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ORIGINAL ARTICLE

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 Dolan[2] · Sarah M. Durant[1] · Hang Lee[3,4] · John D. C. Linnell[5,6] · Samuel T. Turvey[1] · Jan C. Axmacher[2]

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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 km^2 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 ≥ 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 spatiotemporal 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 standard 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)

[a] Combined figure for the provinces of North and South Hwanghae

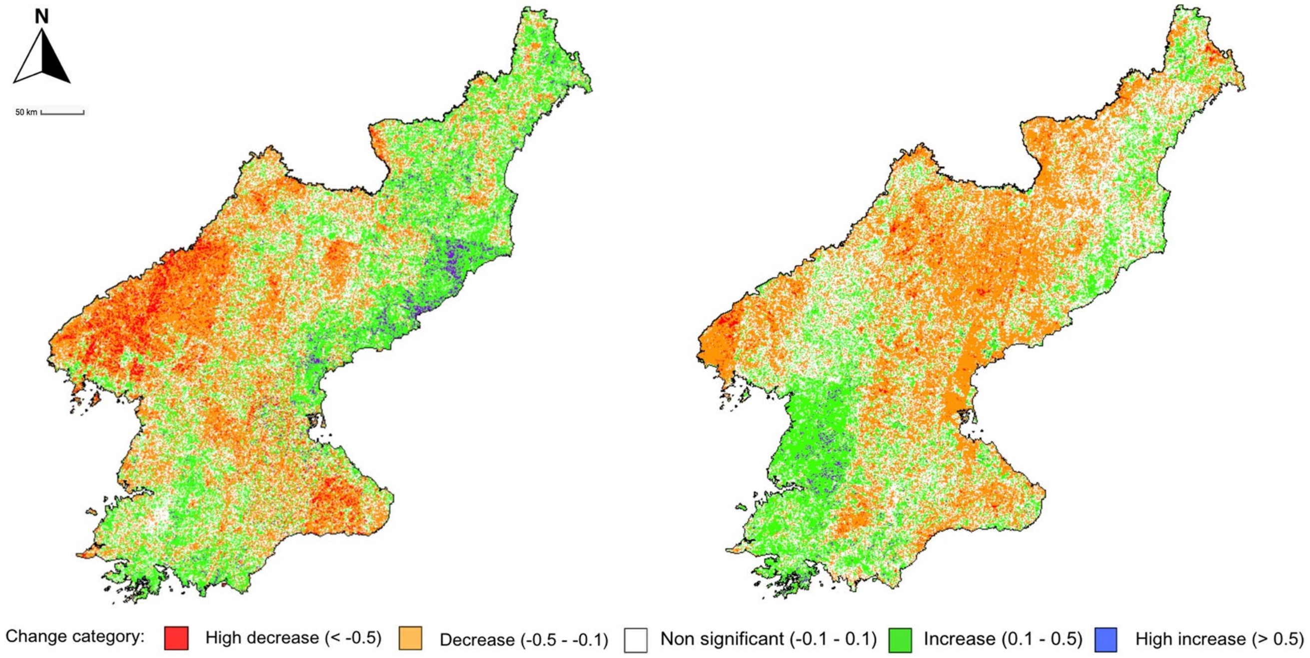

Fig. 2 Mann–Kendall trend test (MKTT) analyses for NDVI changes across North Korea for 1986–1995 (left) and 1996–2010 (right)

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 km^2. 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 km^2 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

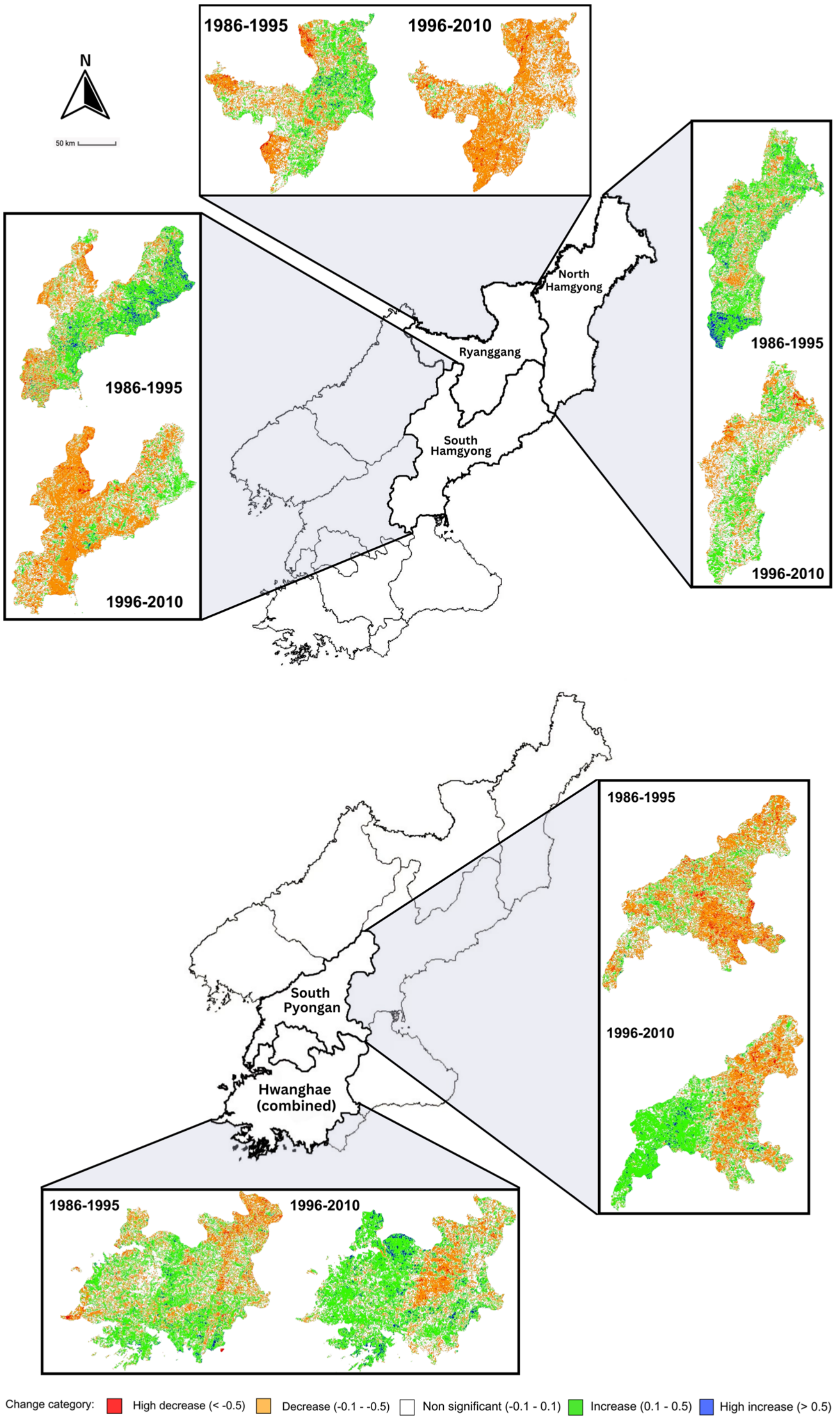

Fig. 3 Mann–Kendall trend test (MKTT) analyses confirm declines in NDVI values in northeastern provinces (Ryanggang, North and South Hamgyong) (upper row) and increases in southwestern provinces (South Pyongan, North and South Hwanghae) (lower row), between 1986 and 1995 and 1996 and 2010

data appears to again coincide with a suspected intensification of food shortages in North Korea (Lee and Oh 2018; Noland 2022).

Previous studies have linked an increase in deforestation with the economic hardship that North Korea suffered during the 1990s (Lee and Oh 2018; Liu and Sheng 2023). The LEK data we present provide some supporting evidence for this linkage and specifically indicate that residents felled trees for fuel or to create small, agricultural plots, referred to as "mountain fields", where they could cultivate staples such as potatoes. North Korean state policy has sought to increase the amount of land under cultivation in response to food shortages (Park and Lee 2014), but regular mention by participants that some clearance was conducted covertly and could result in punishment suggests that individual families clearing forest areas for their own use was not officially tolerated. This illustrates how LEK can provide valuable information on household level activities, including

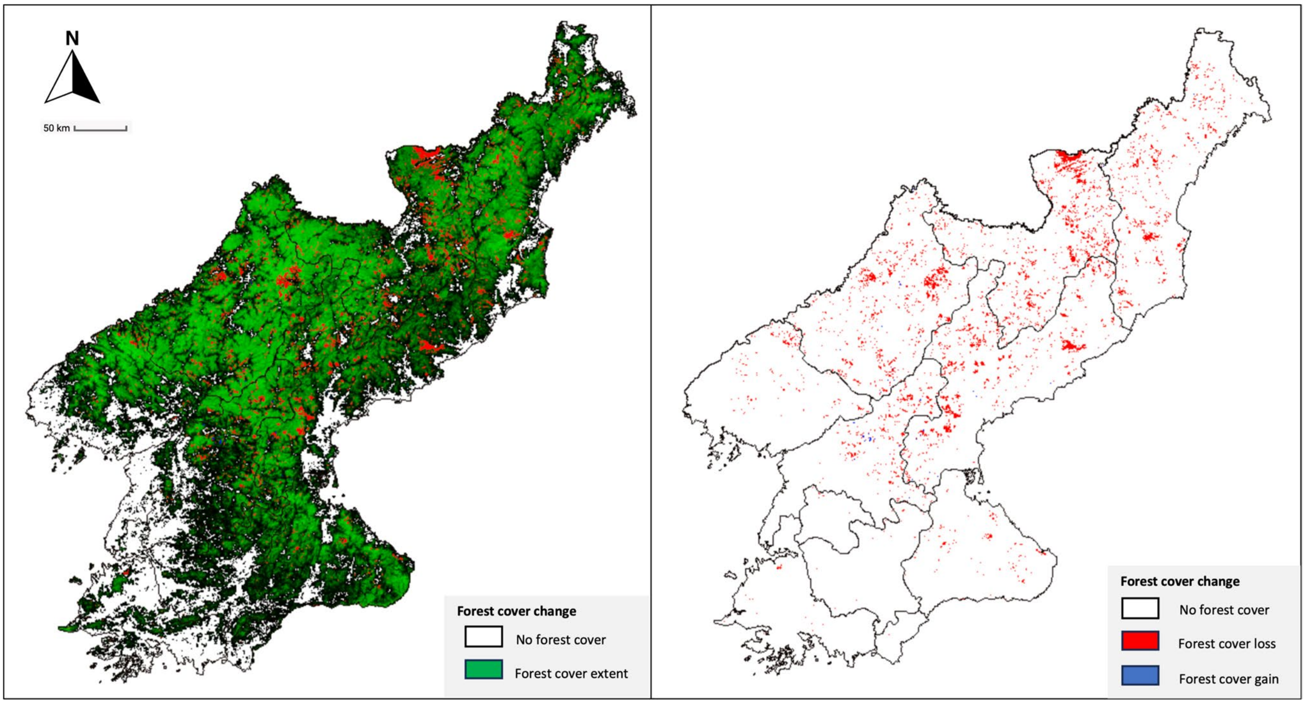

Fig. 4 Forest cover loss and gain estimation across North Korea, between 2001 and 2021. Based on data from Hansen et al. (2013). Forest cover extent for 2000 is shown in green, with loss or gain calculated from this baseline

Table 3 Forest cover loss estimation for North Korea and selected provinces between 2001 and 2021. Based on data from Hansen et al. (2013). Data are displayed alongside standard deviations

GFC calculated tree loss (km^2)[a]							
	North Korea	Ryanggang	Chagang	N. Hamgyong	S. Hamgyong	S. Pyongan	Hwanghae[b]
2001–2003	86.87 (28.00)	10.40 (1.39)	13.67 (2.94)	15.56 (10.88)	20.16 (6.95)	11.85 (7.19)	2.30 (0.40)
2004–2006	146.85 (23.36)	25.89 (4.33)	20.86 (3.09)	18.93 (9.15)	39.34 (17.76)	15.02 (4.97)	5.30 (1.45)
2007–2009	160.34 (28.52)	33.90 (14.92)	51.88 (10.43)	20.56 (8.33)	17.78 (3.13)	15.06 (5.83)	1.83 (0.44)
2010–2012	146.09 (77.26)	41.21 (28.09)	29.63 (20.00)	20.22 (4.41)	20.32 (7.94)	14.92 (13.47)	4.18 (0.72)
2013–2015	100.55 (31.17)	12.94 (4.55)	21.85 (16.82)	22.54 (1.27)	32.32 (24.68)	5.34 (1.12)	0.67 (0.25)
2016–2018	186.35 (17.00)	23.49 (3.14)	25.51 (2.17)	22.29 (3.91)	20.06 (8.14)	6.36 (0.68)	1.68 (0.73)
2019–2021	237.14 (75.22)	71.41 (42.91)	36.26 (2.06)	36.23 (11.11)	50.56 (24.70)	18.88 (5.18)	4.66 (1.19)

[a] Mean. [b] Combined figure for the provinces of North and South Hwanghae

"hidden" illegal activities, which may be difficult to detect from other data sources. In North Korea, the use of burning to illegally clear forest areas and reports of these fires subsequently getting out of control is concerning. The Korean Peninsula has a long winter dry season and is seasonally vulnerable to forest fires between October and May (Seol et al. 2011). Forest fires have been considered one of the main causes of deforestation in the DMZ (Kwon et al. 2021) and our findings suggest they should be considered a wider risk in North Korea.

LEK data was particularly useful for interpretation of NDVI increases recorded across some western and southern provinces between 1996 and 2010. The LEK data we present suggest that the most likely explanation for this trend is that formerly cleared areas were converted to cropland (Qu et al. 2023), resulting in an increase in recorded NDVI values. It is known that at this time, the North Korean state sought to maximise food production, as the country was experiencing a major famine (Noland 2004; Park and Lee 2014). This explanation is further supported by the marginal forest cover gains detected by the HGFC in these provinces post-2000. Furthermore, high NDVI increases were recorded in lower-lying coastal areas and areas relatively close to urban centres, which are more vulnerable to conversion to agriculture.

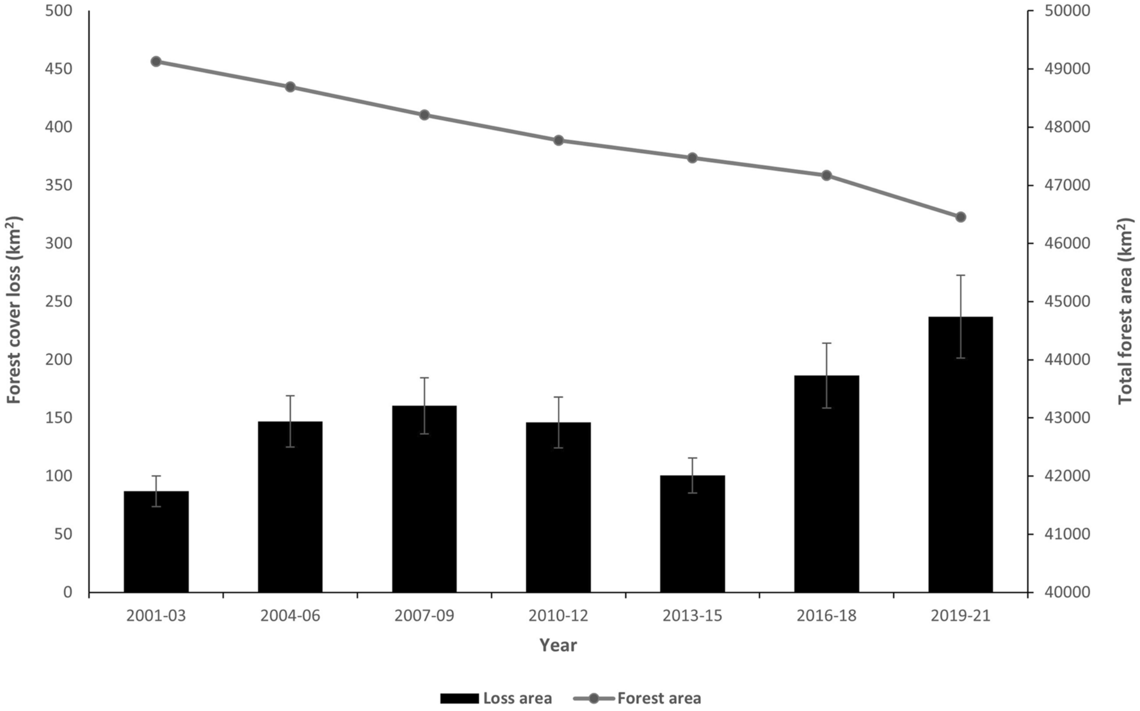

Fig. 5 Forest cover loss estimations between 2001 and 2021 for North Korea. Based on data from Hansen et al. (2013). Error bars represent one standard deviation for each period

The continued loss of forest cover in North Korea, including the observed northward shift in deforestation patterns, may have important consequences for biodiversity conservation for the wider Korean Peninsula. At the start of the twenty-first century, the northern provinces contained some of North Korea's largest remaining tracts of forest cover and provided the only overland dispersal route for terrestrial species from China and Russia to the Korean Peninsula (Jo et al. 2018). For this reason, these northern provinces have been identified as priority areas for habitat preservation, for example to support recovery of the Critically Endangered Amur leopard (*Panthera pardus orientalis*) (Li et al. 2024). The ongoing loss of forest in North Korea will also reduce the resilience of local socio-ecological systems to global climate change. North Korea has experienced one of the largest mean temperature increases over the past century of any country (Jeung et al. 2019) and is ranked among the most vulnerable to the impacts of climate change (Harmeling and Eckstein 2013). For example, North Korea's topography makes it particularly vulnerable to flooding (Lim et al. 2019), which is likely to be exacerbated by the reported loss of forest cover on higher elevation slopes.

Recollecting environmental change

A distinctive feature of the LEK data used in this study was that it was collected with former, not current, residents of North Korea. Participants were therefore both describing changes that occurred outside of their current place of residence and recalling past events. The use of LEK data that concern historical changes is not uncommon, for example in fisheries science (Colloca et al. 2020). However, it is widely understood that memories of ecological change should be handled with caution, due to lack of experience of past conditions and the potential for memory loss or distortion (Boerma 2012; Soga and Gaston 2018). It is also important to recognise that many of our participants had experienced severe trauma before, during or immediately after leaving North Korea. Although poorly understood in the context of LEK, this could reasonably be expected to impact memory recall (Zoellner et al. 2000). Despite this, some participants discussed changes in forest cover that happened in the 1950s, and fairly detailed information was provided about changes that were observed in the early 1980s. We were unable to corroborate reports of forest clearance prior to 1986, which was the earliest satellite data available in this study. However, the fact that this information could be recalled by participants, and the high concordance between reports from the mid- and late-1980s and satellite data, suggests that deforestation, which is dramatic and cannot be rapidly reversed, is an event that may leave a deep impression on human memory (Sahoo et al. 2013) and can be recalled in some detail years later. More generally, most of the LEK data presented in this study involve a memory of a discrete event (forest clearance), rather than a trend in the state of the environment (for example, regarding weather patterns or temperature), which may be more difficult to detect from personal experience alone (Hansen et al. 1998; Weber and Stern 2011). These reports also typically concerned changes that had occurred during an individual's own lifetime, rather than over successive generations (Soga and Gaston 2018). Forest cover change in North Korea likely also has direct consequences for the country's human population, especially in rural areas (Lim and Lee 2018; Kim et al. 2020). Each of these factors may increase the likelihood of accurate recall of information within this context.

Limitations

LEK data, particularly when based on personal observations, can often be highly localised (Chalmers and Fabricius 2007). This issue is particularly pertinent in North Korea, given restrictions on personal movement (Han et al. 2017). This contrasts with satellite-based data and makes direct comparison difficult. For example, the HGFC has an estimated accuracy of 90% for forest/non-forest delineation and > 80% for forest cover loss (Hansen et al. 2013; Mitchard et al. 2015). However, despite the dataset's high resolution, highly localised changes in forest cover may be harder to detect and may be under-reported (Galiatsatos et al. 2020). The challenges of identifying and recruiting participants among a "hidden" and vulnerable population meant that our LEK sample size was relatively small. Additionally, more data were available for certain provinces and time periods, limiting the conclusions that could be drawn from the LEK data alone. For example, limited information was available regarding forests in Chagang province, which has been designated a "Special *Songun* (military-first) Revolutionary Zone".

Although widely used in studies of forest cover change, NDVI is an index reflecting plant productivity and the detection of long-term trends can be disrupted, for example by drought (Guo et al. 2018; Das et al. 2023). Some agricultural croplands, such as densely planted paddy fields at their peak greenness, can record NDVI values above 0.6, like dense forest (Zheng et al. 2018). As a result, deforestation may not always be reflected in strongly declining NDVI values. We were also unable to mitigate for the potential impact of tree age, as mature trees generally have larger and more complex canopies, resulting in higher NDVI values (Berra et al. 2017). A considerable proportion of Korean forests are secondary, with trees aged < 70 years old, due to damage caused by the Korean War (Kim et al. 2019). Biomass in recovering forests should have accumulated since 1953, with consequences for recorded NDVI values. Similarly, while it is not currently possible to precisely quantify the impacts of climate change and increased atmospheric CO_2 on NDVI trends (Zhe and Zhang 2021), it is suspected that these novel environmental changes will lead to increasing vegetation greenness across North Korea (Lim and Yeo 2022). The existence of these potentially confounding factors makes the recorded declines in NDVI values particularly notable. We note that emerging methodologies may provide more precise measures of change for future investigations. For example, Normalized Difference Vegetation Change Index (NDVCI) is reported to detect vegetation change between two different time images with higher classification than a range of existing methods (Rokni and Musa 2019).

Conclusion

The difficulty of conducting ecological field surveys to ground truth satellite data presents a major challenge to better understanding forest changes in some of the world's most understudied environments, including North Korea. In this study, LEK data from North Korean defectors, who were not trained forest scientists or managers, are no longer resident in the country, and sometimes recounted observations of forest cover change over long time periods, showed broad concordance with findings from two different satellite-derived vegetation indices. Some participants identified changes in forest cover with 1–2-year precision, such as the reported intensification of deforestation in Ryanggang province between 2009 and 2010, which was strongly corroborated by analysis of Landsat data. Combining LEK and remote sensing data indicated that rates of forest cover loss in North Korea were high and exhibited spatio-temporal variation, including a pronounced northwards shift in deforestation patterns from the mid-1990s onwards. LEK data also provided key information to enable interpretation of satellite-derived data. For example, our LEK data indicate that the most likely explanation for observed NDVI trends is that following the collapse of the North Korean economy in the mid-1990s and the onset of famine, trees were increasingly felled in the more forested northern provinces as an economic resource, for fuel, and to clear land for cultivation, while areas of the country that had already been cleared of trees were converted to agricultural cropland. Data from the HGFC provide further support for this explanation and indicate that forest cover in North Korea has continued to decline into the twenty-first century. Concerningly, these data suggest there has been a recent increase in the rate of forest loss up to a rate of > 200 km^2 per annum during 2019–2021, coinciding with suspected intensification of food shortages. Overall, our study shows that LEK can be an informative addition to a suite of complementary techniques for analysing forest cover change. Retaining North Korea's remaining forest cover, particularly in its northernmost provinces, is important to maintaining viable habitat corridors that might allow the potential recovery of threatened or extirpated Korean species via dispersal from metapopulations in China and Russia, and to sustaining the resilience of North Korean socio-ecological systems to future climate change.

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Author contribution Joshua Elves-Powell and Jai Dolan contributed equally to this study. Joshua Elves-Powell conceived the study, collected and analysed the LEK data, and wrote the final manuscript. Jai Dolan collected and analysed the remote sensing data, and wrote a first draft of the manuscript. All authors contributed to editing of the manuscript.

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References

Ahammad R, Stacey N, Eddy IMS, Tomscha SA, Sunderland TCH (2019) Recent trends of forest cover change and ecosystem services in eastern upland region of Bangladesh. Sci Total Environ 647:379–389. https://doi.org/10.1016/j.scitotenv.2018.07.406

Aswani S, Lemahieu A, Sauer WHH (2018) Global trends of local ecological knowledge and future implications. PLoS ONE 13(4):e0195440. https://doi.org/10.1371/journal.pone.0195440

Atkinson R, Flint J (2001) Accessing hidden and hard-to-reach populations: snowball research strategies. Soc Res Update 33:1–4

Berra EF, Fontana DC, Kuplich TM (2017) Tree age as adjustment factor to NDVI. SciELO Brazil 41(3):e410307

Boerma P (2012) Myths, memories and metaphors: recollecting landscape change in the Eritrean highlands. J Eastern Afr Stud 6(2):246–269. https://doi.org/10.1080/17531055.2012.669573

Brown MI, Pearce T, Leon J, Sidle R, Wilson R (2018) Using remote sensing and traditional ecological knowledge (TEK) to understand mangrove change on the Maroochy River, Queensland, Australia. Appl Geogr 94:71–83. https://doi.org/10.1016/j.apgeog.2018.03.006

Bureau of Democracy, Human Rights and Labor Affairs (2022) Democratic People's Republic of Korea 2022 Human Rights Report. US Department of State: Washington DC

Chalmers N, Fabricius C (2007) Expert and generalist local knowledge about land-cover change on South Africa's Wild Coast: can local ecological knowledge add value to science? Ecol Soc 12(1):10

Choi W, Kang S, Choi J, Larsen JJ, Oh C et al (2017) Characteristics of deforestation in the Democratic People's Republic of Korea (North Korea) between the 1980s and 2000s. Reg Environ Change 17(2):379–388. https://doi.org/10.1007/s10113-016-1022-3

Colloca F, Carrozzi V, Simonetti A, Di Lorenzo M (2020) Using local ecological knowledge of fishers to reconstruct abundance trends of elasmobranch populations in the Strait of Sicily. Front Mar Sci 7:508. https://doi.org/10.3389/fmars.2020.00508

Das AC, Shahriar SA, Chowdhury MA, Hossain ML, Mahmud S et al (2023) Assessment of remote sensing-based indices for drought monitoring in the north-western region of Bangladesh. Heliyon 9(7):e13016. https://doi.org/10.1016/j.heliyon.2023.e13016

Eddy IMS, Gergel SE, Coops NC, Henebry GM, Levine J et al (2017) Integrating remote sensing and local ecological knowledge to monitor rangeland dynamics. Ecol Ind 82:106–116. https://doi.org/10.1016/j.ecolind.2017.06.033

Elves-Powell J, Kim JH, Axmacher JC, Durant SM (in press) The trade of Eurasian otter *Lutra lutra* in North Korea. IUCN/SSC Otter Specialist Group Bulletin.

Engler R, Teplyakov V, Adams JM (2014) An assessment of forest cover trends in South and North Korea, From 1980 to 2010. Environ Manage 53:194–201. https://doi.org/10.1007/s00267-013-0201-y

Estoque RC, Dasgupta R, Winkler K, Avitabile V, Johnson BA et al (2022) Spatiotemporal pattern of global forest change over the past 60 years and the forest transition theory. Environ Res Lett 17(8):084022. https://doi.org/10.1088/1748-9326/ac7df5

Fassnacht FE, Schiller C, Kattenborn T, Zhao X, Qu J (2019) A Landsat-based vegetation trend product of the Tibetan Plateau for the time-period 1990–2018. Scientific Data 6:78

Galiatsatos N, Donoghue DNM, Watt P, Bholanath P, Pickering J et al (2020) An assessment of global forest change datasets for national forest monitoring and reporting. Remote Sens 12:1790. https://doi.org/10.3390/rs12111790

Goldstein A, Turner WR, Spawn SA, Anderson-Teixeira KJ, Cook-Patton S et al (2020) Protecting irrecoverable carbon in Earth's ecosystems. Nat Clim Chang 10:287–295

Goodman LA (1961) Snowball sampling. Ann Math Stat 32(1):148–170. https://doi.org/10.1214/aoms/1177705148

Guo M, Jing L, Hongshi HE, Jiawei X, Yinghua YN (2018) Detecting global vegetation changes using Mann-Kendal (MK) trend test for 1982–2015 time period. Chin Geogra Sci 28(6):907–919. https://doi.org/10.1007/s11769-018-1002-2

Han D-H, Kim S, Lee K (2017) Freedom of movement in North Korea. Korea Institute for National Unification: Seoul, Republic of Korea

Hansen J, Sato M, Glascoe J, Ruedy R (1998) A common-sense climate index: is climate changing noticeably? Proc Natl Acad Sci 95:4113–4120. https://doi.org/10.1073/pnas.95.8.4113

Hansen MC, Potapov PV, Moore R, Hancher M, Turubanova SA et al (2013) High-Resolution Global Maps of 21st-Century Forest Cover Change. Science 342(6160):850–853. https://doi.org/10.1126/science.1244693

Harmeling S, Eckstein D (2013) Global Climate Risk Index 2013. Germanwatch: Bonn, Germany

Hayes P (2009) Unbearable legacies: the politics of environmental degradation in North Korea. Asia-Pacific J 7(41):2

Huang S, Tang L, Hupy JP, Wang Y, Shao G (2021) A commentary review on the use of normalized difference vegetation index (NDVI) in the era of popular remote sensing. J Forest Res 32(1):1–6

Jeung SJ, Sung JH, Kim BS (2019) Assessment of the impacts of climate change on climatic zones over the Korean Peninsula. Adv Meteorol 5418041. https://doi.org/10.1155/2019/5418041

Jia R, Ku H (2019) Is China's pollution the culprit for the choking of South Korea? Evidence from the Asian dust. Econ J 129(624):3154–3188. https://doi.org/10.1093/ej/uez021

Jin Y, Song S, Lee DK, Biging GS, Jeong S (2016) Mapping deforestation in North Korea using phenology-based multi-index and random forest. Remote Sensing 8(12):997. https://doi.org/10.3390/rs8120997

Jo Y, Baccus JT, Koproswki J (2018) Mammals of Korea. Incheon, Republic of Korea, National Institute of Biological Resources

Joa B, Winkel G, Primmer E (2018) The unknown known – a review of local ecological knowledge in relation to forest biodiversity conservation. Land Use Policy 79:520–530. https://doi.org/10.1016/j.landusepol.2018.09.001

Kang S, Choi W (2014) Forest cover changes in North Korea since the 1980s. Reg Environ Change 14:347–354. https://doi.org/10.1007/s10113-013-0497-4

Kang S, Choi J, Yoon H, Choi W (2019) Changes in the extent and distribution of urban land cover in the Democratic People's Republic of Korea (North Korea) between 1987 and 2010. Land Degradation Dev 30(16):1887–2017

Kim ES, Lee SH, Cho HK (2010) Segment-based land cover classification using texture information in degraded forest land of North Korea. Korean J Remote Sens 26:477–487

Kim HY, Kim J, Heo E (2008) Analysis of North Korean energy shortage using energy supply data. J Korean Soc Geosyst Eng 45(5):567–577

Kim M, Kraxner F, Son Y, Jeon SW, Shvidenko A,, , et al (2019) Quantifying impacts of national-scale afforestation on carbon budgets in South Korea from 1961 to 2014. Forests 10(7):579. https://doi.org/10.3390/f10070579

Kim S, Jeong Y, Park S (2020) Why is inter-Korean forestry cooperation hard to accomplish? Asian J Peacekeep 8(2):309–331. https://doi.org/10.18588/202011.00a098

Kim J, Lim C, Jo H, Lee W (2021) Phenological classification using deep learning and the sentinel-2 satellite to identify priority afforestation sites in North Korea. Remote Sensing 13(15):2946. https://doi.org/10.3390/rs13152946

Kwon S, Kim E, Lim J, Yang A-R (2021) The analysis of changes in forest status and deforestation of North Korea's DMZ using RapidEye Satellite Imagery and Google Earth. J Korean Assoc Geogr Inform Stud 24(4):113–126. https://doi.org/10.11108/kagis.2021.24.4.113

Lee H-K, Oh M-K (2018) Analysis of forest change characteristics in North Korea using multi-temporal satellite images. J Korea Academia-Indust Coop Soc 19(1):633–638. https://doi.org/10.5762/KAIS.2018.19.1.633

Li H, Pandey P, Li Y, Wang T, Singh R et al (2024) Transboundary cooperation in the Tumen River basin is the key to Amur leopard (*Panthera pardus*) population recovery in the Korean Peninsula. Animals 14(1):59. https://doi.org/10.3390/ani14010059

Lim C, Choi Y, Kim M, Jeon SW, Lee W (2017) Impact of deforestation on agro-environmental variables in cropland North Korea. Sustainability 9(8):1354. https://doi.org/10.3390/su9081354

Lim C, Yeo H (2022) Understanding the long-term vegetation dynamics of North Korea and their impact on the thermal environment. Forests 13(7):1053. https://doi.org/10.3390/f13071053

Lim J, Lee K-S (2018) Flood mapping using multi-source remotely sensed data and logistic regression in the heterogeneous mountainous regions in North Korea. Remote Sensing 10(7):1036. https://doi.org/10.3390/rs10071036

Lim J, Kim K-M, Lee K-S (2019) Does deforestation trigger severe flood damage at Hoeryeong City in North Korea? Forests 10(9):789. https://doi.org/10.3390/f10090789

Liu J, Sheng C (2023) A historic review of deforestation and afforestation in North Korea. Third World Quarterly 44(11):2391–2403. https://doi.org/10.1080/01436597.2023.2233918

McCarthy C, Banfill J, Hoshino B (2021) National parks, protected areas and biodiversity conservation in North Korea: opportunities for international collaboration. J Asia-Pacific Biodivers 14(3):290–298. https://doi.org/10.1016/j.japb.2021.05.006

Millennium Ecosystem Assessment (2005) Ecosystems and human well-being: synthesis. Island Press, Washington, DC

Mitchard E, Viergever K, Morel V, Tipper R (2015) Assessment of the accuracy of University of Maryland (Hansen et al.) forest loss data in 2 ICF project areas – component of a project that tested an ICF indicator methodology. Ecometrica: Edinburgh, UK

Morozova AO, Nyland KE, Kuklina VV (2023) Taiga landscape degradation evidenced by indigenous observations and remote sensing. Sustainability 15(3):1751. https://doi.org/10.3390/su15031751

Nath B (2014) Quantitative assessment of forest cover change of a part of Bandarban Hill tracts using NDVI techniques. J Geosci Geom 2(1):21–27. https://doi.org/10.12691/jgg-2-1-4

NBSAP (2007) National Biodiversity Strategy and Action Plan of DPR Korea [online]. Pyongyang, DPR Korea. Available from: https://www.cbd.int/doc/world/kp/kp-nbsap-v2-en.pdf Accessed 10 July 2023

Neary DG, Ice GG, Jackson CR (2009) Linkages between forest soils and water quality and quantity. For Ecol Manage 258(10):2269–2281. https://doi.org/10.1016/j.foreco.2009.05.027

Noland M (2004) Famine and Reform in North Korea. Asian Economic Papers 3(2):1–40

Noland M (2022) North Korea as a complex humanitarian emergency: assessing food insecurity. Asia Global Econ 2(3):100049. https://doi.org/10.1016/j.aglobe.2022.100049

Parida BR, Kumar P (2020) Mapping and dynamic analysis of mangrove forest during 2009–2019 using Landsat–5 and sentinel–2 satellite data along Odisha Coast. Trop Ecol 61:538–549. https://doi.org/10.1007/s42965-020-00112-7

Park MS, Lee H (2014) Forest policy and law for sustainability within the Korean Peninsula. Sustainability 6(8):5162–5186. https://doi.org/10.3390/su6085162

Pendrill F, Gardner TA, Meyfroidt P, Persson UM, Adams J, et al. (2022) Disentangling the numbers behind agriculture-driven tropical deforestation. Science 377(6611):eabm9267

Peterson DA, Hyer EJ, Han S, Crawford JH, Park RJ et al (2019) Meteorology influencing springtime air quality, pollution transport, and visibility in Korea. Elementa 7:57. https://doi.org/10.1525/elementa.395

Piao Y, Jeong S, Park S, Lee D (2021) Analysis of land use and land cover change using time-series data and random forest in North Korea. Remote Sensing 13(17):3501. https://doi.org/10.3390/rs13173501

Phiri D, Morgenroth J (2017) Developments in Landsat land cover classification methods: a review. Remote Sensing 9(9):967. https://doi.org/10.3390/rs9090967

Qu S, Ryu Y, Liu J, Wang J (2023) Greening rate in North Korea doubles South Korea. Environ Res Lett 18:084020. https://doi.org/10.1088/1748-9326/acdaad

Rao Y, Zhu X, Chen J, Wang J (2015) An improved method for producing high spatial-resolution NDVI time series datasets with multi-temporal MODIS NDVI data and Landsat TM/ETM+ images. Remote Sensing 7(6):7865–7891. https://doi.org/10.3390/rs70607865

Rokni K, Musa TA (2019) Normalized difference vegetation change index: a technique for detecting vegetation changes using Landsat imagery. CATENA 178:59–63. https://doi.org/10.1016/j.catena.2019.03.007

Sahoo S, Puyravaud J, Davider P (2013) Local knowledge suggests significant wildlife decline and forest loss in insurgent affected Similipal Tiger Reserve India. Tropic Conserv Sci 6(2):230–240. https://doi.org/10.1177/194008291300600205

Seol A, Lee B, Chung J (2011) Analysis of the seasonal characteristics of forest fires in South Korea using the multivariate analysis approach. J for Res 17:45–50

Shim D (2012) Seeing from above: the geopolitics of satellite vision and North Korea. GIGA Working Papers 201, GIGA German Institute for Global and Area Studies

Shimizu K, Ota T, Mizoue N (2020) Accuracy assessments of local and global forest change data to estimate annual disturbances in temperate forests. Remote Sensing 12(15):2438. https://doi.org/10.3390/rs12152438

Soga M, Gaston KJ (2018) Shifting baseline syndrome: causes, consequences, and implications. Front Ecol Environ 16(4):222–230

Song J, Habib B (2020) The hidden variable: environmental migration from North Korea. Pac Rev 34(6):973–994. https://doi.org/10.1080/09512748.2020.1778061

Song J, Denney S (2019) Studying North Korea through North Korean migrants: lessons from the field. Critical Asian Studies 51(3):451–466. https://doi.org/10.1080/14672715.2019.1611462

Takasaki Y, Coomes OT, Abizaid C, Kalacska M (2022) Landscape-scale concordance between local ecological knowledge for tropical wild species and remote sensing of land cover. Sustain Sci 119(40):e2116446119. https://doi.org/10.1073/pnas.2116446119

Weber EU, Stern PC (2011) Public understanding of climate change in the United States. Am Psychol 66(4):315–328. https://doi.org/10.1037/a0023253

Xiang-Ao X, Hong-Bin C, Pu-Cai W, Xue-Mei Z, Jin-Huan Q et al (2005) Aerosol properties and their spatial and temporal variations over North China in spring 2001. Tellus b: Chem Phys Meteorol 57(1):28–39. https://doi.org/10.3402/tellusb.v57i1.16770

Yeom J-M, Han K-S, Lee C-S, Park Y-Y, Kim Y-S (2008) A detection of vegetation variation over North Korea using SPOT/VEGETATION NDVI. J Korean Assoc Geogr Inform Stud 11(2):28–37

Yu J, Kim K (2015) Spatio-temporal changes and drivers of deforestation and forest degradation in North Korea. J Korea Soc Environ Restor Technol 18:73–83. https://doi.org/10.13087/kosert.2015.18.6.73

Zhe M, Zhang X (2021) Time-lag effects of NDVI responses to climate change in the Yamzhog Yumco Basin South Tibet. Ecol Indic 124:107431. https://doi.org/10.1016/j.ecolind.2021.107431

Zheng K, Ye J, Jin B, Zhang F, Wei J et al (2018) Effects of agriculture, climate, and policy on NDVI change in a semi-arid river basin of the Chinese Loess Plateau. Arid Land Res Manag 33(3):321–338. https://doi.org/10.1080/15324982.2018.1555562

Zhong X, Lie J, Wang J, Zhang J, Liu L et al (2022) Linear and nonlinear characteristics of long-term NDVI using trend analysis: a case study of Lancang-Mekong River Basin. Remote Sensing 14(24):6271. https://doi.org/10.3390/rs14246271

Zhu Z, Wang S, Woodcock CE (2015) Improvement and expansion of the Fmask algorithm: cloud, cloud shadow, and snow detection for Landsats 4–7, 8, and Sentinel 2 images. Remote Sens Environ 159:269–277. https://doi.org/10.1016/j.rse.2014.12.014

Zoellner LA, Foa EB, Brigidi BD, Przeworski A (2000) Are trauma victims susceptible to “false memories”? J Abnorm Psychol 109(3):517–524. https://doi.org/10.1037/0021-843X.109.3.517