



Integrating local ecological knowledge and remote sensing reveals patterns and drivers of forest cover change: North Korea as a case study

Joshua Elves-Powell^{1,2,3} · Jai Dolan² · Sarah M. Durant¹ · Hang Lee^{3,4} · John D. C. Linnell^{5,6} · Samuel T. Turvey¹ · Jan C. Axmacher²

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Abstract

Satellite-based remote sensing approaches provide a cost-efficient means to collect information on the world's forests and to repeatedly survey large, or inaccessible, forest areas. However, it may not always be possible to ground truth-associated findings using direct ecological field surveys conducted by trained forest scientists. Local ecological knowledge (LEK) is an alternative form of data which could be used to complement, interpret and verify information from satellite data. Using a case study on the Democratic People's Republic of Korea (North Korea), we evaluate the potential for integrating remote sensing and LEK data, gathered with non-specialist former residents, to understand patterns and drivers of forest cover change. LEK reports often concurred with, or provided key information to enable interpretation of, satellite data. This revealed that between 1986 and 2021, North Korea experienced high, but uneven, rates of deforestation. There was a pronounced northwards deforestation shift in the mid-1990s, coinciding with a period of extreme hardship and famine (the "Arduous March"), and associated with clearance of trees in more forested northern provinces as an economic and fuel resource, and conversion of forest to agricultural cropland. Loss of forest cover in North Korea has continued and recently accelerated, to a rate of > 200 km² per annum between 2019 and 2021. This increases the vulnerability of North Korean socio-ecological systems to future environmental change and is an obstacle to the recovery of threatened species across the Korean Peninsula. We recommend that LEK- and remote sensing-based approaches are considered within a suite of complementary techniques to analyse forest changes where ecological field surveys cannot be conducted.

Keywords Democratic People's Republic of Korea (DPRK) · Northeast Asia · Normalized Difference Vegetation Index (NDVI) · Deforestation · Cropland expansion · Mixed methods research

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✉ Joshua Elves-Powell
joshua.powell.19@ucl.ac.uk

✉ Jai Dolan
jai.dolan.22@ucl.ac.uk

Sarah M. Durant
sarah.durant@ioz.ac.uk

Hang Lee
hanglee@snu.ac.kr

John D. C. Linnell
john.linnell@nina.no

Samuel T. Turvey
samuel.turvey@ioz.ac.uk

Jan C. Axmacher
j.axmacher@ucl.ac.uk

¹ Institute of Zoology, Zoological Society of London, London, UK

² Department of Geography, University College London, London, UK

³ Tiger and Leopard Conservation Fund in Korea, Seoul, Republic of Korea

⁴ College of Veterinary Medicine, Seoul National University, Seoul, Republic of Korea

⁵ Norwegian Institute for Nature Research, Lillehammer, Norway

⁶ Department of Forestry and Wildlife Management, Inland Norway University of Applied Sciences, Evenstad, Norway

Introduction

Deforestation remains a preeminent global environmental challenge (Pendrill et al. 2022). Forests contribute significantly to global biodiversity and provide habitat for an extremely wide range of species (Millennium Ecosystem Assessment 2005). They also provide a variety of ecosystem services, such as the provision of building and fuel resources, purification of ground and surface water, and regulation of soil erosion, which directly benefit human economies and societies, including some of the world's most vulnerable communities (Hayes 2009; Neary et al. 2009; Engler et al. 2014). Recently, forests have been increasingly valued for their potential to serve as carbon sinks and to reduce or mitigate the impacts of natural disasters (Goldstein et al. 2020). However, global forest cover continues to decline, with an estimated 81.7 million ha lost between 1960 and 2019 (Estoque et al. 2022).

In order to investigate patterns of forest cover change, scientists increasingly rely on satellite-based remote sensing data, which are typically ground truthed using ecological field surveys (Phiri and Morgenroth 2017; Galiatsatos et al. 2020). However, collecting data on-the-ground may be extremely challenging, or even impossible, in certain locations. Geographical remoteness, armed conflict, or access restrictions are just some of the obstacles that may limit the use of field surveys (Shim 2012). In such cases, local ecological knowledge (LEK), a type of data that captures the knowledge of local communities about ecosystems and wildlife (Joa et al. 2018; Aswani et al. 2018), may provide an alternative source of field data. LEK-based approaches have increasingly been incorporated into vegetation studies, including investigations of forest cover change (Sahoo et al. 2013; Brown et al. 2018), land degradation (Eddy et al. 2017), and the distribution of specific plants (Takasaki et al. 2022). However, while some studies have reported that findings based on LEK and remote sensing data were complementary and strongly concordant (for example, Takasaki et al. 2022; Morozova et al. 2023), other studies have recorded discrepancies, including regarding changes in forest cover (Ahammad et al. 2019). There remains a need for further work to identify the circumstances in which LEK can complement, and potentially enrich, satellite imagery analysis.

In this study, we investigated a particularly challenging case study, the Democratic People's Republic of Korea (DPRK, or North Korea). North Korea is a highly mountainous country in north-east Asia, which was historically covered by large tracts of forest and has relatively small areas of lowland suitable for supporting large-scale agriculture (Kim et al. 2021). Deforestation in North Korea is of particular concern because the country's forests provide

important fuel resources for heating and cooking for many of its poorest citizens (Kim et al. 2020); perform essential functions for watershed management in a country with a temperate monsoon climate and prone to both droughts and flooding (Lim and Lee 2018); and provide habitat for a diverse range of native species (Jo et al. 2018). Protected areas cover just 2.4% of North Korea's total land area (McCarthy et al. 2021).

Heavily damaged during the Korean War (A.D. 1950–1953), North Korea's forests were nationalised and forest policy initially focussed on timber production to support post-war recovery (Park and Lee 2014). An important feature of North Korean policy over the intervening 70 years has been the concept of controlled isolation. During this time, the North Korean government has published limited (and potentially highly selective) data on forest cover, while independent researchers have faced severely restricted access (Yeom et al. 2008; Park and Lee 2014). Former North Korean forestry officials have reported that government data records "forest cover" irrespective of how much forest actually exists (Liu and Sheng 2023). Obtaining reliable data on North Korea's forests therefore remains challenging, especially the verification of local patterns of change.

In the absence of field surveys, a number of studies have attempted to investigate forest cover change in North Korea using historical sources (Kang and Choi 2014; Choi et al. 2017; Kang et al. 2019) or remote sensing data (Kim et al. 2010; Park and Lee 2014; Yu and Kim 2015; Jin et al. 2016; Lee and Oh 2018; Piao et al. 2021; Kwon et al. 2021; Lim and Yeo 2022). These studies indicate that land cover in North Korea has undergone substantial changes since the 1940s. It has variously been suggested that North Korean forest cover has declined by 40% since 1985 (McCarthy et al. 2021); that from 1970 to 1999, the country's forest cover decreased from 9.77 to 7.53 million ha (Hayes 2009); and that from 1990 to 2010, forest cover decreased from 8.1 to 6.9 million ha, while denuded forest area tripled to over 1.45 million ha (Liu and Sheng 2023). When taken together, these indicate that over the last four decades, North Korea may have suffered one of the worst deforestation rates of any country (Piao et al. 2021).

Several government afforestation programmes have been introduced (most recently the Total Forest Construction Plan in 2012, which aims to restore 2.2 million ha of forest cover by 2042), but there is little reliable information regarding implementation (Park and Lee 2014). While forestry has previously been the subject of some inter-Korean cooperation (Park and Lee 2014) and North Korean representatives have attended some international conservation meetings (NBSAP 2007), sanctions introduced in response to North Korea's nuclear weapons programme have rendered further cooperation on forest management and conservation extremely difficult. Most studies of forest cover change in North Korea

have therefore been unable to ground truth their findings. However, LEK from North Korean defectors (refugees) could provide an innovative means to do so. While mention of deforestation by North Korean defectors is not uncommon (Song and Habib 2020), few studies have sought to incorporate this valuable source of data into their analysis of forest cover change.

As combatting climate change and biodiversity loss are global issues, it is important that stocktaking of forests is as comprehensive as possible. In this study, we examined the potential for combining remote sensing data and LEK data collected with former residents of North Korea. We investigated the following research questions:

- (i) What was the spatio-temporal change in forest cover in North Korea from 1986 to 2021, at a national and provincial level?
- (ii) Do LEK data provide explanatory information on changes in forest cover observed from satellite imagery?

Our findings reveal new insights into patterns and underlying processes of forest cover change in North Korea, and provide wider implications for the integration of remote sensing and LEK-based approaches in studies of environmental change.

Methods

Local ecological knowledge

Forty-one interviews were conducted in 2021–2022 with North Korean defectors living in the United Kingdom (UK) and the Republic of Korea (ROK, or South Korea). As this involved a vulnerable survey population (Bureau of Democracy, Human Rights and Labor Affairs 2022), participants were recruited using “snowball sampling” (Goodman 1961; Atkinson and Flint 2001). All interviews were conducted anonymously and no personal data were discussed or recorded at any time. All participants were aged 18 years or older, but were not selected or excluded on the basis of any other socio-demographic parameters. All participants were non-specialists (i.e. not trained forest scientists or managers).

The researchers explained the study’s aims (to better understand environmental states in North Korea) and research protocol (Online Resource 1) before arranging and conducting an interview. If an individual provided informed, written consent to participate, an interview was conducted in Korean, either in person or via an encrypted online platform.

Interviews used a series of open-ended questions regarding the environment in North Korea. Changes in forest cover or

composition were not identified by the interviewer as a specific subject of interest, in order to reduce the risk of prompting a particular response (Krosnick et al. 2018). Instead, if a participant reported changes to forest cover during an interview, the researcher asked for information regarding the timing and location of observed changes; the impacts (if any) of the changes observed; and any further details the participant was able to provide. As we did not exclude or select for specific localities within North Korea, participants provided information for North Korea as a whole, or specifically for the provinces of Ryanggang (17 responses), North Hamgyong (20), South Hamgyong (7), South Pyongan (2), North Hwanghae (2) and South Hwanghae (4), which in total comprise approximately 65.6% of North Korea’s land area (Fig. 1). In addition, some general information was provided for North Pyongan (4 responses), Chagang (3) and Kangwon (2). That far more participants reported information about Ryanggang and North Hamgyong is to be expected, as it is believed that up to 76% of all North Korean defectors are from these two provinces (Song and Denney 2019). As a result, our data for these provinces should be considered more complete than for others.

LEK data was recorded as a series of short narrative reports of environmental change in North Korea. Reports of forest cover change were organised by province and date, before being compiled. The provinces where more detailed information was provided in the LEK data formed the focus of our remote sensing analysis.

Remote sensing

We selected two different satellite-based remote sensing methods, based on their known ability to detect patterns of vegetation change and their coverage of North Korea between 1986 and 2021. The first involved vegetation trend analysis, using Landsat 5–derived Normalized Difference Vegetation Index (NDVI) data as a proxy for vegetation cover change (Nath 2014; Huang et al. 2021) from 1986 to 2010. The second used Hansen’s Global Forest Change (HGFC) dataset (Hansen et al. 2013) to assess forest cover change from 2000 to 2021. Two different methods were used because while the HGFC is a more specific measure of forest cover change, the earliest available data are from 2000. As the two methods provide different information, we ran the analyses separately. These methods can be conceived as providing converging evidence in relation to forest cover change. Data was accessed using Google Earth Engine (GEE), utilising the Earth Engine’s JavaScript API.

Landsat 5 Normalized Difference Vegetation Index data (1986–2010)

Landsat 4–5 Tier 1 SR images with a resolution of 30 m were selected in GEE. Tier 1 SR images are atmospherically

Fig. 1 Provinces of North Korea



corrected using the LEDAPS method (Parida and Kumar 2020). Images were taken from the highest greening period in North Korea, 1st June to 30th September (Lim and Yeo 2022).

Persistent cloud cover is a common feature during the growing season in North Korea, particularly in the mountainous northern provinces, which can limit detection of NDVI changes (Rao et al. 2015). North Korea is also affected by high levels of industrial air pollution originating from northern China (Xiang-Ao et al. 2005), including haze events (Jia and Ku 2019), which impact reflected light values (Peterson et al. 2019). To mitigate these issues, built-in cloud masking tools and Landsat 5's quality control band (pixel-qa) were used to filter out images with cloud cover of $\geq 40\%$. Snow, clouds and cloud shadows were masked in GEE using the CFMask method (Fassnacht et al. 2019). Potential atmospheric haze was then masked, and a scaling factor applied to remove hazy pixels. However, these cannot entirely mitigate the impact of persistent high pollution levels, or errors relating to misidentification of high-altitude bright surfaces (such

as snow-covered mountains) and cirrus clouds (Zhu et al. 2015). As a result, images with very high cloud cover and missing data were inspected and removed where necessary to avoid introducing potential errors into the analysis.

NDVI values can be used to infer vegetation cover and, to a degree, also forest cover (Yeom et al. 2008; Jin et al. 2016; Piao et al. 2021). Due to the inherent difficulty in verifying land cover classifications for North Korea, change in NDVI was selected as a proxy for vegetation cover change as per Nath (2014) and Lim and Yeo (2022). NDVI values were calculated in GEE for each pixel. These values were derived from the reflectance ratio of near-infrared (NIR) and red (R) band data (Fassnacht et al. 2019).

NDVI composites for five 5-year periods between 1986 and 2010 were then produced by calculating the median NDVI value using all available images for the greening season of each year. Temporal fusion was used to increase the number of available images, reduce noise and enable the creation of complete composites (Lim and Yeo 2022).

Statistical analysis

As a larger coverage and higher density of vegetation in each pixel result in a higher NDVI value, deforestation is associated with decreasing NDVI values (Nath 2014). To calculate time-specific increases or decreases in NDVI values, Mann–Kendall trend tests (MKTT) were applied and visualised in GEE using custom JavaScript. The MKTT enables the identification of monotonic trends in NDVI and has been shown to be robust to the influence of outliers (Zhong et al. 2022). Pixels were classified based on their MKTT value and organised into 5 classes: *high increase* (> 0.5), *increase* (0.5 to 0.1), *non-significant change* (0.1 to -0.1), *decrease* (-0.1 to -0.5) and *high decrease* (< -0.5). To compare associated findings to the LEK data, the Landsat 5 data (1986–2010) were split into two distinct time periods that reflected dates mentioned in the LEK reports (1986–1995 and 1996–2010). MKTT values were mapped for each time period, for each focus province and for North Korea as a whole, allowing direct comparison with the narratives of change from the LEK data.

Forest cover change analysis

We used the HGFC to quantify forest cover change between 2000 and 2021. The HGFC provides high-resolution (30 m resolution) satellite datasets of global forest cover, produced from a time series analysis of Landsat 7/8 TM and ETM+ images (Hansen et al. 2013). Forest is classified as vegetation of ≥ 5 m in height. Data from the HGFC were used to generate an estimated forest cover map for the year 2000, which served as our baseline from which to calculate forest gain or loss. Gain is defined as the establishment of tree cover in an area that previously had none at the Landsat pixel scale; loss is defined as stand replacement disturbance, or the total removal of tree cover canopy, at the Landsat pixel scale (Galiatsatos et al. 2020). We then calculated cumulative forest cover loss between 2000 and 2021. This helped to mitigate for the potential impact of short-term forestry cycles, whereby areas of forest may be felled and then allowed to reestablish.

To improve the potential reliability of forest cover loss estimations in our study, temporal fusion for loss data was undertaken. Data averaging across 3-year time periods was conducted to mitigate the impact of noise in the data without compromising temporal resolution (Mitchard et al. 2015). This was then used to provide a reference comparison for later Landsat 5–derived vegetation cover classifications, while observed trends were compared to LEK reports.

Results

Local ecological knowledge

Participants identified deforestation as a major driver of defaunation in North Korea and provided a general timeline of landscape-scale changes in the country (Table 1). Some of these reports were specific to 1–2-year time periods. A major shift was identified as having occurred in the early 1990s, when multiple participants reported an increase in deforestation, starting between 1992 and 1995. Trees were reportedly felled by the state to sell as timber, predominantly to China; for use as fuel; or were cleared by residents to create small-scale agricultural fields, known as “mountain fields”, sometimes illegally. Fire was reported to often be used by residents to clear vegetation and was identified as a major cause of deforestation. Participants reported that occasionally fires got out of control and spread, unintentionally leading to larger forest areas being destroyed. Although areas of lower elevation and closer to human settlements were generally reported to have less remaining forest cover, high elevation areas were also reported as being cleared for small-scale agriculture.

Reports of forest cover loss exhibited distinct spatio-temporal variation. Earlier dates were usually given for reports of deforestation in southern provinces. For example, deforestation in South Hwanghae province was reported up until the mid-1980s. Both North and South Hwanghae were reported to be largely devoid of woodland cover as early as the late 1980s and early 1990s, with agriculture the dominant land use. In South Pyongan, remaining forest cover was reported to be low due to the expansion of coal mining (an

Table 1 Timeline of environmental change in North Korea, as identified by North Korean defectors

Time period	Narratives of environmental change
1950s–1980s	Post-Korean War (1950–1953), initial increase in construction, with localised impacts on forest cover Some mountainous areas cleared between 1984 and 1987 to create agricultural fields Some burning, but forest cover remained largely intact
1990s	Period of widespread economic hardship and famine, many provinces experiencing major increases in deforestation
2000–present	Lower slopes of many mountains, particularly near settlements, cleared entirely of trees or showing greatly reduced tree cover Not many mature trees left across much of North Korea Recent attempts at afforestation (for example, in Ryanggang province)

important economic resource for the North Korean state) and local use of timber as a fuel source. By contrast, participants only reported deforestation in the mountainous north of the country, including Ryanggang (1993–1994 and 2009–2010) and North Hamgyong (1993–2004), in later time periods.

Some participants tried to quantify the extent of deforestation in North Korea. One participant who had resided in North and South Hamgyong reflected that they learnt in school that “80% of North Korea used to be (forested) mountains. I think 80% of that has now been lost and the remaining 20% is concentrated in Paektusan (Mount Paektu), Ryanggang, and Gaemagowon (the Kaema Plateau)”. The identification of Ryanggang province, particularly Paektusan, as an area where primary forest remained was common, both by participants from Ryanggang and other provinces. Participants occasionally also mentioned North Hamgyong and Chagang provinces; upland areas along the border between South Hamgyong and South Pyongan; and Mount Myohyang, a UNESCO Biosphere Reserve in North Pyongan, as locations that had greater forest cover. However, even these areas include reports of localised deforestation, with several participants reporting that trees in their local area had been completely cleared or that trees were felled from mountain slopes. One participant described that the amount of forest converted to human land use was “several tens of kilometres”.

Participants also described government efforts at afforestation, led by forestry officers and with obligatory participation by local school students and state workers. However, one respondent who had participated in organised tree-planting in Ryanggang as a student described that in their experience, many of the trees did not survive because “they were planted by students, not professionals”.

Remote sensing

Landsat 5 vegetation analysis (1986–2010)

Almost all provinces that had been mentioned in detail by participants exhibited NDVI declines between 1986 and 1990 and 1991 and 1995, with the exception of North Hamgyong (Table 2). This pattern was reversed by 1996–2000, and all provinces recorded an increase in mean NDVI between 2001 and 2005 and 2006 and 2010. Overall, therefore, there was little change in mean NDVI for North Korea between the first (1986–1990) and last (2006–2010) time periods.

Mann–Kendall time series analysis (1986–1995 and 1996–2010)

Between 1986 and 1995, the strongest NDVI trend decreases were evident in the north-west and south-east of North Korea (Fig. 2), whereas positive trends were observed in the north-east and along the western sector of the Korean Demilitarized Zone (DMZ), North Korea’s southern border. However, between 1996 and 2010, while positive NDVI trends in the south-west intensified, negative trends were recorded through much of the north and centre of the country.

Focus provinces in the north-east of the country, where LEK data indicated deforestation from 1993 onwards, showed widespread declines in NDVI values between 1986 and 1995 and 1996 and 2010 (Fig. 3). For example, during 1986–1995, only 32.7% of Ryanggang province was classified as exhibiting negative trends in NDVI values. This area doubled to 70% during 1996–2010. Similar patterns, indicating a shift towards negative trends in vegetation cover, were recorded in North and South Hamgyong. In contrast, the provinces of South Pyongan, and North and South Hwanghae, in the west and south of the country, showed an increase in positive NDVI trends between 1986 and 1995 and 1996 and 2010 (Fig. 3). Particularly notable NDVI increases were recorded in the west of these three provinces, close to the

Table 2 Landsat 5–derived mean NDVI values for focus provinces in North Korea between 1986 and 2010. Mean NDVI values are presented for five 5-year periods and are displayed alongside the stand-

ard deviation. Higher NDVI values indicate higher recorded levels of vegetation greenness

Mean NDVI values (0.0–1.0)							
	North Korea	Ryanggang	Chagang	N. Hamgyong	S. Hamgyong	S. Pyongan	Hwanghae ^a
1986–1990	0.70 (0.15)	0.71 (0.10)	0.77 (0.10)	0.71 (0.13)	0.70 (0.15)	0.63 (0.15)	0.69 (0.16)
1991–1995	0.67 (0.15)	0.69 (0.10)	0.73 (0.11)	0.73 (0.13)	0.68 (0.14)	0.57 (0.15)	0.63 (0.15)
1996–2000	0.70 (0.14)	0.74 (0.10)	0.76 (0.10)	0.70 (0.13)	0.73 (0.14)	0.59 (0.15)	0.66 (0.15)
2001–2005	0.67 (0.15)	0.70 (0.10)	0.70 (0.12)	0.72 (0.15)	0.67 (0.15)	0.61 (0.16)	0.63 (0.15)
2006–2010	0.70 (0.15)	0.73 (0.10)	0.75 (0.11)	0.73 (0.13)	0.68 (0.16)	0.64 (0.14)	0.68 (0.14)

^aCombined figure for the provinces of North and South Hwanghae

capital, Pyongyang and the West Sea (Yellow Sea) coastline. The LEK data did not report increased forestation in these provinces during this time.

Hansen's Global Forest Change analysis (2000–2021)

The forest cover map for 2000 (Fig. 4), generated using HGFC data, confirms that North Korea's northern regions remained among the most densely forested areas of the country at that time. In contrast, there was relatively little forest cover remaining along the West Sea (Yellow Sea) coastline. This corresponded to higher rates of forest cover loss post-2000 in the more forested northern provinces of the country (Table 3 and Online Resource 2).

Total forest cover loss across North Korea between 2000 and 2021 was 2930 km². Forest cover loss broadly increased through the early 2000s, slowed down around 2011, but increased sharply again from 2016, up to a rate of > 200 km² loss per annum during 2019–2021 (Fig. 5).

Discussion

Although North Korea has experienced high rates of deforestation over the past 40 years compared to other countries (Piao et al. 2021), our analysis indicates that forest cover loss has not occurred evenly. The LEK and remote sensing data aligned in identification of deforestation between 1986 and 1995 in the west and south of the country, including the

provinces of South Pyongan, North and South Hwanghae. These data indicated that from the mid-1990s onwards, high rates of deforestation increasingly occurred in the north-east, including in Ryanggang and North Hamgyong, along the North Korea-China border. However, there was a notable lack of reports of increased forestation that could support the simultaneous increases in NDVI observed in other areas. Data from the HGFC indicate that forest cover in North Korea has declined since 2000 and that since 2016, the rate of loss has begun to accelerate.

Integrating local ecological knowledge and remote sensing reveals patterns and drivers of forest cover change

Our data shows a marked northwards shift in deforestation patterns in North Korea in the mid-1990s. The apparent timing of this shift coincides with the "Arduous March", a period of extreme hardship following the collapse of the North Korean economy, which resulted in severe food and energy crises (Kim et al. 2008; Elves-Powell et al. in press). Other studies have also suggested that deforestation accelerated at this time and continued until either 2000 (Kang and Choi 2014) or 2010 (Liu and Sheng 2023). Our analysis shows that deforestation in North Korea has in fact continued until at least 2021, as while rates of forest cover loss did previously appear to have slowed, they increased more rapidly again from 2016 onwards. We note with concern that this recent increase in deforestation detected in the HGFC