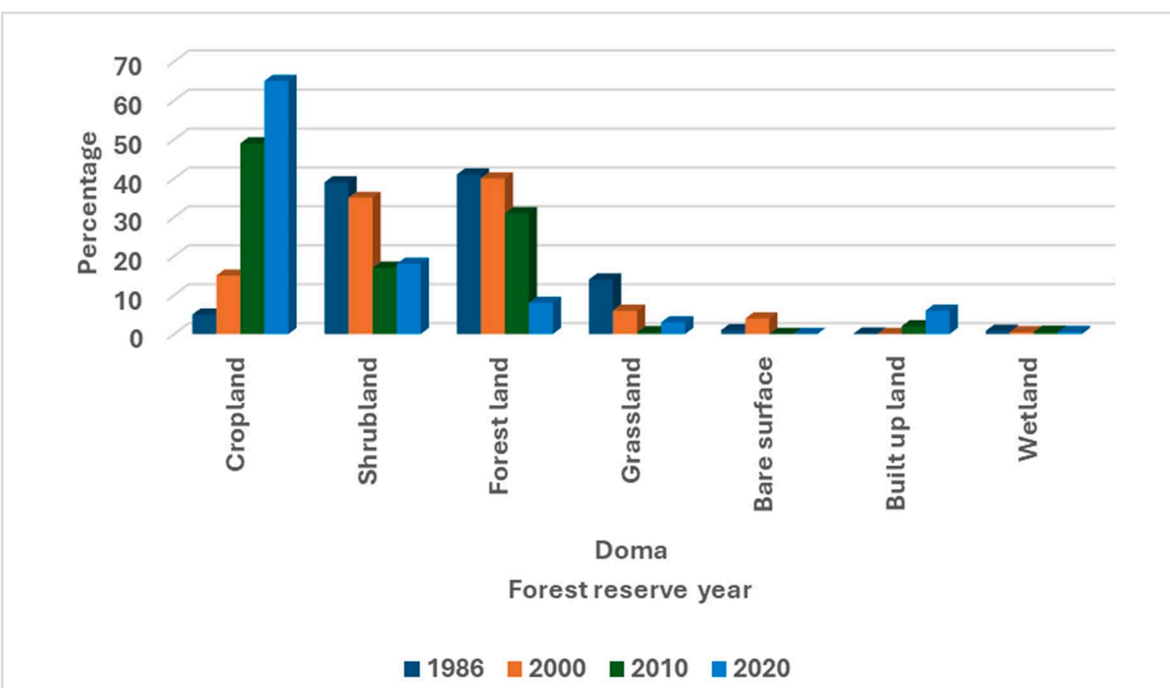

Fig. 6. LULCC for the Doma gazetted forest area from 1986 to 2020.

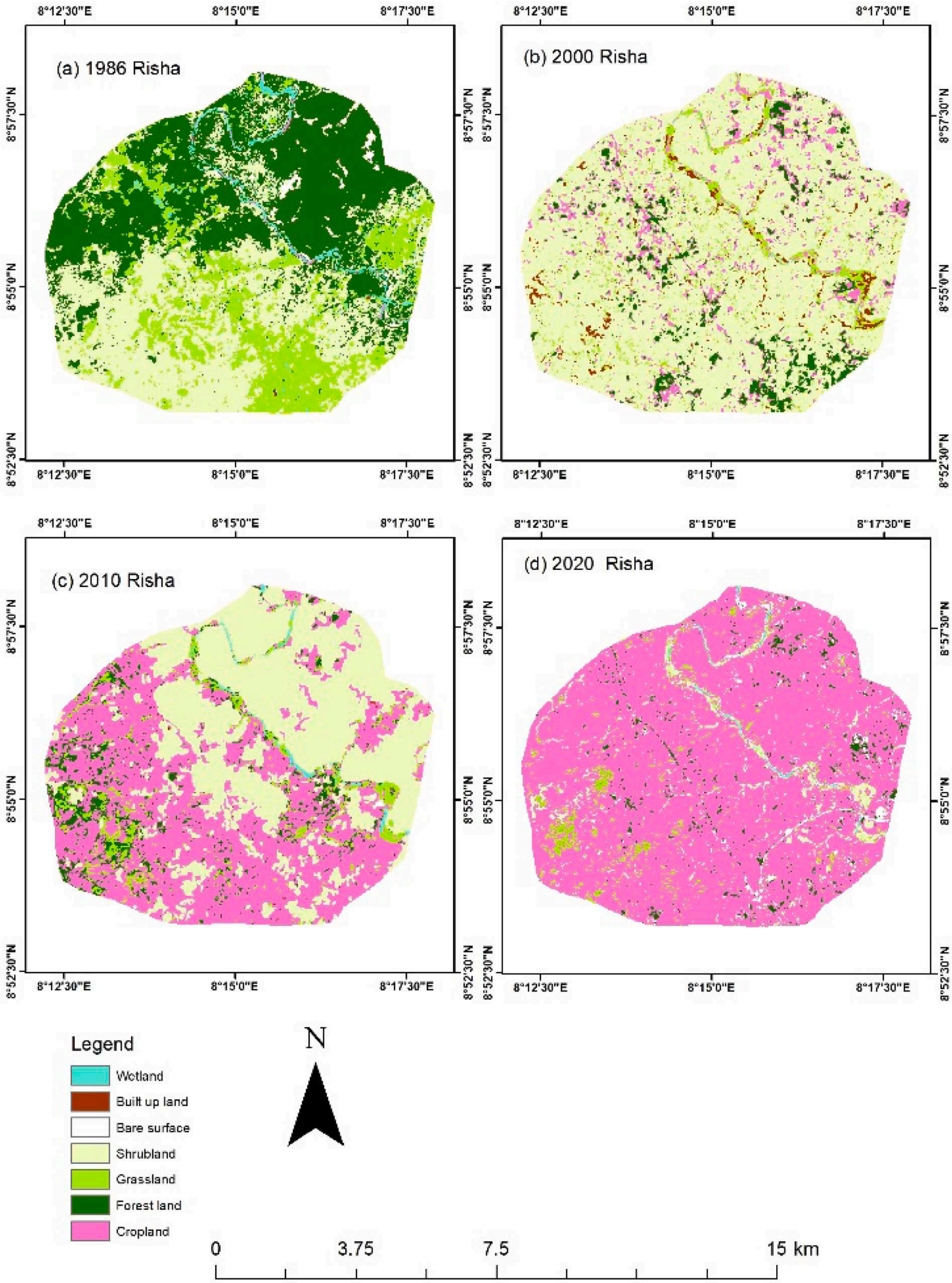

Fig. 7. Classified image map of LULCC for Risha gazetted forest area for 1986 to 2020.

period, primarily due to cropland encroachment. Croplands steadily expanded, becoming the dominant permanent land cover observed by 2020 (Figs. 7, 8). While built-up lands remained a minor land use type, they gradually increased over time. The increase in bare surfaces highlighted issues such as soil erosion, overgrazing, and land degradation.

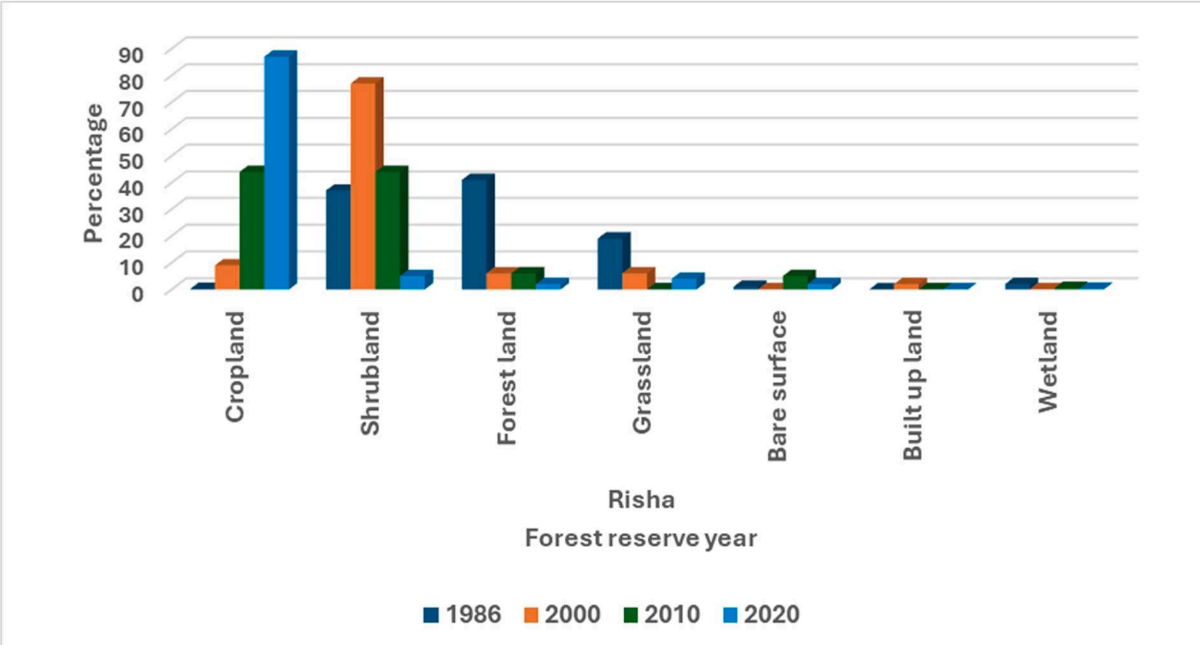

Fig. 8. LULCC for the Risha gazetted forest areas from 1986 to 2020.

3.4. Trends of LULCC around Odu gazetted forest reserves

Figs. 9 and 10 present the map of land use and land cover results for the years 1986, 2000, 2010, and 2020 for Odu. These figures demonstrate that the forest cover experienced substantial changes. The observed result in 1986 indicates that forests dominated much of the area, with grasslands and shrublands also scattered across the forest region (Fig. 9). Croplands and built-up areas were minimal, reflecting a predominantly natural landscape with limited anthropogenic interference. Built-up lands and bare surfaces were nearly absent, suggesting minimal settlements or infrastructural developments at this time. However, in 2000 forest cover and grassland noticed a decline, while shrubland increased and other parts of the area had increasingly converted to croplands in 2000 (Fig. 10). The expansion of cropland became more prominent, particularly in the southeastern and southwestern parts of the region while forest cover is observed to change appearance observed in the northern part of the area (Fig. 10). The expansion of croplands reflects intensified agricultural activity pressures in the area.

In 2010, forest cover further diminished, with significant areas transitioning to croplands and shrublands. The change in conversion between croplands and shrublands is observed, possibly due to an increased focus on agriculture, suggesting a shifting cultivation pattern. Grasslands increased slightly while shrublands expanded, potentially indicating land degradation or abandonment of certain cropland areas. For 2020, the forest class exhibited a dramatic substantial increase, and grassland also increased, suggesting improved preservation of vegetation compared to Risha and Doma. However, the croplands continued to expand at the expense of shrubland, which declined significantly as observed from the classified map. The cropland expanded more from the southeastern and western parts of the area. Built-up areas in Odu showed only an increased trend around the reserves in the classified map of 2020, suggesting population growth and infrastructure development that could contribute toward the increase in settlements around the forest reserve area. Some settlements are observed inside the core forest area and appear towards the southeastern and western parts of the region signifying cropland expansion was far from their settlement, which could indicate that shifting cultivation has been taking place. This system involves extensive cropland use followed by a fallow period to allow nutrient regeneration before returning to the same lands in subsequent years. This is evidenced by the classified map as the shrublands and cropland were fluctuating within the proportion of land cover type. In the classified maps of the reserve, all years reveal an absence of wetlands (Figs. 9, 10). However, the research observed some river courses along this during the ground truthing fieldwork around the forest boundary in the area in 2022.

The overall results indicate dynamic changes in land use and land cover within the forest reserves, with shifts towards croplands, variations in forest cover with an increase in forest cover type to 45 % for 2020, and fluctuations in shrublands, wetlands, and built-up areas.

3.5. Comparative analysis of LULCC around the three gazetted forest reserves

Fig. 11 shows the comparative results for the three forest reserves (Doma, Risha and Odu).

The comparison revealed that the rate of LULCC varied significantly among the three forest reserves, although all three displayed substantial changes. Doma forest reserve has experienced a change in all land cover classes and a significant decrease in forest cover between 1986 and 2020 (Fig. 11). The forest cover declined steadily from 1986 to 2020, with croplands becoming the dominant land cover by 2000. The region's forests were particularly vulnerable to cropland expansion and settlement growth, with minimal forest patches remaining by 2020. The trends indicate continuous loss of forest cover without any sign of substantial recovery. Similarly, Risha's forest lands experienced a severe decline over the 34-year period. The extent of forest cover within the Risha forest reserve diminished from 40 % in 1986 to 2 % in 2020, with croplands largely occupying the landscape. The forest cover loss and degradation were particularly intense, leading to a near-complete loss of forest cover by 2020 without recovery. The lack of substantial forest remnants suggests unsustainable land-use practices. Unlike Doma and Risha, Odu showed a more dynamic pattern. Although the Odu forest reserve displayed a distinct change trend compared to the other study regions, the forest cover experienced a decrease from 1986 to 2010. Notably, areas classified as shrubland in 2010 have transitioned to agriculture by 2020, while former agricultural land has become grasslands. Between 2010 and 2020, there was a substantial increase of 45 % in the forest cover, reflecting possible conservation or natural

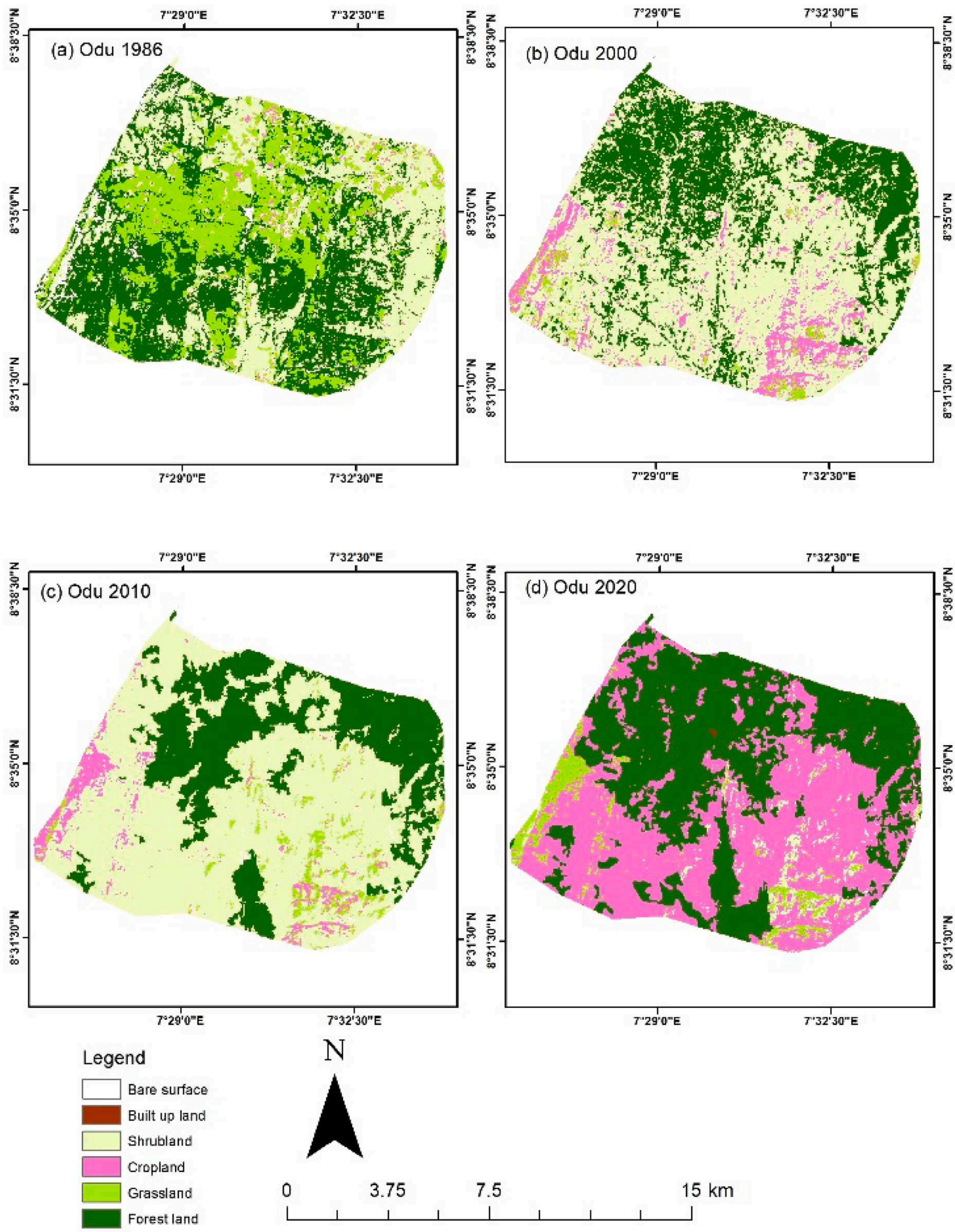

Fig. 9. Classified image map of LULCC for Odu gazetted forest area for 1966 to 2020.

regeneration efforts. This rebound sets Odu apart as a region with fluctuating but potentially recoverable forest conditions.

From this comparison, croplands occupied the largest area of two forest reserves by 2020, with Risha having the highest (87 %), followed by Doma and Odu (Fig. 11). This expansion, in Doma particularly after 2000, indicates intensive agricultural pressures (likely subsistence farming), while in Risha cropland encroachment was the most dramatic, where croplands permanently replaced nearly all classes of land cover by 2020. This reflects the high demand for farmland, exacerbated by population pressures and limited conservation initiatives. Although croplands also expanded in Odu, the region demonstrated a more dynamic balance between cropland expansion and other land cover classes such as shrublands and forests. These suggest the evidence of shifting cultivation and land fallow systems, highlighting a different agricultural approach compared to Doma and Risha.

In the Risha reserve, grassland and bare surfaces fluctuated similarly

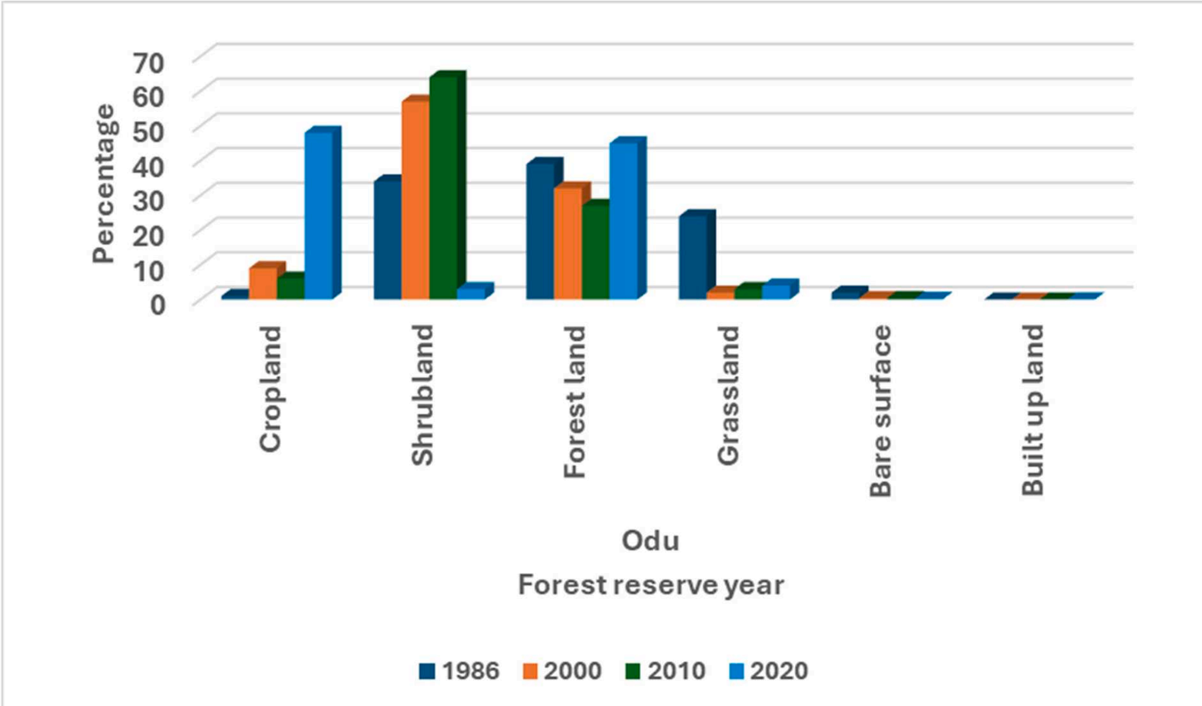

Fig. 10. LULCC for the Odu gazetted forest areas from 1986 to 2020.

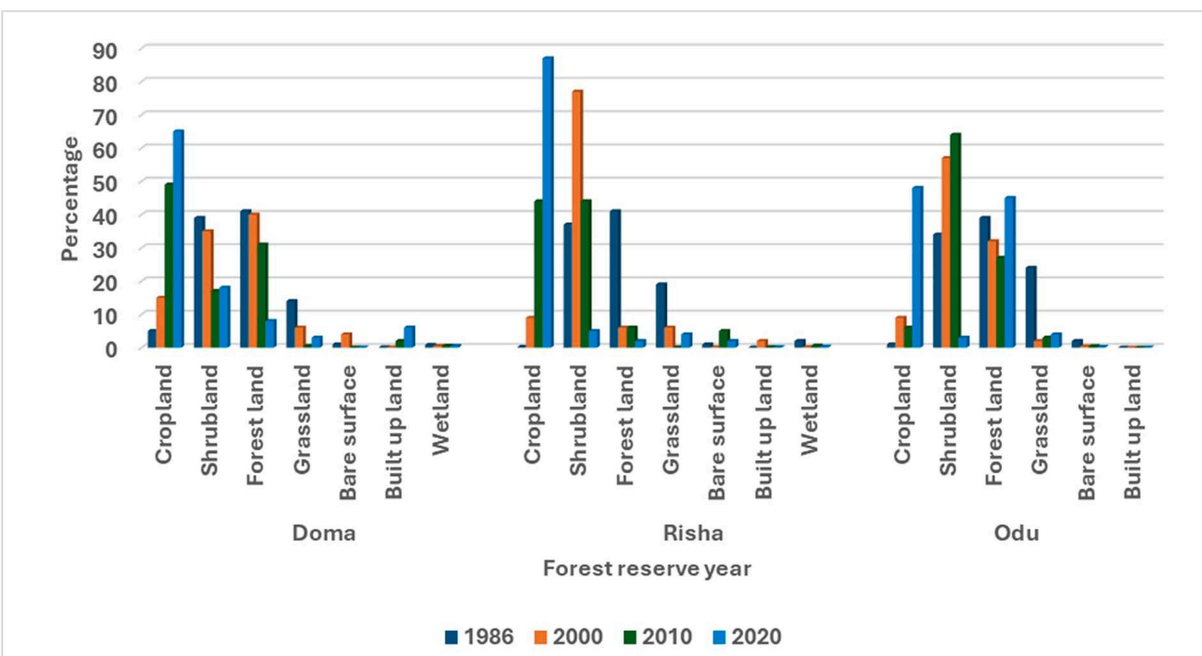

Fig. 11. LULCC for the three gazetted forest areas from 1986 to 2020.

to those of the Doma and Odu, although the percentages varied (Fig. 11). The Doma shrubland cover declined between 1986 and 2000, whereas the shrublands in the Risha forest area rose between 1986 and 2000 but decreased between 2010 and 2020, which could have contributed to a reduction in these natural vegetation types. The Odu shrublands fluctuated over the same periods. This reflects a shifting pattern of land use, potentially tied to land fallow systems or environmental conservation. From 1986 to 2020, the extent of wetlands fluctuated erratically, with the wetland cover in the Doma reserve increasing between 2000 and 2010 and decreasing towards 2020. In Risha, wetlands experienced an extent of decline between 1986 and 2000, increased between 2010 and 2000, and decreased significantly by 2020. Overall, a sharp decline was observed between 1986 and 2020. In the Odu reserve, all years reveal an absence of wetlands . The dynamics of wetland extent in Doma and Risha reserves may be primarily influenced by rainfall and temperature changes. Higher rainfall and moderate temperatures may promote wetland expansion, whereas lower rainfall and higher temperatures can cause decline. The lack of wetlands in the Odu reserve suggests consistently unfavourable climatic conditions for wetland formation during the studied period, or vegetation plays a crucial role in water regulation by capturing water and enhancing soil porosity and organic matter content. Consequently, a reduction in vegetation cover can result in increased surface water accumulation, commonly referred to as ponding. Doma forest reserve experienced a doubling in built-up area between 2010 and 2020. Risha experienced an increase in built-up areas between 1986 and 2020, reflecting settlement growth and infrastructure development around the forest area which could lead to more encroachments on forest cover for resource exploitation. However, Odu Forest cover showed no portion of the built land in the reserve, except in 2020. The presence of settlements inside the core forest region in Odu 2020 reflects unique spatial pressures, likely tied to shifting cultivation practices.

In summary, the three reserves exhibited varying trends in land use and cover changes over the studied periods. In 1966, all three forest reserves were largely forest class covered according to the historical boundaries survey map of the study reserve. Doma forest reserve cover experienced a decrease between 1986 and 2020. Risha forest reserve cover decreased to 2 % in 2020, while Odu forest reserve cover showed a declining trend from 1986 to 2010 but saw a substantial increase to 45 % in forest cover between 2010 and 2020.

The analysis highlights the dynamic nature of LULCC within the three gazetted forest reserves. Doma and Risha show persistent loss of forest cover over cropland expansion in the permanent fields with no recovery, while Odu demonstrates more dynamic land use patterns with potential for regeneration. These findings suggest the need to understand the drivers of change in these reserves (see Chunwate et al., 2025), as well as targeted conservation and management strategies tailored to the specific dynamics observed in each reserve. Overall, the comparative analysis provides valuable insights into the evolving landscape dynamics and underscores the importance of ongoing monitoring and conservation efforts within these forest reserves.

4. Discussion and implications

This study applied remote sensing and GIS as effective tools for assessing LULCC in gazetted forest reserves over multi-decadal periods. Classification accuracy consistently exceeded established standards for remote sensing studies (Anderson, 1976; MacLean and Congalton, 2012), with all classes achieving over 80 % accuracy (Thomlinson et al., 1999). These robust results, confirmed through ground-truthing and supported by user and producer accuracy metrics, align with similar findings from Yesuph & Dagnew (2019), Latham (2013), and Dibaba & Miegel (2020). While the 30-meter resolution limited the detection of very small-scale changes such as finer landscape features, the methodology remains reliable for landscape-level monitoring (Dibaba and Miegel, 2020), with ground-truth validation confirming the reliability of the classification outputs. This supports the view that moderate-resolution satellite imagery remains a practical and cost-effective tool for developing regions with limited resources for high-resolution data acquisition (Kraatz et al., 2023; Assefa and Bork, 2014).

Over the 34-year period, all three reserves experienced significant forest cover loss primarily due to conversion to cropland. Cropland expansion was especially pronounced in Doma and Risha, where large, contiguous areas of forest and shrubland were permanently converted. In contrast, Odu exhibited a different trajectory: shifting cultivation practices facilitated cycles of fallow and natural regeneration, resulting in a reappearance of forest cover in certain areas. This dynamic supports findings by Kusimi (2015) and Appiah et al. (2021), who observed forest recovery in landscapes where traditional land-use systems such as bush fallow remain active. The contrasting patterns underscore how local socio-economic drivers and land management practices can either exacerbate or mitigate deforestation, and demonstrate that context plays a critical role in shaping forest outcomes. These findings echo similar broader trends documented widely across sub-Saharan Africa, where agricultural expansion remains the predominant cause of forest loss (Fasona et al., 2020; Janssen et al., 2018). However, the degree of forest cover loss in Doma and Risha exceeds rates reported in comparable reserves in Ghana (Appiah et al., 2021) and Ethiopia (Yesuph and Dagnew, 2019), indicating that enforcement and governance challenges may be more severe in these Nigerian contexts.

The severe decline in forest cover in Risha and Doma, where forest cover dropped from 40 % in 1986 to just 2 % in 2020, largely due to the unchecked expansion of cropland, illustrates the limitations of gazettement alone without effective governance and enforcement (Onilude and Vaz, 2020; Onyekwelu et al., 2016). In contrast, Odu's partial forest recovery highlights the potential benefits of community-driven restoration and sustainable land-use practices, which could enhance sustainable land management and community engagement to reverse degradation trends (Otokiti et al., 2019). This contrast mirrors evidence from East Africa, where participatory forest management schemes have been linked to lower deforestation rates than strictly protected areas with minimal local involvement (Robinson et al., 2013)

These findings suggest that forest policy must go beyond formal protection on paper and should integrate agroforestry, participatory management, and alternative livelihoods that align with local needs into national forest policy frameworks (Akamani and Hall, 2019; Acheampong et al., 2016). This matches broader research advocating for integrated landscape approaches that reconcile conservation with food security, especially in forest–agriculture protected areas (Phiri and Nyirenda, 2022). Integrating conservation efforts with local development priorities such as balancing food security with forest conservation is essential for sustaining the ecological and socio-economic functions of gazetted forests in Nigeria and beyond, particularly given the high rates of conversion of forest to croplands.

The divergent LULCC trajectories demonstrate both the challenges and opportunities for conservation in gazetted reserves. The near-total forest loss in Doma and Risha highlights how inadequate conservation measures and weak governance can accelerate degradation (Crouzeilles et al., 2019). Conversely, Odu's experience shows that well-managed traditional land-use systems, such as shifting cultivation, can maintain or even restore forest cover when supported by appropriate policy frameworks (Hecht, 2014). These outcomes support the argument that community tenure security and recognition of indigenous practices are central to effective forest conservation (Chazdon et al., 2020). Proactive conservation strategies are urgently needed to address agricultural encroachment and settlement expansion, while promoting sustainable land-use alternatives that protect biodiversity and ecosystem services.

Odu's forest cover increase demonstrates that restoration is feasible through natural regeneration and sustainable land management practices. This finding supports Chazdon & Uriarte (2016) and Chomba et al. (2020), who advocate for Farmer-Managed Natural Regeneration (FMNR) and agroforestry as cost-effective, community-led approaches. However, in highly degraded reserves like Doma and Risha, large-scale restoration will require substantial/extensive interventions, including active reforestation, afforestation, and sustained support with incentives for sustainable agriculture (Stanturf et al., 2014; Zomer et al., 2016). Ensuring that restoration strategies and efforts most align with local socio-economic contexts will be vital for their long-term success and sustainable realities. This is consistent with evidence from Brazil and Indonesia, where integrated incentives and community participation have proven more effective than top-down restoration mandates (Brancalion et al., 2019; Reed et al., 2017).

The findings underscore the limitations of traditional forest governance models that overlook local realities and land pressures (Loconto et al., 2018). A more effective approach must adopt integrated, landscape-level management that connects forest reserves with surrounding agricultural land zones and local communities. Practices such as agroforestry, the Taungya system, and co-management can help balance conservation goals with livelihood needs (Akamani and Hall, 2019). Ongoing monitoring using remote sensing tools and community-based land management approaches will be essential for adaptive and responsive forest governance and management (Amoah et al., 2022). The findings overall provide actionable insights for policymakers and stakeholders and for achieving progress towards meeting Sustainable Development Goals 13 (climate action) and 15 (life on land) (Amoah et al., 2022).

The LULCC trends in Doma, Risha, and Odu provide critical insights into the dynamics of forest change in Nasarawa State, Nigeria, offering the first quantification of the extent to which gazetted forest reserves have failed or succeeded in maintaining forest cover evidence in this region. Without urgent and context-specific interventions, continued conversion to permanent cropland in Doma and Risha will result in nearly complete forest cover loss, while the Odu forest offers a potential model for sustainable land use management, where community practices and natural cycles have allowed for partial forest recovery, and can maintain and even increase forest cover despite surrounding agricultural activity pressure. However, if agricultural trends also continue without a proper sustainable management model, it is likely that Odu may soon experience the same pattern of expanding cropland permanently in the reserve area, which could lead to total deforestation in this area. This potential trajectory mirrors documented cases in Kenya and Uganda where traditional practices alone were insufficient to prevent deforestation once commercial agricultural pressures intensified (Mwavu and Witkowski, 2008).

This study's findings are relevant to local communities in understanding the implications of change in the forest reserves, as well as those working within the environmental sector in Nasarawa State and Nigeria at large. The findings underscore the need for the integration of land use planning for proper, effective policy decision making and implementation. Through analysis of Landsat images over the study period, this research contributes important new knowledge on the study area's land cover/land use in terms of its protected forests. By providing empirical evidence, this research strengthens the case for urgently prioritizing governance reforms, community co-management, and integrated livelihood strategies to tackle deforestation trends. In addition, this research presents fresh insights for developing nations, particularly those where deforestation remains prevalent. Specifically, the findings on forest cover modifications in this study can aid these countries in formulating and executing more efficient conservation measures, thus decreasing the speed of forest loss. Hence, this should be a wake-up call to policymakers regarding the management of PAs and gazetted forest reserves, as encroachment is increasing across the forest regions in Nigeria. Reserves are currently not protecting the forest in the way that they were originally intended. The change in the forest has negative implications in diverse ways, such as the loss of genetic resources, unsustainable food production and the loss of potentially valuable medical and other forest products in this area. The loss of forests which are essential for environmental functions, encompassing biodiversity, climate regulation, and preserving water catchment areas, poses a significant threat to societies. In addition, this could reduce opportunities for livelihood and income generation but also hampers efforts that seek to preserve the cultural values of society.

5. Conclusion

The LULCC trends observed in Doma, Risha, and Odu gazetted forest reserves provide critical insights into the dynamics of forest change in Nasarawa state, Nigeria. This research represents the first quantification of the failure of the forest reserve approach in these areas, providing unprecedented insights into the extent of deforestation in Doma and Risha. Doma and Risha showed nearly complete forest loss to cropland expansion, with the establishment of permanent fields. Continued trends in this direction will eventually lead to the complete loss of forest in the area. However, Odu forest reserve retained substantial forest cover increases in 2020 despite increasing cropland as a result of shifting cultivation around the reserve. The comparative analysis of LULCC in the Doma, Risha, and Odu forest reserves highlights the varied impacts of human activities and environmental factors on forest ecosystems. A comprehensive understanding of the changing patterns of LULCC within forest reserves is crucial for formulating effective management strategies. Assessing these changes using multi-temporal remote sensing data is vital for making well-informed decisions at local, national, and international levels. The divergent trends observed underscore the need for context-specific conservation, restoration, and forest management strategies that are responsive to local socio-economic realities and land-use pressures.

Practically, this study provides clear evidence to guide policymakers and land managers in prioritizing urgent interventions in forest reserves facing severe deforestation, such as Doma and Risha, while reinforcing and replicating successful practices evident in Odu. Theoretically, the research contributes to the broader discourse on the limitations of the gazetted forest reserve model under weak enforcement and shifting agricultural practices, and highlights the importance of integrating community-based management approaches. Lessons learned from Odu's recovery trajectory and the failures in Risha and Doma offer valuable insights for guiding national forest policy and management.

Future research should build on this study by evaluating the effectiveness of community involvement, and developing scalable conservation models. It is essential to focus on and learn from these findings and collaborate with the communities (Nasarawa State and beyond) involved in maintaining, enhancing and preserving the forest cover.

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CRediT authorship contribution statement

Banki T. Chunwate: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Robert A. Marchant:** Writing – review & editing, Writing – original draft, Visualization, Supervision, Project administration. **Eleanor K.K. Jew:** Writing – review & editing, Visualization, Validation, Supervision. **Lindsay C. Stringer:** Writing – review & editing, Visualization, Validation, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Reports a relationship with that includes:. Has patent pending to. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendices

Appendix A Table 1
A table Landsat images and their characteristics used from USGS, Glovis, NASA.

Path/Row	Date of acquisition	Sensor	Image resolution
187/054	10-01-1986	L5 TM	30m
187/055	28-12-1986	L5 TM	30m
188/054	19-12-1986	L5 TM	30m
188/055	19-12-1986	L5 TM	30m
189/054	08-01-1986	L5 TM	30m
187/054	08-11-2000	L7 ETM+	30m
187/055	27-01-2001	L7 ETM+	30m
188/054	17-12-2000	L7 ETM+	30m
188/055	04-03-2000	L7 ETM+	30m
189/054	06-12-1999	L7 ETM+	30m
187/054	04-01-2010	L7 ETM+	30m
187/055	20-01-2010	L7 ETM+	30m
188/054	13-12-2010	L7 ETM+	30m
188/055	13-12-2010	L7 ETM+	30m
189/054	02-01-2010	L7 ETM+	30m
187/054	08-01-2020	L8 OLI	30m
187/055	24-01-2020	L8 OLI	30m
188/054	31-01-2020	L8 OLI	30m
188/055	31-01-2020	L8 OLI	30m
189/054	22-01-2020	L8 OLI	30m

Source: Satellite Image characteristics USGS, Glovis, NASA 2021.

Appendix A Table 2
A table showing ground truthing coordinate points from the gazetted forest reserve sites for the study area.

	Doma forest points			Risha forest points			Odu forest points		
S/N	X	y	Class Name	X	y	Class Name	x	y	Class name
1	8°15′46.77″	8°21′51.54″	Bare surface	8°56′48.14	8°14′31.28″	Bare surface	8°32′56.74″	7°30′51.57″	Cropland
2	8°17′13.40″	8°21′45.93″	Bare surface	8°54′59.52″	8°14′51.11″	Bare surface	8°33′19.83″	7°27′25.98″	Cropland
3	8°18′57.96″	8°21′39.19″	Bare surface	8°54′32.85″	8°16′6.56″	Bare surface	8°33′2.83″	7°26′25.06″	Cropland
4	8°19′12.28″	8°21′4.39″	Bare surface	8°54′54.50″	8°17′1.87″	Built up land	8°32′49.44″	7°29′51.53″	Cropland
5	8°16′52.10″	8°13′15.44″	Built up land	8°54′50.53″	8°17′30.26″	Built up land	8°32′52.45″	7°31′15.21″	Cropland
6	8° 0′22.52″	8° 5′11.93″	Built up land	8°56′1.56″	8°14′0.46″	Built up land	8°33′28.22″	7°30′40.94″	Cropland
7	7°59′53.83″	8°20′12.50″	Built up land	8°54′12.51″	8°12′56.47″	Cropland	8°33′36.09″	7°31′22.45″	Cropland
8	8°14′29.68″	8°24′2.32″	Cropland	8°54′20.84″	8°13′24.78″	Cropland	8°34′5.19″	7°27′27.96″	Cropland
9	8° 8′5.45″	8°23′6.61″	Cropland	8°55′18.01″	8°13′48.31″	Cropland	8°33′25.30″	7°26′53.12″	Cropland
10	8° 9′30.09″	8°27′35.73″	Cropland	8°55′11.70″	8°12′58.55″	Cropland	8°34′24.59″	7°27′33.33″	Cropland
11	8° 1′23.82″	8°17′55.54″	Cropland	8°55′26.38″	8°12′33.96″	Cropland	8°34′51.01″	7°30′22.33″	Cropland
12	8°18′30.65″	8°26′59.23″	Cropland	8°55′43.02″	8°12′43.41″	Cropland	8°35′10.08″	7°32′0.56″	Cropland
13	8°19′25.39″	8°24′50.49″	Cropland	8°56′4.56″	8°12′46.07″	Cropland	8°34′17.00″	7°31′46.00″	Bare surface
14	8°16′23.62″	8°27′32.92″	Cropland	8°56′14.83″	8°13′2.84″	Cropland	8°31′28.72″	7°32′15.67″	Bare surface
15	8°15′31.62″	8°23′58.94″	Cropland	8°55′47.49″	8°14′1.92″	Cropland	8°33′8.23″	7°28′42.60″	Bare surface
16	8°18′22.39″	8°22′3.16″	Cropland	8°54′37.30″	8°14′9.25″	Cropland	8°36′18.46″	7°30′32.64″	Bare surface
17	8°17′56.21″	8°23′2.23″	Cropland	8°55′26.04″	8°16′46.50″	Forestland	8°35′43.89″	7°30′2.60″	Built up land
18	8°17′34.37″	8°14′4.32″	Forestland	8°55′3.59″	8°17′37.58″	Forestland	8°35′38.32″	7°30′7.92″	Built up land
19	8°17′22.40″	8°13′26.98″	Forestland	8°56′5.42″	8°17′47.13″	Forestland	8°33′4.70″	7°28′2.38″	Grassland
20	8°18′46.42″	8°15′50.56″	Forestland	8°57′19.86″	8°15′55.15″	Forestland	8°33′49.99″	7°29′14.88″	Grassland
21	8° 9′9.83″	8°24′49.48″	Grassland	8°55′44.23″	8°14′33.10″	Grassland	8°35′31.52″	7°28′48.08″	Grassland
22	8°10′34.66″	8°18′48.14″	Grassland	8°54′34.87″	8°12′45.66″	Grassland	8°35′35.79″	7°27′45.98″	Grassland
23	8°23′59.90″	8°26′32.29″	Grassland	8°54′43.90″	8°12′56.82″	Grassland	8°36′37.82″	7°29′39.31″	Grassland
24	8° 5′25.02″	8°14′46.15″	Shrubland	8°53′59.33″	8°13′33.26″	Shrubland	8°36′38.39″	7°31′42.58″	Shrubland
25	7°59′59.80″	8°16′25.92″	Shrubland	8°53′40.70	8°13′25.96″	Shrubland	8°32′39.67″	7°31′32.47″	Shrubland
26	8° 3′41.67″	8°21′41.01″	Shrubland	8°54′12.84″	8°13′21.26″	Shrubland	8°32′56.91″	7°29′34.12″	Shrubland
27	8°23′20.78″	8°27′22.05″	Shrubland	8°54′21.70″	8°14′41.90″	Shrubland	8°33′42.10″	7°26′24.21″	Shrubland
28	8°18′35.77″	8°20′11.10″	Wetland	8°56′14.16″	8°15′11.56″	Wetland	8°35′10.86″	7°28′17.10″	Forest land
29	8°18′11.85″	8°18′34.94″	Wetland	8°57′7.81″	8°14′21.46″	Wetland	8°34′39.47″	7°30′19.27″	Forest land
30	8°19′40.24″	8°17′7.41″	Wetland	8°57′22.69″	8°14′51.66″	Wetland	8°36′58.98″	7°28′5.11″	Forest land

Sources: Authors field exercise on ground truthing coordinate points from the gazetted forest reserve sites for the study area.

Appendix B. Identified land use activities within the gazetted forest reserves in the study locations

From top right: (ai, ii) Evidence of Forest land clearing for agriculture activities and settlement within Odu Forest reserve; (bi, bii) Farming cultivation and Agricultural activities in Doma forest; (ci, cii) Agricultural land use and farming in Risha forest reserve; di, dii) Human settlement in Doma and road construction in Risha forest reserves. Sources: Fieldwork July 2023.

Data availability

Data will be made available on request.

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