Land-use/land-cover change and forest fragmentation in the Jigme Dorji National Park, Bhutan

Kiran Sharma, Scott M. Robeson, Pankaj Thapa and Anup Saikia

ABSTRACT
Monitoring land-cover change and understanding the dynamics of forest cover is critically important for the management of forest ecosystems. This study assesses land cover change (1990–2015) in the Jigme Dorji National Park, one of the largest national parks in Bhutan, using Landsat imageries. Overall changes in forest cover, as well as the fragmentation of dense forests within the park, were analyzed using landscape metrics. The results show that total forest area, dense forest area, and moderately dense forest area decreased while open forest area and shrub area increased. During the 25-year study period, the annual deforestation rate was 821 ha year⁻¹, equivalent to 0.63% year⁻¹. The total number of patches of all type increased by 176%, from 250,353 to 691,811, while the mean patch size of forest patches decreased from 1.7 ha to 0.6 ha. The number of smaller patches (0–100 ha size class) in dense forest increased rapidly, indicating that a more fragmented landscape accrued over time, a trend that does not bode well for the maintenance of biodiversity in the national park.

Introduction
Mountain ecosystems and forests are experiencing extensive land use changes, due to natural and anthropogenic processes (Klein, 2001; Liu, Daily, Ehrlich, & Luck, 2003). These changes have not only led to the conversion of land cover but also to increased fragmentation of the landscape, with serious environmental implications (Hansen, Dale, Flather, Iverson, & Currie, 2001; Lung & Schaab, 2010; Tuff, Tuff, & Davies, 2016). Land-use/land-cover change (LULCC) is one of the main driving forces of global environmental change and, therefore, is central to issues related to sustainable development (Lambin, Geist, & Lepers, 2003). The impacts of LULCC are profound and range from biodiversity to the global carbon and hydrologic cycles (Skole et al., 2004). In recent decades, most LULCC is attributable to human activities and development (Hurni et al., 1996), although anthropogenic factors also interact with natural environmental change processes (Verburg & Chen, 2000).
Changes in forest cover are a matter of global concern due to the ability of forests to sequester carbon and their significance in sustaining global and regional biodiversity. However, with global rates of forest loss currently reported to be 0.6% per year (Hansen, Stehman, & Potapov, 2010), there is a premium on the conservation of the remaining biodiversity in areas where forests remain. Although moderate levels of disturbance sometimes can increase biodiversity locally (Hughes, 2010; McKinney, 2002), habitat loss and fragmentation caused by deforestation are the single largest threat to biodiversity (Sala et al., 2000). Conversion of forested areas to cropland or other land use types, as well as forest degradation as a result of resources extraction, are leading to widespread forest fragmentation (Crooks, Burdett, Theobald, Rondinini, & Boitani, 2011). Forest conversion and degradation has been identified as the most important factor contributing to the decline and loss of species diversity worldwide (Noss & Cooperrider, 1994).

Apart from the impact on biodiversity, fragmentation can also negatively impact ecosystem processes and services (Burkhard, Kroll, Muller, & Windhorst, 2009; Laurance, 2007). Quantifying changes in the landscape is imperative for understanding the spatial and structural variability in land use and their associated ecological effects (Turner, 2005). Remote-sensing-based monitoring techniques are particularly effective for forest management and to formulate land-use policies (Nellis, 2005; Tomppo et al., 2008; Wu, De Pauw, & Zucca, 2013). The analysis of fragmentation using landscape metrics has been a useful approach to assessing land-use change in a wide range of environments (Batistella, Robeson, & Moran, 2003; Cakir, Sivrikaya, & Keles, 2008; Hayes & Robeson, 2009, 2011; Lele, Joshi, & Agrawal, 2001; Li, Lu, Cheng, & Xiao, 2001). In particular, a number of recent studies have quantified landscape patterns within protected areas (Garbarino, Sibona, Lingua, & Motta, 2014; Klauro, Gregorova, Stankov, Markovic, & Lemenkova, 2013; Saikia, Hazarika, & Sahariah, 2013; Terzioğlu et al., 2010; Tomaselli, Tenerelli, & Sciandrello, 2012).

Nestled between India, Nepal, and China, Bhutan has substantial forest resources and its constitution explicitly states, “a minimum of sixty percent of Bhutan’s total land shall be maintained under forest cover for all time” (Anonymous, 2008).

Studies of forest fragmentation in Bhutan’s protected areas, however, do not exist, although a few recent analyses of land-use/land-cover (Bruggeman, Meyfroidt, & Lambin, 2016; Gilani et al., 2015) as also an earlier study using Landsat 2 data (Sargent, Sargent, & Parsell, 1985) are available. Over the period 1990–2010, forest area increased in Bhutan’s protected areas and biological corridors as well as in areas outside protected areas and biological corridors. In the latter instance, non-forest areas were converted to forest areas, such a regeneration being brought about through planting of trees (Gilani et al., 2015). Forest cover in Bhutan remained over 60% during 1990–2011 (Bruggeman et al., 2016).

This study analyses the landscape structure of the Jigme Dorji National Park (JDNP), the second largest protected area of Bhutan. JDNP is part of the Himalayan forest ecosystem and possesses rich biodiversity, but there has been no assessment of its land-cover change or degree of fragmentation. Particular focus here is on dense forest cover in JDNP, as this category is of key importance in terms of canopy cover, tree density, and providing habitats for flora and fauna. Here, dense forest cover is defined as forest areas with crown density greater than 70%. As a result, the objectives of this study are (a) to derive land-cover change in the study area during 1990–2015 and (b) to assess the change in landscape structure of the dense-forest land-cover category at class and patch level using landscape metrics.
Study area

Bhutan is a small country situated in the Eastern Himalaya and is a part of the Himalayan biodiversity hotspot (Banerjee & Bandopadhyay, 2016; Chandrappa, Gupta, & Kulshrestha, 2011; Mittermeier, Turner, Larsen, Brooks, & Gascon, 2011; Singh, 2016). With 70% of its area under forest cover (Ministry of Agriculture & Forests [MoAF], 2011), Bhutan has recognized the importance of the landscape approach to biodiversity conservation. For instance, policies in Bhutan have provisioned space for linking protected areas by establishing biological corridors (Wangchuk, 2007). Transboundary programs also have been implemented with some degree of success in the Himalayas and elsewhere (Chettri & Sharma, 2006; Chettri, Sharma, Shakya, & Bajracharya, 2007; Gurung, 2004; Gurung et al., 2006; Sherpa, Wangchuk, & Wikramanayake, 2004). The combination of the protected areas and biological corridors forms a Bhutan Biological Conservation Complex (B2C2), or a landscape conservation unit, that encompasses all of the ecosystem types that exist in Bhutan (Sherpa et al., 2004).

JDNP is the second largest protected area in Bhutan and is on the Tentative List for UNESCO World Heritage Site designation. JDNP encompasses an area of 4316 km² in the northwestern corner of Bhutan and falls within the biologically rich Eastern Himalayan alpine ecosystem (Figure 1). It represents one of the last remaining tracts of the upper Himalayan mountain ecosystem. The park is endowed with temperate broadleaved to alpine forest types, and includes more than 100 species of mammals, 317 species of birds, and many species of insects, reptiles, amphibians and butterflies (Tharchen, 2013). Its habitat zones range from riverine areas to alpine meadows spanning elevations from 1400 to 7000 m (Riley & Riley, 2005). A survey of fauna by Thinley et al. (2015) using camera traps revealed 12 predators, of which two species were listed as endangered, three as vulnerable, and two as threatened on the IUCN Red List. Five species, namely clouded leopard (*Neofelis nebulosa* Griffith), tiger, leopard, leopard cat (*Prionailurus bengalensis* Kerr), and Himalayan black bear (*Ursus thibetanus* [Baron] Cuvier) were listed in Schedule I of Forest and Nature Conservation Act of Bhutan 1995, which accords them the highest protection. Though most predators occurred in all four major habitat types, the highest diversity of wild predators

![Figure 1. The location of Jigme Dorji National Park in Bhutan (inset) and its land use/land cover in 1990. Source: Image date: 7 November 1990.](image-url)
was found in the mixed conifer forest. Such studies underscore the JDNP as an important conservation area for wild predators, most notably cat species. Two more species of wild predators, namely the snow leopard (*Panthera uncia* Schreber) and manul or Pallas’s cat (*Otocolobus manul* Pallas) have been documented at elevations above 4200 m in the JDNP (Thinley, 2013; Thinley et al., 2015). JDNP also is one of the larger tiger habitats among protected areas in Bhutan (Johnsingh, Panda, & Madhusudan, 2010).

Such a rich biodiversity notwithstanding, increasing population in the region is placing greater pressure on the park, including demands for already scarce fuel wood and pasture (Sherpa & Norbu, 1999). In some areas of JDNP, grazing is a major concern, though in other national parks of Bhutan (such as Jigme Singye Wangchuck and Royal Manas) it does not pose any immediate threats to ecosystem stability (Ministry of Agriculture [MoA], 2002). The park also suffers from “extensive harvesting of medicinal plants for the Chinese market and from other forms of poaching – euphemistically called ‘traditional harvesting of nonforest produce’” (Rijksen, 2002).

**Data and methods**

Landsat 5 TM and Landsat 8 OLI satellite imagery were selected for LULC classification of the study area. Selection of the dates for this imagery was based on minimal cloud cover, time of year, and the time frame in which land-cover change could be monitored since the designation of the protected area (no suitable Landsat 7 ETM + data are available during the period of this study). The images were acquired at the same time of the year to avoid problems of seasonal variation (Table 1) and to access images with minimal cloud cover content. Using ERDAS Imagine 9.2 software, a supervised classification using the maximum likelihood algorithm was adopted. The forest areas were classified into dense forest, moderately dense forest, open forest, and shrub (Table 2) following the Forest Survey of India (FSI, 2013) forest classification scheme. Google Earth and data collected using GPS and a spherical densiometer (to assess canopy cover) served as ground control points (GCPs) and training sites. This study used six GCPs. The accuracy of the images was checked with the overall accuracy of 88% in 1990, 76.2% in 2010 and 87.7 in 2015, respectively, and Kappa accuracy of 84, 81 and 78% for 1990, 2010, and 2015, respectively.

While there are myriad metrics for assessing landscape pattern and quantifying their spatial heterogeneity (Lele et al., 2008; Yuan et al., 2015), we use the indices that are most applicable for forest-fragmentation studies (Batistella et al., 2003; Cakir et al., 2008; Galicia,

### Table 1. Satellite data used in LULC classification.

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Number of bands</th>
<th>Resolution (m)</th>
<th>Path/row</th>
<th>Observation date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Landsat 5</td>
<td>7</td>
<td>30</td>
<td>138/4</td>
<td>7 November 1990</td>
</tr>
<tr>
<td>Landsat 5</td>
<td>7</td>
<td>30</td>
<td>138/4</td>
<td>6 February 2010</td>
</tr>
<tr>
<td>Landsat 8</td>
<td>12</td>
<td>30</td>
<td>138/4</td>
<td>25 November 2015</td>
</tr>
</tbody>
</table>

### Table 2. Description of forest categories.

<table>
<thead>
<tr>
<th>Forest</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dense forest</td>
<td>Forest areas with crown density greater than 70%</td>
</tr>
<tr>
<td>Moderately dense forest</td>
<td>Forest areas with crown density greater than 40–70%</td>
</tr>
<tr>
<td>Open forest</td>
<td>Forest areas with crown density greater than 10–40%</td>
</tr>
<tr>
<td>Shrub</td>
<td>Vegetation cover less than 10%</td>
</tr>
</tbody>
</table>
Zarco-Arista, Mendoza-Robles, Palacio-Prieto, & Garcia-Romero, 2008; Hargis, Bissonette, & David, 1998; Keles, Sivrikaya, Cakir, & Kose, 2008; O’Neill et al., 1988; Sivrikaya, Kadiogullari, Keles, Baskent, & Terzioglu, 2007). Using the spatial metrics program Fragstats (McGarigal, Cushman, & Ene, 2012), we analyze the following: (a) number of patches (NP), (b) percentage of landscape in a particular class or patch type (PLAND), (c) the mean patch size in a particular class or patch type (MPS), (d) percentage of the landscape composed of the largest patch (LPI), and (e) the sum of the lengths of all edge segments on a per unit area basis (or edge density, ED).

Annual deforestation rates were calculated using the compound growth rate formula (Puyravaud, 2003; Vuohelainen, Coad, Marthews, Malhi, & Killeen, 2012):

\[
P = \left[ \frac{100}{(t_2 - t_1)} \right] \ln \left( \frac{A_2}{A_1} \right)
\]

where, \( P \) is percentage of forest loss per year, and \( A_1 \) and \( A_2 \) are the amount of forest cover at time \( t_1 \) and \( t_2 \), respectively. These quantitative landscape indices not only represent the ecological functions of individual patches (Forman & Godron, 1986; Gardner, O’Neill, & Turner, 1993; Imbernon & Branthome, 2001; Patton, 1975), but also reflect spatial structure within the entire landscape (Fuller, 2001; Gustafson & Parker, 1992; O’Neill, Riitters, Wickham, & Jones, 1999; Viedma & Melia, 1999). In addition, LandScan gridded population data (http://web.ornl.gov/sci/landscan/index.shtml) have been used to show population distribution within the JDNP.

Results and discussion

Landscape-level land-cover change

Analyzing the overall land cover dynamics between 1990 and 2015 shows that dense forest is the predominant land-cover class in JDNP, but that these forests are under increasing pressure primarily from anthropogenic influences including grazing of domestic cattle and yak herds (Thinley & Tharchen, 2014). This is most clearly evidenced by a declining percentage of the dense forest category from 32.8% in 1990 to 27.9% in 2015 (Table 3). The average rate of deforestation for dense forest was 821 ha year\(^{-1}\), amounting to a rate of loss of −0.63% year\(^{-1}\). Open forest, shrub, and agriculture classes increased, with open forests

Table 3. Land-cover change of the Jigme Dorji National Park 1990–2015.

<table>
<thead>
<tr>
<th>LULC categories</th>
<th>1990 (ha)</th>
<th>2010 (ha)</th>
<th>2015 (ha)</th>
<th>% change 1990–2010</th>
<th>% change 2010–2015</th>
<th>% change 1990–2015</th>
<th>Rate of gain/loss (ha year(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow</td>
<td>76,984.70</td>
<td>61,764.10</td>
<td>63,637.50</td>
<td>−19.77</td>
<td>3.03</td>
<td>−17.30</td>
<td>−533.80</td>
</tr>
<tr>
<td>Water</td>
<td>14,610.60</td>
<td>3362.60</td>
<td>1849.00</td>
<td>−76.98</td>
<td>−45.01</td>
<td>−87.30</td>
<td>−510.40</td>
</tr>
<tr>
<td>Dense forest</td>
<td>140,987.10</td>
<td>121,558.00</td>
<td>120,439.80</td>
<td>−13.80</td>
<td>−0.92</td>
<td>−14.50</td>
<td>−821.80</td>
</tr>
<tr>
<td>Moderately dense forest</td>
<td>46,206.00</td>
<td>34,157.10</td>
<td>37,811.10</td>
<td>−26.07</td>
<td>10.70</td>
<td>−18.10</td>
<td>−335.80</td>
</tr>
<tr>
<td>Open forest</td>
<td>47,439.50</td>
<td>78,804.60</td>
<td>81,619.40</td>
<td>66.11</td>
<td>3.60</td>
<td>72.10</td>
<td>+1367.10</td>
</tr>
<tr>
<td>Shrub</td>
<td>25,923.20</td>
<td>49,433.80</td>
<td>54,167.80</td>
<td>90.70</td>
<td>9.60</td>
<td>108.90</td>
<td>+1129.70</td>
</tr>
<tr>
<td>Agriculture</td>
<td>108.90</td>
<td>1071.90</td>
<td>1117.50</td>
<td>884.80</td>
<td>4.30</td>
<td>926.80</td>
<td>+40.30</td>
</tr>
<tr>
<td>Barren land</td>
<td>77,897.00</td>
<td>79,710.60</td>
<td>69,144.60</td>
<td>2.40</td>
<td>−13.20</td>
<td>−11.30</td>
<td>−350.09</td>
</tr>
<tr>
<td>Built-up</td>
<td>40.80</td>
<td>319.10</td>
<td>394.70</td>
<td>782.60</td>
<td>23.70</td>
<td>868.20</td>
<td>+14.15</td>
</tr>
<tr>
<td>Total</td>
<td>430,197.40</td>
<td>430,181.51</td>
<td>430,181.50</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
and shrub registering large gains in area (Table 3). Thus, over a mere quarter century, a landscape dominated by dense forest evolved into a landscape that contained much more open forest and agricultural land cover. An increase of the importance of the built-up class also is noted, ostensibly due to the pressures exerted by increases in population. Similar trends of deforestation have occurred in other tropical and temperate realms of the world.

For comparison, the Nameri NP in the neighboring state of Assam, India saw dense forests decrease at an average annual rate 0.56%, while the overall rate of forest loss was 4.84% annually during 1973–2007 (Saikia et al., 2013). Likewise, in Nepal's Kailash Sacred Landscape, forest area decreased by about 9% during 1990–2009 (Uddin et al., 2015). Compared to other forest-dominated landscapes, Bhutan is well placed with several factors weighing in its favor, as it “possesses the lowest population and the highest forest cover of any nation in Eurasia, (and) the highest percentage of its natural territory conserved” (Rijksen, 2002). But, the fact that its dense forest cover has declined markedly during 1990–2015 requires continued attention and monitoring (Figure 2).

**Landscape metrics and fragmentation**

The most important indicators of landscape fragmentation are the number of patches and the change in the number of smaller patches, as measured by patch density (Echeverria et al., 2006; Kammerbauer & Ardon, 1999; Southworth, Munroe, & Nagendra, 2004). Changes in NP, PLAND, MPS, and ED during the study period of 1990–2015 point towards an increasing fragmentation of forest areas (Table 4). PLAND for dense and moderately dense forests declined markedly during 1990–2010.
### Table 4. Landscape metrics of the JDNP.

<table>
<thead>
<tr>
<th>Land-use/land-cover categories (Year)</th>
<th>PLAND(^a) (%)</th>
<th>NP (number of patches)</th>
<th>MPS (mean patch size) ha</th>
<th>ED (edge density) (m ha(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow</td>
<td>9.56</td>
<td>7.67</td>
<td>8.14</td>
<td>8617</td>
</tr>
<tr>
<td>Water</td>
<td>1.82</td>
<td>0.41</td>
<td>0.23</td>
<td>14,090</td>
</tr>
<tr>
<td>Dense forest</td>
<td>17.52</td>
<td>15.09</td>
<td>15.21</td>
<td>13,046</td>
</tr>
<tr>
<td>Moderately dense forest</td>
<td>5.74</td>
<td>4.25</td>
<td>4.78</td>
<td>58,261</td>
</tr>
<tr>
<td>Open forest</td>
<td>5.9</td>
<td>9.78</td>
<td>10.31</td>
<td>39,699</td>
</tr>
<tr>
<td>Shrub</td>
<td>3.22</td>
<td>6.13</td>
<td>6.84</td>
<td>61,165</td>
</tr>
<tr>
<td>Agriculture</td>
<td>0.013</td>
<td>0.13</td>
<td>0.14</td>
<td>794</td>
</tr>
<tr>
<td>Barren land</td>
<td>9.67</td>
<td>9.9</td>
<td>8.73</td>
<td>54,369</td>
</tr>
<tr>
<td>Built-up</td>
<td>0.0051</td>
<td>0.044</td>
<td>0.039</td>
<td>308</td>
</tr>
</tbody>
</table>

\(^a\)Percentage of landscape in a particular class or patch type.
However, both categories gained marginally during the 2010–2015 period, most likely showing the results of a policy of forest plantation undertaken across Bhutan. PLAND for the open forest category and shrub, however, registered a consistent decline over the entire 1990–2015 span. Agriculture, barren land, and built-up areas showed a nominally declining trend for PLAND.

Of the various land-cover classes, the dense forest category showed very rapid fragmentation patterns characterized by a fourfold increase in the number of patches, increasing edge density, and decreasing mean patch size. In contrast, cultivated land and built-up area showed increased MPS, as well as increased NP and ED (as PLAND for these categories also increased).

Increases in edge density are a primary outcome of habitat fragmentation and involves an increase in habitat along edges but a decrease in habitat in large, homogeneous patches. This measure is entirely dependent on the ratio of patch area to patch edge, so landscapes with small patches or irregular shapes will have higher edge density values than landscapes with large patches or simple shapes (Hargis et al., 1998). Edge density in the JDNP increased by 11% in dense forest, 56% in moderately dense forest, and 72% in open forest during 1990–2015. Differences in biotic and abiotic factors accrue within adjoining patches and over time increased edge habitats and their effects as well as greater loss of connectivity (Kabba & Li, 2011) come into play. Edge effects are dominant drivers of change in many fragmented landscapes and can cause serious impacts on ecosystem functioning and undermine habitat quality (Dantas de Paula, Groeneveld, & Huth, 2016; Haddad et al., 2015; Laurance et al., 2007).

The NP reveals interesting tendencies among the dense, moderately dense, and open forests and shrub categories. The NP of dense forest more than tripled while the open forest category registered a fourfold increase. In contrast, NP for moderately dense forest and shrub doubled (or more) during 1990–2015. Such a trend was consistent during both 1990–2010 and 2010–2015 for dense forest. However, the rate of growth or fragmentation slowed during 2010–2015 for the moderately dense and open forests and the shrub categories. Thus fragmentation strengthened in JDNP during the period, giving rise to a more isolated and diverse assemblage of landscape patches and ecological processes.

Results for Largest Patch Index (LPI) show that dense forest had the largest LPI among the LULC classes, but the rate of change in dense forest for LPI decreased 17% during the 1990–2015 period (Table 5). On the other hand, LPI for other land use class including agriculture and built-up land increased marginally (Figure 3).

Table 5. Changes over time in LPI (percent of the landscape occupied by the largest patch).

<table>
<thead>
<tr>
<th>LU category</th>
<th>1990</th>
<th>2010</th>
<th>2015</th>
<th>Rate of change (%) 1990–2015</th>
</tr>
</thead>
<tbody>
<tr>
<td>Snow</td>
<td>3.7</td>
<td>1.81</td>
<td>2.6551</td>
<td>−28.24</td>
</tr>
<tr>
<td>Water</td>
<td>0.032</td>
<td>0.01</td>
<td>0.0027</td>
<td>−91.56</td>
</tr>
<tr>
<td>Dense forest</td>
<td>14.14</td>
<td>11.4</td>
<td>11.6959</td>
<td>−17.28</td>
</tr>
<tr>
<td>Mod. dense forest</td>
<td>0.07</td>
<td>0.06</td>
<td>0.0223</td>
<td>−68.14</td>
</tr>
<tr>
<td>Open forest</td>
<td>0.14</td>
<td>0.69</td>
<td>0.1304</td>
<td>−6.86</td>
</tr>
<tr>
<td>Shrub</td>
<td>0.0096</td>
<td>0.06</td>
<td>0.0421</td>
<td>338.54</td>
</tr>
<tr>
<td>Agriculture</td>
<td>0.0006</td>
<td>0.0004</td>
<td>0.0007</td>
<td>16.66</td>
</tr>
<tr>
<td>Barren land</td>
<td>0.3882</td>
<td>1.14</td>
<td>0.6548</td>
<td>68.67</td>
</tr>
<tr>
<td>Built-up</td>
<td>0.0002</td>
<td>0.0002</td>
<td>0.0002</td>
<td>0</td>
</tr>
</tbody>
</table>

*Moderately dense forest.*
While human activities generally are the proximate cause of the declines in patch size and associated impacts on wildlife (Bender, Contreras, & Fahrig, 1998), careful planning can help to achieve a more desirable distribution of patches (Baskent & Jordan, 2002). Patchiness in forested area is of special importance because it serves as an important indicator of natural habitat fragmentation (Kammerbauer & Ardon, 1999). Generally, an increase in the number of smaller patches is considered one of the basic indicators of forest fragmentation (Sivríkaya et al., 2007) and when NP increases along with a decrease in MPS it indicates that the landscape pattern is fragmented (Hulshoff, 1995). Changes in patchiness of dense forest are of primary concern, as they are a key indicator of forest fragmentation and prime habitat. For dense forest patches, the NP in the <1 ha size category increased more than four times while MPS for dense forest declined steadily over 1990–2015 (Table 6). Additionally, the area of these smallest patches increased sharply from 2472 ha in 1990 to 7594 ha in 2015. A similar trend was evident in the behavior of patches in the 1–4.9 ha size category, although the fragmentation was not as pronounced.

The NP of the 5–19 ha size declined from 348 to 305 while its MPS grew from 9.21 to 10.34 over 1990–2015, indicating a marginal degree of aggregation. A similar trend was evident in the 100–999 ha category, where NP declined from 16 to 15 and MPS as well as area made marginal gains. Likewise, in the 1000–4999 category, NP and MPS reduced with an appreciable increase in area. However, the gains in these categories were ostensibly at the cost of the largest (5000+ ha) patch and nullified any aggregation tendencies overall. Thus

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**Figure 3.** Land use/land cover of the Jigme Dorji National Park, 2015. Source: Image date: 25 November 2015.

**Patch level metrics of dense forests**
Table 6. Patch metrics of the dense forest land-use category.

<table>
<thead>
<tr>
<th>Patch size</th>
<th>1990</th>
<th></th>
<th></th>
<th>2010</th>
<th></th>
<th></th>
<th>2015</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>NP\textsuperscript{a}</td>
<td>Area (ha)</td>
<td>MPS\textsuperscript{b} (ha)</td>
<td>NP</td>
<td>Area (ha)</td>
<td>MPS (ha)</td>
<td>NP</td>
<td>Area (ha)</td>
</tr>
<tr>
<td>&lt;1</td>
<td>11,184</td>
<td>2472.76</td>
<td>0.22</td>
<td>38,286</td>
<td>7496.9</td>
<td>0.2</td>
<td>45,280</td>
<td>7594</td>
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<td>1–4.9</td>
<td>1387</td>
<td>2991.29</td>
<td>2.15</td>
<td>1912</td>
<td>3835.35</td>
<td>2.0</td>
<td>1841</td>
<td>3849</td>
</tr>
<tr>
<td>5.0–19</td>
<td>348</td>
<td>3205.3</td>
<td>9.21</td>
<td>219</td>
<td>2584.8</td>
<td>11.8</td>
<td>305</td>
<td>3154</td>
</tr>
<tr>
<td>20–99</td>
<td>104</td>
<td>4355.9</td>
<td>41.8</td>
<td>73</td>
<td>2857.68</td>
<td>39.14</td>
<td>110</td>
<td>4461</td>
</tr>
<tr>
<td>100–999</td>
<td>16</td>
<td>4154.9</td>
<td>259.6</td>
<td>20</td>
<td>5156.91</td>
<td>257.8</td>
<td>15</td>
<td>4769</td>
</tr>
<tr>
<td>1000–4999</td>
<td>6</td>
<td>9949.4</td>
<td>1658.2</td>
<td>5</td>
<td>7755.93</td>
<td>1551.2</td>
<td>4</td>
<td>5034</td>
</tr>
<tr>
<td>5000+</td>
<td>1</td>
<td>113,857.4</td>
<td>113,857.4</td>
<td>1</td>
<td>91,870.11</td>
<td>91,870.1</td>
<td>1</td>
<td>91,578</td>
</tr>
<tr>
<td>Total</td>
<td>13,046</td>
<td>140,987.1</td>
<td>10.8</td>
<td>40,516</td>
<td>121,557.7</td>
<td>3.0</td>
<td>47,556</td>
<td>120,439</td>
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</tbody>
</table>

\textsuperscript{a}NP is number of patches.

\textsuperscript{b}MPS is mean patch size.
nominal gains made in area and MPS in the intermediate size categories were more than outweighed by increases in NP in the smallest size category and declines in area as well as MPS of the largest patch size category.

These changes towards a splintering of dense forests are perhaps more evident when the patch – size results are analyzed as proportions of the dense forest class (Table 7). The share of the <1 ha patch size increased from 85.7 to 95.2% while its areal share rose from 1.7 to 6.3% during 1990–2015. In 1990, 86% of the patches were of <1 and 1–4.9 ha size. By 2015, this proportion of NP rose to 99%. On the other hand, the larger size patches of 1000–4999 and 5000+ ha accounted for 87.8% of the dense forest landscape in 1990. This declined to 80.2% by 2015. Thus, NP of the smallest patch increased considerably while the proportionate area of the largest patches declined markedly resulting in a significant patch level fragmentation of the dense forest landscape.

LandScan gridded population data are widely used because of LandScan’s advantages of global coverage and high spatial resolution (30 × 30 arcsec or approximately 1 km²; Bhaduri, Bright, Coleman, & Urban, 2007; Christenson, Elliott, Banerjee, Hamrick, & Bartram, 2014; Galway et al., 2012; Rain, Long, & Ratcliffe, 2007). This data-set shows the distribution of population in the JDNP during 2014 having a maximum of 158 persons per grid cell in parts of the southern and central areas of the park (Figure 4). A recent study states that 1555 households amounting to some 6000 persons live within the JDNP (Thinley & Tharchen, 2014). The upland dwellers (living in areas above 4000 m) are yak herders who cultivate wheat and vegetables during a brief summer season compared to lowland dwellers (settled in areas below 4000 m) who are agriculturalists and cattle herders (Thinley & Tharchen, 2014). With a typical size of over 100 yaks per herder, use of firewood as a fuel and for space heating, and clearance and burning of bushes and trees to maintain grazing pastures (Thinley & Tharchen, 2014) the dependence of this population on the park’s natural resources is considerable. Annual per capita consumption of fuelwood in Bhutan is the highest in the world at 1.2 tons per capita, with 70% of the total energy requirement of its population being met from fuelwood consumption (Ministry of Agriculture, 2009). Fuelwood harvesting in Bhutan is regulated by the government, and households are permitted to use 16 m³ of fuelwood annually if they lack electricity, although verification systems are not in place (Wangchuk, Siebert, & Belsky, 2014). The human population living within Bhutan’s protected areas is largely tolerant of the wildlife, with retaliatory killings of predators being far less than in other parts of the world (Wangchuk & Tharchen, 2016). Retaliatory killings of wildlife in the JDNP, however, are not completely unknown (Thinley & Tharchen, 2014).

Table 7. Proportion of dense forest by patch size.

<table>
<thead>
<tr>
<th>Patch size (ha)</th>
<th>1990 NP</th>
<th>1990 Area</th>
<th>2010 NP</th>
<th>2010 Area</th>
<th>2015 NP</th>
<th>2015 Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1</td>
<td>85.73</td>
<td>1.75</td>
<td>94.5</td>
<td>6.167</td>
<td>95.22</td>
<td>6.3</td>
</tr>
<tr>
<td>1–4.9</td>
<td>10.63</td>
<td>2.12</td>
<td>4.72</td>
<td>3.155</td>
<td>3.87</td>
<td>3.19</td>
</tr>
<tr>
<td>5.0–19</td>
<td>2.67</td>
<td>2.27</td>
<td>0.54</td>
<td>2.126</td>
<td>0.64</td>
<td>2.62</td>
</tr>
<tr>
<td>20–99</td>
<td>0.79</td>
<td>3.09</td>
<td>0.18</td>
<td>2.350</td>
<td>0.23</td>
<td>3.7</td>
</tr>
<tr>
<td>100–999</td>
<td>0.13</td>
<td>2.94</td>
<td>0.049</td>
<td>4.242</td>
<td>0.032</td>
<td>3.96</td>
</tr>
<tr>
<td>1000–4999</td>
<td>0.046</td>
<td>7.057</td>
<td>0.0123</td>
<td>6.38</td>
<td>0.0084</td>
<td>4.18</td>
</tr>
<tr>
<td>5000+</td>
<td>0.0077</td>
<td>80.76</td>
<td>0.0025</td>
<td>75.57</td>
<td>0.0021</td>
<td>76.04</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
<td>100</td>
</tr>
</tbody>
</table>

*NP is number of patches.
Poaching of wildlife and high-value medicinal plants by poachers from across the international border to the north of the park appears to be more of a problem than by settlers within (Thinley & Tharchen, 2014).

Conclusions

This study has analyzed land-cover dynamics of JDNP between 1990 and 2015 using satellite-based estimates. Results showed that forest cover decreased throughout the study period, with an increase in open forest and other land use classes. Importantly, these land use/cover changes have resulted in the reduction of dense and moderately dense forest, as well as increased fragmentation (increases in patch number and decreases in patch size). Due to increasing population density of both humans and livestock, there is ostensibly a relatively higher pressure on the resources of this protected area. The current scenario could be an outcome of the impacts of grazing of feral livestock and firewood collection, as noted in other work (Rijksen, 2002).

Continued monitoring of the spatial and temporal composition and configuration of this forest ecosystem is increasingly important for forest management and maintaining biodiversity. An irreplaceable wealth of biodiversity is concentrated in a very small portion of our planet and an extraordinary concentration of biodiversity within hotspots exists (Mittermeier et al., 2011), with the JDNP typifying this situation considering that Bhutan lies entirely within the Himalayan biodiversity hotspot. Bhutan has had an excellent...
conservation conflict and is a world leader in protected area planning and management (Rajaratnam, Vernes, & Sangay, 2016). If Bhutan's ecosystems and mountain biodiversity are to be protected, this trend of fragmentation of the JDNP must be prioritized and afforded due attention by authorities and its stakeholders.

Acknowledgements

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ORCID

Kiran Sharma http://orcid.org/0000-0002-7546-0736
Pankaj Thapa http://orcid.org/0000-0002-3890-6698
Anup Saikia http://orcid.org/0000-0003-0448-4869

References


