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ORIGINAL PAPER

Using multi-source remote sensing data to classify larch plantations in Northeast China and support the development of multi-purpose silviculture

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Abstract Due to increasing timber demands, large areas of secondary forests have been converted to larch plantations (LPs) in Northeast China because the secondary forests could not produce timber as much as LPs. However, there are a series of ecological problems such as lower soil fertility, reduced water-holding capacity and acidification of surface runoff water occurring in LPs because of the single-species composition of LPs. Therefore, a guidance on how to transform LPs into larch-broadleaf mixed forests (LBMFs) at a large spatial scale is needed for local foresters. First, Landsat time series data set and SPOT-5 images were combined to map the spatial–temporal distribution of LPs in Northeast China. Then, the topographical characteristics of LPs in 2010s were determined. Furthermore, three sub-regions of LPs were divided closely linking to their ecosystem services and forest management aims. Finally, detailed information on how to transform the LPs into LBMFs was given according to the three sub-regions. The results showed that the area of LPs increased during 1980s and 2010s, and reached 2.61 million ha in 2010s. Of which, 0.72 million ha (27.6%) and 1.89 million ha (72.4%) LPs distributed in slopes less than 5° and greater than 5°, respectively. Of the LPs (72.4%) in slopes greater than 5°, 48.7 and 23.7% located in downslope (LPs locating at the down slope of adjacent secondary forests in the same aspect) and upslope (LPs locating at the up slope of adjacent secondary forests in the same aspect), respectively; 0.10 million ha (3.8%) located in slopes greater than 25°. The LPs were divided into Sub-Regions-I, II, III according to slopes. For Sub-region-I (top role is to produce timber), self-fertilizing shrub species can be introduced after clean cutting for young-aged LPs, and release thinning can be applied for middle-aged LPs, fast growth thinning for near-matured LPs, and clear cutting for matured LPs. For Sub-Region-II (the priority is to provide water conservation combined with timber production), the LPs should be induced into LBMFs. The LPs located the downslope positions in Sub-Region-II can be transformed to LBMFs by natural regeneration of broadleaved tree species after thinning because of enough seed sources of broadleaved tree species from the secondary forests locating the upslope positions. The LPs located the upslope positions or the region where seed sources of broadleaved tree species are unavailable in Sub-Region-II must be induced to LBMFs by artificial regeneration. For Sub-Region-III (the preference is only for water conservation because the slope is greater than 25°), the LPs should be particularly protected from intensive disturbances, and induced into LBMFs by natural regeneration.

Keywords Larch plantation · Natural larch forest · Visual interpretation · Slope position · Ecosystem services

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Introduction

Forests in Northeast China (including Liaoning, Jilin, Heilongjiang Provinces, and eastern Inner Mongolia Autonomous Region) occupy more than one third of the total forest area in China, with an area of 8.2×10^7 ha (Ministry of Forestry of China 2014). They provide important ecosystem services including protection of agriculture, industry, food and water security. Historically, because of frequently destructive disturbances caused by human beings and natural events (e.g. storms, fire, and insect attacks), more than 70% of the forests have become secondary forests (Chen et al. 2003; Zhu et al. 2007). In order to meet the increasing timber demands, large areas of secondary forests have been converted to larch (*Larix* spp.) plantations (LPs) since the 1950s (Yu et al. 2011; Mason and Zhu 2014) because of its rapid growth, resistance to cold and high wood quality (Zhu et al. 2008). At present, the planted area of LPs amounts to more than 3.1 million ha in China, and more than 80% of LPs are distributed in Northeast China (Ministry of Forestry of China 2014).

LPs of Northeast China provide a large volume of timber over the past few decades. With the development of economy and the growing environment threat (e.g. the Yangtze River flood in South China and the Nenjiang River flood in North China occurred together in 1998), the forest management goals have been shifted in China. Timber harvesting is no longer the only goal of plantation management, and other forest ecosystem services (mainly including water and soil conservation, carbon sequestration, climate regulation, nutrient cycling, and maintenance of biodiversity) are increasingly important. However, compared with the adjacent secondary forests, LPs are experiencing some serious problems, including acidification of surface runoff (Xi et al. 2009; Xu et al. 2013), lower soil fertility (Yang et al. 2012), and decline of water-holding capacity (Dong et al. 2007). Previous researches have confirmed that the problems mentioned above are mainly resulted from the single-species composition of LPs (Zhu et al. 2008, 2010; Mason and Zhu 2014). For example, in a paired 26-year-old pure larch plantation and the larch-ash (*Fraxinus mandshurica*) mixed plantation, the biomass of mixed plantation increased by more than 12%, soil micro-biomass increased by 17–28%, and soil enzyme activity increased by 10–31% (Yang et al. 2012; Gu et al. 2014). Therefore, one of the silvicultural aims is trying to induce the LPs into larch-broadleaf mixed forests (LBMFs). To get to this target, understanding how to transform the LPs into LBMFs is a key issue (Yan et al. 2013).

Many studies on transforming the LPs into LBMFs have been conducted at stand levels. For example, we tested the effects of thinning on the regeneration of broadleaf tree species in LPs, and found that 50% thinning intensity could improve the seed and seedling regeneration (Zhu et al. 2008, 2010; Gang et al. 2015). We also found that the distribution patterns of LPs within the secondary forests affected the regeneration of broadleaf tree species, e.g. when the LPs locate in downslope positions and the secondary forests distribute in upslope positions, the broadleaf tree species can regenerate in LPs successfully because of the enough seed sources (Yan et al. 2013). Experiment was set up to test the effects of the rodents on regeneration of large-seed species, and the result indicated that *Juglans mandshurica* could not achieve natural regeneration without the seed dispersal by the rodents (Wang et al. 2017). These previous studies focused on a stand level/scale (Zhu et al. 2008, 2010; Yan et al. 2013; Gang et al. 2015). However, LPs distribute a wide range of sites and environments in Northeast China. Some regional strategies for multi-purpose silviculture are urgently needed to guide the local foresters or to provide references to Forestry Administration Agencies. However, little is known about whether and how the use of multi-purpose silviculture at the forest stand scale can be used to guide the development of forestry strategies at a regional scale. Accurately interpreting the spatial–temporal distribution of LPs and the regionally partitioning LPs are two basic approaches to achieve this goal.

Traditional field survey can obtain the detailed information of forest age and topographical characteristics at a stand scale. But this method cannot provide the overall spatial information about the distribution of forest characteristics at a regional scale. The combination with remote sensing and field survey is effective for mapping the spatial distribution of forests, because it provides high levels of detail in the large coverage (Bijalwan et al. 2010; Gao et al. 2013, 2015; Li et al. 2013; Folega et al. 2014). Although the spatial distribution of LPs can be interpreted through remote sensing images, there is yet a problem in identifying the LPs from natural larch forests due to the similar spectral characteristics of LPs and natural larch forests. Forest age is another indispensable parameter for multi-purpose silviculture of LPs. Generally, forest age can be obtained at regional scale by using vegetation indices (VI) of remote sensing images (Jensen et al. 1999) because the changes in internal structure and leaf chlorophyll can affect tree's spectral response pattern during its phenological cycle (Grant 1987). This VI method is applicable for a spatial homogeneous area at a local scale. In various areas of Northeast China, however, the growth rate of LPs is different, leading to a discrepancy between reflection spectrum and vegetation indices of LPs. Another method to obtain the forest age is to use high spatial resolution images (e.g. QuickBird image and SPOT-5 image) in combination with the spectral and texture (Wunderle et al. 2007; Dye et al. 2012). However, the high spatial resolution images and large number of field data required are too expensive to be applied in a large scale region. Therefore, it is necessary to accurately interpret the distribution of LP ages with a new method at a regional scale. Most of the LPs in Northeast China distribute in the mountain regions, which are the rivers' sources (Wang et al. 2008). Thus, besides timber production, water conservation is another most important ecosystem services of LPs. Therefore, the multi-purpose silviculture is defined as balancing the roles of LPs in timber production (productive function) and water conservation (ecological function) in this study. However, the regional partitioning of LPs with multi-purpose silviculture requires site conditions, which can be obtained by combining field survey with a Digital Elevation Model (DEM) and Geographic Information System (GIS) analysis.

The objectives of the present study were (1) to determine the spatial–temporal distribution patterns and topographical characteristics of LPs in Northeast China; (2) to partition the LPs according to the main ecosystem services (productive and ecological functions) of LPs on the basis of the site conditions; and (3) to illustrate the measures for inducing the LPs into larch-broadleaf mixed forests (LBMFs).

Materials and methods

Study area

Northeast China (115°32′–135°05′E, 38°43′–53°33′N) here includes Liaoning, Jilin and Heilongjiang Provinces, and the east of Inner Mongolia Autonomous Region, covering an area of ca. 1.24×10^6 km^2 (Fig. 1). Geographically, Northeast China is characterized by three plains (Sanjiang Plain, Songnen Plain and Liaohe Plain) separated by five major mountain ranges (Changbai Mountains, Zhangguangcai Mountains, Xiaoxing'an Mountains, Daxing'an Mountains and Yan Mountains). The three plains are dominated by farmland, grassland and urban land. The five major mountains are covered by forests, from which many rivers such as Heilongjiang River, Songhua River, Nenjiang River, Mudanjiang River, Liaohe River and Hunhe River originate. The climate in Northeast China is controlled by the monsoon of high latitude East Asia, including cool temperate, temperate and warm temperate zones from north to south; and semi-arid, semi-humid and humid zones from west to east. Annual mean air temperature is from 2.5 to 5.7 °C, and annual precipitation is from 430.4 to 678.7 mm (Wang et al. 2008).

Data collection

Multi-source remote sensing images including Landsat time series (30 m resolution) and SPOT-5 (2.5 m resolution) and field survey data were used to map the spatial–temporal distribution of LPs in the 1980s, 1990s, 2000s and 2010s. In addition, the topographical characteristics of LPs in the 2010s were obtained using topography and GIS technology in Northeast China. Based on the spatial–temporal distribution patterns of LPs and topographical characteristics, the partitioning of LPs were obtained.

Remote sensing data

Landsat time series dataset (Table 1), including Multispectral Scanner (MSS, 80 m resolution), Thematic Mapper (TM, 30 m resolution), Enhanced Thematic Mapper Plus (ETM+, 30 m resolution) and Operational Land Imager (OLI, 30 m resolution) dataset captured in the 1980s (1978–1982), 1990s (1988–1992), 2000s (1998–2002) and 2010s (after 2009) for Northeast China were collected to map the spatial distribution of LPs. If there were no high-quality (i.e. cloudless, good radiometric quality, low contents of aerosols, and high solar elevations angles) images, those from the previous or subsequent years were used instead. Two-seasonal (leaf-on and leaf-off) images were applied to interpret the distribution of LPs. Totally, 696 scenes of Landsat MSS/TM/TM+/OLI images were collected from the Global Land Cover Facility (GLCF) (http://glcf.umd.edu) and the United States Geological Survey (USGS) (http://edc.usgs.gov).

Two SPOT-5 images, which had the K-J numbers 299/258 and 297/265 taken on 30 September 2013 and 27 September 2011, were used in this study to rectify the area of LPs that obtained by Landsat dataset. The two SPOT-5 images consisted of both multi-spectral and panchromatic images. The multi-spectral images have a resolution of 10 m in the near-infrared (780–890 nm), red (610–680 nm) and green (500–590 nm) bands and 20 m in the shortwave infrared (1580–1750 nm) band. The panchromatic image was recorded at a resolution of 2.5 m.

Field data

A large-scale field survey (the route is approximately 1.8×10^4 km) was conducted through Northeast China during the summers (July and August) of 2014 and 2015. 8883 interpretation locations were recorded by GPS (Fig. 1), which were used to set up the interpretation standards and validate the accuracy of the interpretation. The relative positions of LPs and secondary forests were also recorded. A total of 239 sample plots were surveyed. The sample plot had a dimension of 30 m × 30 m in order

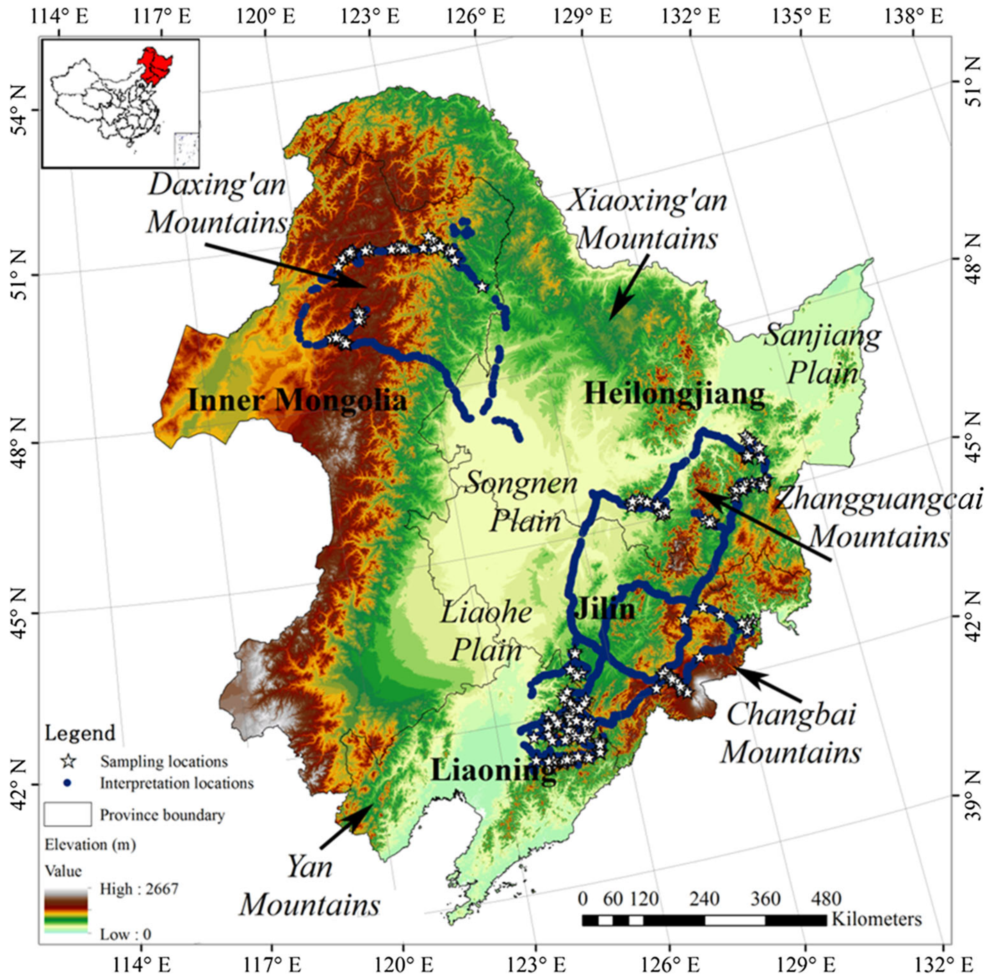

Fig. 1 Geographic location map, topography map and field survey routes in the study area

Table 1 Landsat time series dataset

Periods	Sensors	Leaf-on season	Leaf-off season	Years
1980s	Landsat MSS	87 scenes	87 scenes	1978–1982
1990s	Landsat TM	87 scenes	87 scenes	1988–1992
2000s	Landsat TM/ETM+	87 scenes	87 scenes	1998–2002
2010s	Landsat TM/ETM +/OLI	87 scenes	87 scenes	After 2009

to be consistent with a pixel of TM/ETM+/OLI images. There was at least a 15 m buffer zone surrounding the boundary of a LP plot, i.e. the actual sample plot area was 60 m × 60 m. For each plot, diameter at breast height (DBH) were measured for stems with DBH $\geq$ 4 cm, tree height of 10% stems with different DBH and stocking density were recorded. Stand age was determined using increment borers with a minimum of 3 trees (dominant trees with the average DBH of the stand) cored per sample plot. Then, stand age was adjusted to that in 2010 to correspond temporally to remote sensing data (2010s). The slope and slope position of LP in each sample plot were recorded.

Other data

The Advanced Spaceborne Thermal Emission and Reflection Radiometer Global Digital Elevation Model (DEM) version 2 (ASTER-GDEM2, 30 m resolution) was used to project into Albers Equal Area Conic Projection, with the same parameters as the Landsat dataset using the ENVI 5.0 images processing system. The altitude, slope and slope position were obtained based on the DEM. Besides, China's forest resource inventory data during the period of 2009–2012 were used in this study for providing general distribution area of plantations and natural forests.

Mapping the spatial distribution of LPs

Mapping the spatial distribution of larch forests (both plantations and natural forests)

In order to reduce the error to less than 30 m, geometric correction of the 2000s ETM+ images was performed for each image by approximately 50 uniformly distributed ground control points (GCPs), which were derived from a 1:100,000 topographic maps in Northeast China. MSS images from 1980s, TM images from 1990s and TM/OLI images from 2010s were matched with the 2000s ETM+ images using an image-to-image matching method. Then, atmospheric correction of the images was carried out using the Fast Line-of-Sight Atmospheric Analysis of Spectral Hypercubes (FLAASH) software package in ENVI 5.0 (Gao et al. 2015). Parameter setup was automatically generated on the basis of acquisition time and location information of images and ancillary data (Gong et al. 2013). The false-color band composites were employed, which were composited by 4, 2, 1 (R, G, B) for MSS images, 4, 3, 2 (R, G, B) for TM/ETM+ images, and 5, 4, 3 (R, G, B) for OLI images, respectively (Luo et al. 2003, Zheng et al. 2012). Geometric correction of two SPOT-5 images was also performed by approximately 50 uniformly distributed GCPs with a root mean square error (RMSE) of less than 0.5 pixel per image. All the images (MSS/TM/ETM+/OLI and SPOT-5) were projected in Albers Equal Area Conic Projection, with parameters including first standard parallel of 25.0000°, second standard of 47.0000°, the central meridian of 105.0000°, and the Krasovsky ellipsoid. All image data were pre-processed using the ENVI 5.0 images processing system.

Larch species (*Larix* spp.) are the only deciduous conifers planted in Northeast China. With the unique deciduous phenology of *Larix* spp., the interpretation standard for larch forests (including plantations and natural larch forests) was established (Table 2). At a pixel level, an unsupervised classification (K-mean) was applied for the images in each period of summer to discriminate coniferous forests from broadleaved forests by referring the interpretation standard. Furthermore, the similar method was employed for winter images in each period to exclude evergreen coniferous forests. By overlaying the two results from summer and winter images, the spatial distributions of larch forests (including plantations and natural forests) in the four periods were obtained.

Discriminate larch plantations from natural larch forests

First, the distribution of natural larch forests can be extracted by their natural distribution areas based on China's forest resource inventory data (Ministry of Forestry of China 2014). According to China's forest resource inventory data, plus the field survey data in this study, the natural larch forests only distributed in the mountainous areas of Daxing'an Mountain regions, Xiaoxing'an Mountain regions and Changbai Mountain regions. Second, the texture and boundary shapes are different between LPs and natural larch forests. Most LPs are even-aged pure forests, which have regular shapes and apparent boundaries. The visual texture of LPs is smooth, regular and homogeneous in remote sensing images. In contrast, natural larch forests are more complicated in structure, and do not have clear boundaries. The visual texture of natural larch forests in remote sensing images is coarser than that of LPs. According to the differences of texture and boundary shapes between LPs and natural larch forests in remote sensing images, visual interpretation was employed to discriminate between LPs and natural larch forests in the study regions. With visual interpretation, the spatial distributions of LPs in 2010s were obtained. On the basis of the spatial distributions of LPs in 2010s, the spatial distributions of LP in 2000s, 1990s and 1980s were obtained

Table 2 Interpretation standards for larch plantations (LPs)

Forest type	Canopy density	Height of trees (m)	Imagery feature
Coniferous forest (Larch forests)	> 0.6	> 2	The color was dark red or brown in leaf-on season and was dark yellow in leaf-off season. The tonal was homogeneous and the shape was well-regulated
Coniferous forest (Evergreen forests)	> 0.3	> 2	The color was dark red or brown in leaf-on season and was red in leaf-off season. The tonal was homogeneous and the shape was well-regulated
Broadleaved forest	> 0.3	> 2	The color was red in leaf-on season. The tonal was homogeneous and the shape was always larger than the shape of larch forest
Mixed broadleaf-conifer forest	> 0.3	> 2	The color was dark red but more bright than the color of coniferous forest in leaf-on season. The tonal was inhomogeneous and the shape was irregular
Shrubbery	> 0.4	> 2	The color was bright red in leaf-on season, and the tonal was homogeneous. The shape was irregular

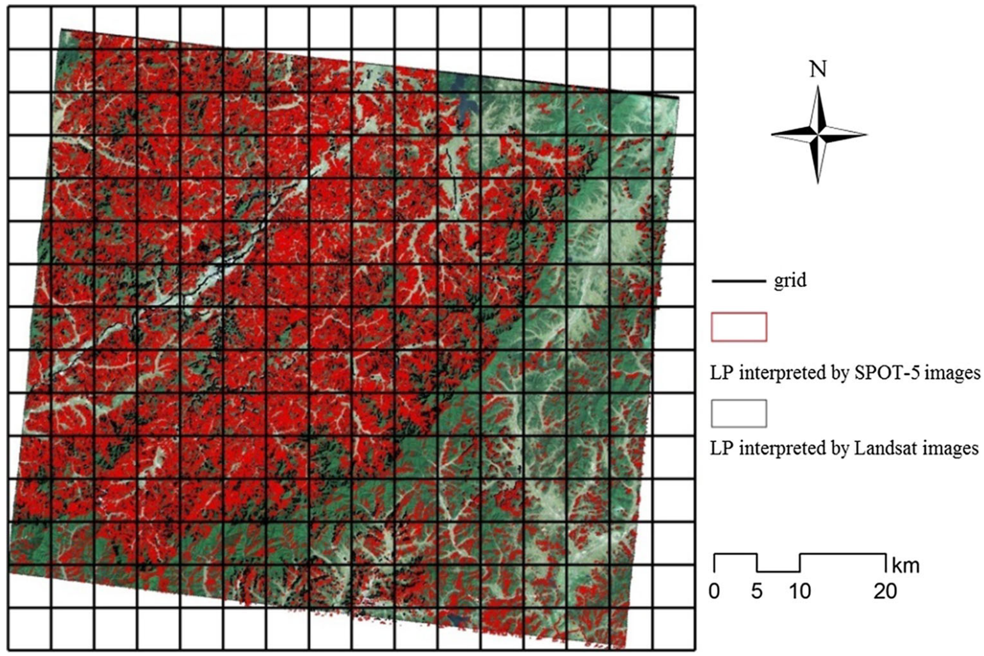

Fig. 2 Plots with a size of 5 km × 5 km. LP = Larch plantations

with a combination of unsupervised classification and visual interpretation. Third, the discriminated results for LPs from natural larch forests was checked through visual inspection. The interpretation locations (from ground survey in 2014 and 2015) were used to check the discriminated results.

Accuracy of the spatial distribution of LPs

In order to validate the mapping result of larch forests (including plantations and natural forests) in 2010s, all interpretation locations (8883) were used to test the validation of larch forests with Eq. (1).

$$Pre = 1 - \frac{\sum X_{l,o} + \sum Y_{l,o}}{n} \times 100\% = (92.5\%) \quad (1)$$

where *Pre* is the interpretation accuracy (%) of the spatial distribution of LP areas in 2010s; n is the sample number of interpretation locations (8883); l (2822) and o (6061) stand for LP and other land use types; $X_{l,o}$ is the sample number that misclassified LP as other land use types (131); and $Y_{o,l}$ is the sample number that misclassified other land use type as LP (537).

In general, the higher spatial resolution of remote sensing images is, the higher interpretation accuracy we can obtain. In order to improve the interpretation accuracy obtained by Landsat images, two SPOT-5 images were used to adjust the LP areas that interpreted from Landsat images because SPOT-5 image has a high spatial resolution of 2.5 m. First, the two SPOT-5 images were overlapped on the same period of Landsat images. Then, we interpreted the LP areas from SPOT-5 images and Landsat images, respectively. Third, the plots with a size of 5 km × 5 km (541 plots) were selected from the overlapped images (Fig. 2). Finally, the regression relationship between LP areas interpreted by SPOT-5 images and by Landsat images was established as in Eq. (2).

$$Y_{SPOT-5} = 10.898X_{Landsat} \left(R^2 = 0.7838,\ p < 0.05\right) \quad (2)$$

where $Y_{SPOT\text{-}5}$ is the LP area interpreted by SPOT-5 images in each grid; $X_{Landsat}$ is the area of LP interpreted by Landsat images in each grid.

With Eq. (2), the Landsat-based mapping results can be calibrated. So, the accuracy interpreted LP areas from Landsat images was improved from ± 3.24 to ± 0.04 ha (Zheng et al. 2013).

Estimating the age-classes of LPs

By overlaying the four periods of LPs' spatial distributions, the age-classes of LPs in 2010s (the interval was 10 years) can be obtained. Nevertheless, compared with field surveyed data and images, it was found that the LP could not be discriminated in the images when the LP was too young (less than 10 years old), because they had similar spectrum characteristics to shrubs. Thus, in this study, the LPs are older than 10 years old, i.e. the LPs less than 10 years old could not be discriminated in the remote sensing images.

The steps for identifying LP ages were as follows. If a LP patch did not appear in the Landsat ETM+ images in 2000s whereas it appeared in the Landsat TM/ETM+/OLI in 2010s, the LP patch was supposed to be planted between

Table 3 Method of mapping spatial distribution of larch plantations (LPs) age-classes

2010	2000	1990	1980	Age (years)	Age classes
Yes	No	–	–	10–20	Young LP
Yes	Yes	No	–	20–30	Middle-aged LP
Yes	Yes	Yes	No	30–40	Near-matured LP
Yes	Yes	Yes	Yes	> 40	Mature LP

2010/2000/1990/1980 means the map of spatial distribution of LPs in 2010/2000/1990/1980. Yes/no means whether there was a LP patch in the map

1990s and 2000s; thus, the age of these LPs was 10–20 years (young LP). If a LP patch did not appear in the Landsat TM images in 1990s whereas it appeared in the Landsat TM/ETM+/OLI images in 2000s and 2010s, the LP patch was supposed to be planted between 1980s and 1990s; thus, the age of these LPs was 20–30 years (middle-aged LP). If a LP patch did not appear in the Landsat MSS images in 1980 whereas it appeared in the Landsat TM/ETM+/OLI images in 1990s, 2000s, and 2010s, the LP patch was supposed to be planted between 1970 and 1980; thus, the age of these LPs was 30–40 years (near-matured LP). If a LP patch appeared in the Landsat MSS/TM/ETM+/OLI images in 1980s, 1990s, 2000s and 2010s, the LP patch was supposed to be planted before 1970; thus, the age of these LPs was more than 40 years (mature LP) (Table 3). According to the identification steps (Table 3), the spatial distribution of the LPs ages in 2010s was acquired using ArcGIS software (Zheng et al. 2016).

In order to validate the interpretation accuracy of the spatial distribution of LPs' age classes in 2010s, a number of 239 sample plots age data were used with Eq. (3).

$$Pre = 1 - \frac{\sum X_{a,p}}{n} \times 100\% = (87.2\%) \tag{3}$$

where Pre is the interpretation accuracy (%) of the spatial distribution of LP age classes in 2010s; n is the total number of samples (239) for validating the interpretation accuracy; $X_{a,p}$ is the LP that predictive age class different from the actual age class.

Site conditions of LPs

Altitude, slope, aspect and slope position are basic parameters of topographical characteristics for a given forest stand, which are closely linking to site conditions (Chang and Tsai 1991). Altitude was obtained from dataset of DEM. Compared with altitude, it was not directly available for slope, aspect and slope position. Therefore, the slope (S) and aspect (A) of the study area (the whole Northeast China) were calculated by using ArcGIS software with Eqs. (4) and (5) (Zhou and Liu 2004).

$$S = \arctan\sqrt{{f_x}^2 + {f_y}^2} \tag{4}$$

$$A = 270^\circ + \arctan\left(\frac{f_y}{f_x}\right) - 90^\circ\frac{f_x}{|f_x|} \tag{5}$$

where f_x and f_y were the gradients at N–S and W–E directions, respectively.

We obtained the information of slope position mapping using the ridge-lines of mountains or hills. A ridge-line refers to a curve including a set of maximum points which are in the same direction (Maio and Maltoni 1998). Then, DEM data was used to obtain the ridge-lines of mountains in Northeast China. The slope position information can be determined by combining the spatial distribution of LPs, i.e. by overlaying the ridge-lines and the spatial distribution of LPs, LP patches were divided into two types. One type was intersected with the ridge-lines, which is defined as upslope position LPs. The other type was not intersected with the ridge-lines, which is defined as downslope, which is defined as downslope position LPs.

Results

The spatial–temporal distribution of LPs

The spatial distribution of LPs (Fig. 3) in Northeast China in the 2010s was obtained by interpreting the Landsat images and calibrated by SPOT-5 images. The total area of LPs was 2.61 million ha (adjusted by SPOT-5) in Northeast China in the 2010s. After verification, the interpretation accuracy of LP distribution area in the 2010s was 86.4%. The result indicated that most LPs are found in mountainous areas, including Changbai Mountains, Zhangguangcai Mountains, Daxing'an Mountains and Xiaoxing'an Mountains. Moreover, some areas of LPs are also distributed in the Yan Mountains (Fig. 1). In plain areas, most LPs are found in Sanjiang Plain, and almost no LPs occur in Songnen Plain and Liaohe Plain (Fig. 1). The results of the four periods of spatial distribution of LPs indicated that the area of LPs in Northeast China showed a strong growth trend from 1980s to 2010s, with area of 2.16, 2.22, 2.36 and 2.61 million ha in the 1980s, 1990s, 2000s and 2010s, respectively (an annual increasing rate was 0.6%).

The LPs age-classes (Fig. 4) in the 2010s were obtained by overlaying the four periods of spatial distribution of LPs, and the accuracy was 87.2% validated by 239 field-based samples. The results showed that the proportions of young LPs, middle-aged LPs, near-matured LPs and

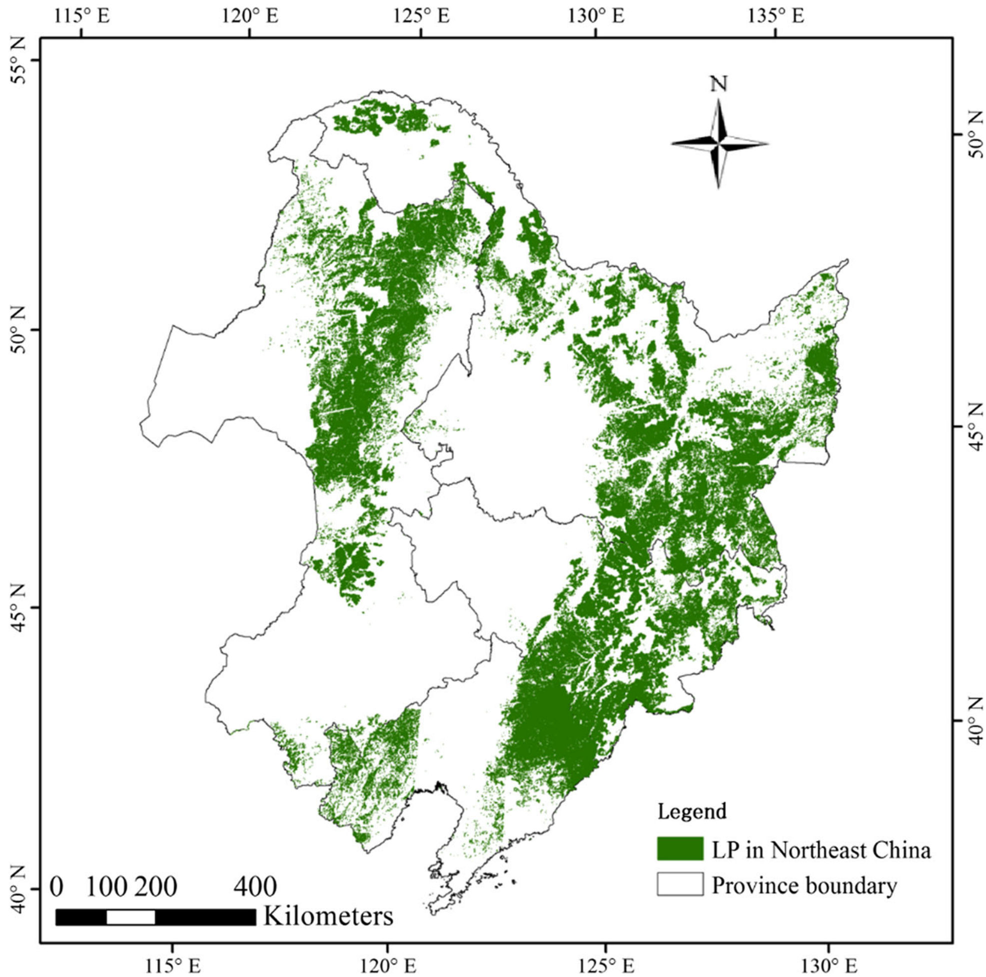

Fig. 3 Spatial distributions of larch plantations (LPs) in Northeast China. In order to show obviously in the map, each LP patch was added a border

mature LPs, were 49.3, 28.4, 14.3 and 8.0%, respectively. Young LPs and middle-aged LPs are the main part of LPs, accounting for 77.7% of the total area of LPs, which means that in the next few decades, LPs will be in a rapid growth period.

The LPs on different site conditions

The average altitude of LPs is 504 m in Northeast China. The average altitude of LPs is more than 800 m in Daxing'an Mountains regions, about 360 m in Xiaoxing'an Mountains and Sanjang Plain regions, about 520 m in Changbai Mountain regions, and about 460 m in Yan Mountain regions.

The area of LPs distributed in slope less than 5° was 0.72 million ha, occupying approximate 27.6% of the total area of LPs in Northeast China, mainly distributed in Xiaoxing'an Mountain and Sanjiang Palin regions. The area of LPs distributed in slope from 5° to 25° was 1.79 million ha, occupying approximate 68.6% of the total area. Other LPs were distributed on a slope of more than 25°, mainly distributed in east of Liaoning province and Yan Mountain regions.

About 48.7% of the total area of LPs was distributed on a downslope position, and about 23.7% distributed in an upslope position, and the rest of LPs was located on flat ground (slope less than 5°). For the LPs distributing on slopes, more than 48.7% distributed on south/north/west/east slopes. There were 42.0% of the total area of LPs distributed in northwest, west and southwest aspect, and about 7.2, 6.5, 6.5, 7.2% of the total area of LPs distributed in south, southeast, east and northeast aspect, respectively, and only 3% of the total area of LP distributed in north aspect.

By overlaying the maps of DEM, slope, aspect and slope position and the map of the spatial–temporal distribution of LPs in the 2010s, we obtained the map of LPs locating on different site conditions (Fig. 5), which can be used for planning the management of LPs.

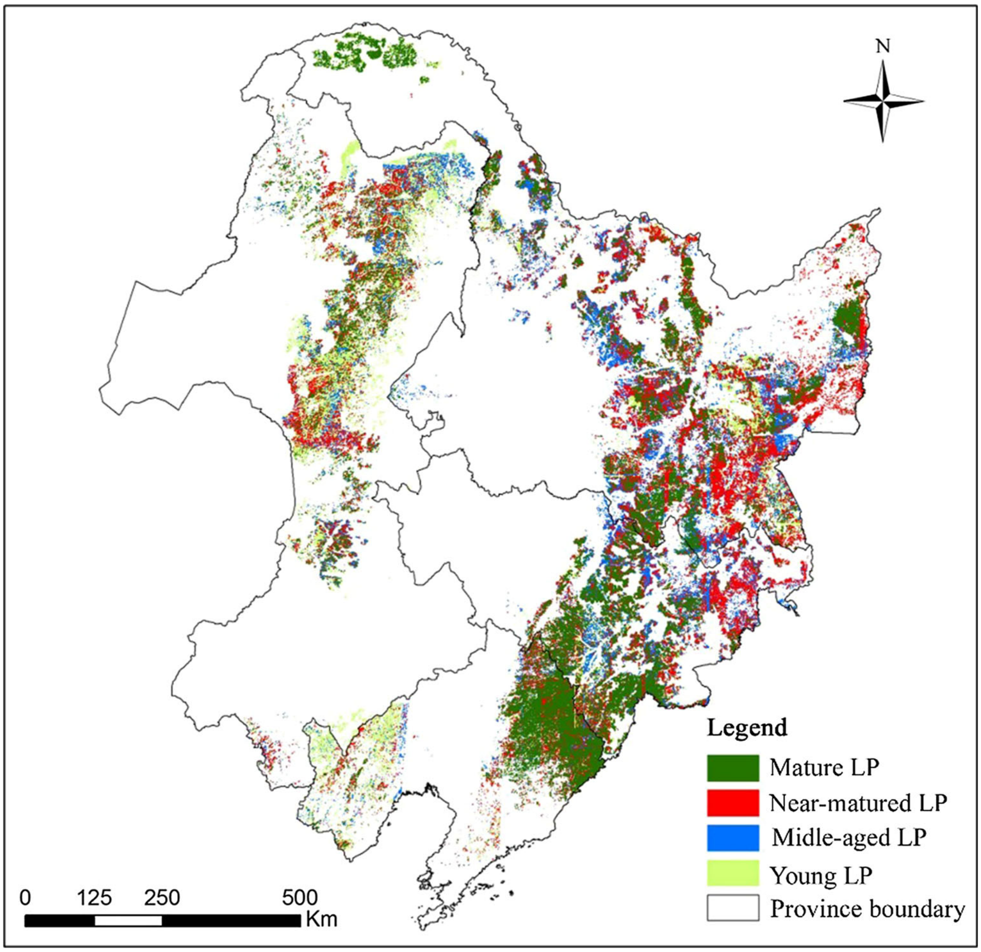

Fig. 4 Age-classes of larch plantations (LPs) in Northeast China in 2010. Young LPs: LPs with the ages less than 20 years. Middle-aged LPs: LPs with the ages from 20 to 30 years. Near-matured LPs: LPs with the ages from 30 to 40 years. Mature LPs: LPs with the ages more than 40 years

Discussion

The spatial–temporal distribution of larch plantations (LPs) is the key to manage the LPs, particularly, for the transforming LPs into larch-broadleaf mixed forests (LBMFs) at a large spatial scale. Therefore, the interpretation accuracy of current LPs distribution patterns is important. In this study, man–machine interactional interpretation was used to determine the spatial distribution of LPs. The interpretation accuracy of larch forest validation and LPs distribution area in the 2010s were 92.5 and 86.4%, respectively. The accuracy of LPs age-classes was 87.2%. These results indicated that the man–machine interactional interpretation and change detection were effective to map LPs and to evaluate the age of LPs. The LPs and natural larch forests were discriminated by visual interpretation successfully. Due to the experts' integrated geo-scientific knowledge involved in the interpret process, this method has a higher mapping accuracy (Zhuang et al. 1999; Zheng et al. 2012). Using SPOT-5 images to calibrate the LP areas obtained from Landsat images improve the accuracy of LPs' area greatly, the same as Zheng et al. (2013).

Both the total LP areas and age structure obtained in this study were very close to those of China's forest resource inventory (Table 4, Fig. 6) (Ministry of Forestry of China 2014), which further indicated that the results of distribution patterns of LPs in our study were reliable.

However, there were some differences when comparing the LP areas and age structure on province level (4 provinces included in Northeast China). The LP areas in Jilin Province and Inner Mongolia Autonomous Region obtained in this study were close to those in China's forest resource inventory, with differences of 1.9 and 3.6%, respectively (Table 4). While the LPs area in Liaoning and Heilongjiang Provinces obtained in this study were different from those in China's forest resource inventory, with differences of 12.5 and 6.6%, respectively (Table 4). The same as the LP areas, the age structures in Jilin Province and Heilongjiang Province obtained in this study were close to those of China's forest resource inventory; but were different from those in Liaoning Province and Inner Mongolia Autonomous Region, especially for the young LPs and middle-aged LPs (Fig. 6). These differences may be mainly caused by different statistical methods. In

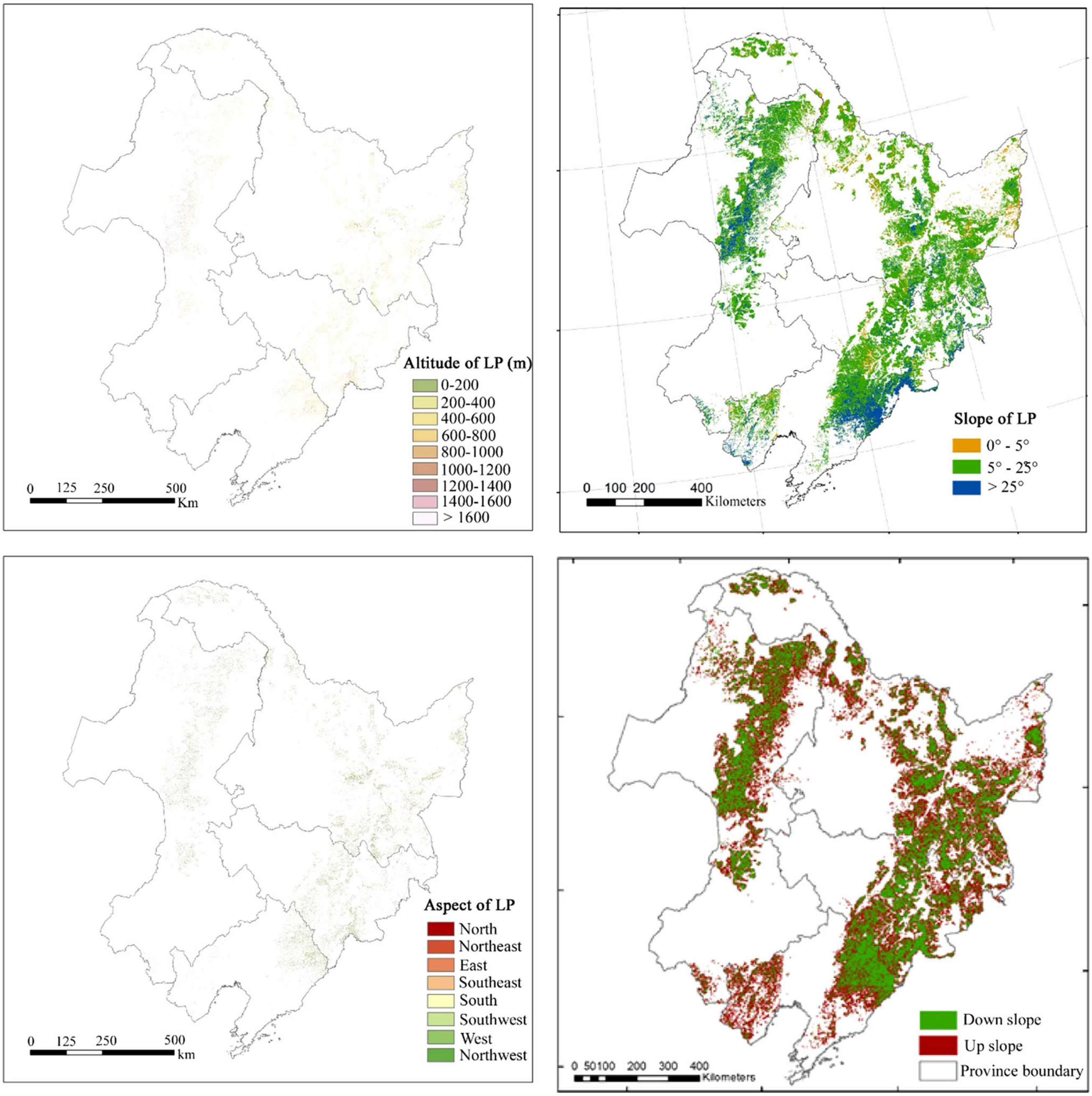

Fig. 5 The slope (**a**) and slope position (**b**) of larch plantations

China's forest resource inventory, the method of "Continuous Forest Inventory" was employed, which was based on probability and statistics theory; i.e. the fixed sample plots were set up at the first sampling time, and continuous multi-phase inventories at the scale of forest stand were carried out at subsequent times (Ministry of Forestry of China 2014). First of all, the method of China's forest resource inventory can hardly obtain comprehensive spatial distribution information of the forest characteristics. The underestimation of LP area may be caused by LPs' fragmentation in Liaoning Province. The LPs with small areas were ignored according to the mapping requirement. On the contrary, the overestimation occurred in Heilongjiang Province because of the wide distribution of natural larch forests in Xiaoxing'an Mountain and Daxing'an Mountains. The misclassification came from the identification of LPs and natural larch forests, i.e. some natural larch forests were misclassified as LPs. Altogether, the higher accuracy was reached in this study, including both area and age of LPs with detailed spatial distribution

Table 4 The larch plantations' (LPs') area of this study and China's forest resource inventory

Provinces	A: the area of LP in this study (million ha)	B: the area of LP in China's forest resource inventory (million ha)	Differences between A and B (A–B) (million ha)
Liaoning	0.357	0.408	− 0.051
Jilin	0.563	0.574	− 0.011
Heilongjiang	1.146	1.075	0.071
Eastern Inner Mongolia	0.543	0.560	− 0.017
Northeast China	2.609	2.617	− 0.008

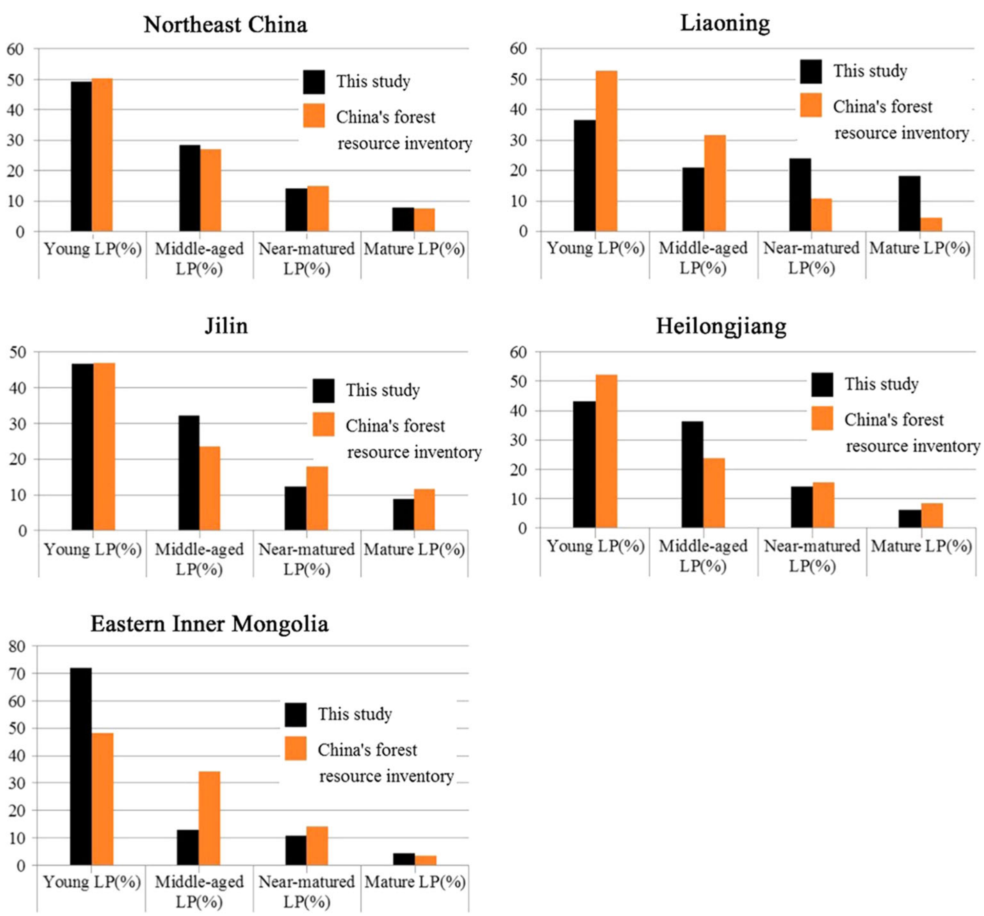

Fig. 6 Comparisons of age-classes of larch plantations (LPs) between this study and China's forest resource inventory

patterns. The site conditions of LPs were also presented with a resolution of 30 m at a large scale, which is useful in planning the management of LPs in Northeast China.

Although encouraging interpretation results were obtained in this study, the uncertainties still remained. First, the remote sensing data source was not to meet the ideal conditions that the spatial distribution of LPs should be interpreted using images for the same period in the whole area of Northeast China. However, not each image covering the study area was cloudless in the same period. Thus the images of the adjacent years were used. These images were different in satellite incidence angles, atmospheric conditions and phenological characteristics, which would cause the phenomenon of either 'the same object with different spectra' or 'different objects with the same spectra'. Consequently, the same object might be classified as the other types, and different objects might be classified as the same one (Tian et al. 2012). The possibility of this error primarily contributed the misclassification.

Second, there were some uncertainties in the processes of interpretation of LPs. Though a lot of efforts were made, the interpretation errors were unavoidable. One of the most important errors during the interpretation is the misclassification between LPs and natural larch forests. For example, LPs with poor management for a long period might be misclassified into natural forests due to the same texture and spectral to natural larch forests, and natural pure larch forests with regular shape and apparent boundaries might be misclassified into LPs because of the same texture and spectral to LPs. The field interpretation locations that recorded in Changbai Mountain and Daxing'an Mountain also supported this analysis.

Third, two uncertainties in the estimation of LP areas existed in this study. One, the monitoring of LP area was estimated using visual interpretation based on Landsat Satellite remote sensing data. Although the mapping accuracy of visual interpretation method was higher than that of image classification using only the algorithms provided by image-processing software for the low spatial and spectral resolutions of Landsat images, the accuracy was 92.5% based on field survey (8883 GPS locations). Two, to acquire more accurate estimations of forested areas, the correction models in different precipitation areas between TM and SPOT5 images were applied. The accuracy of the correction of LP area was 86.4%. Considered the possible errors that generated by the interpretation of SPOT5 image, the accuracy based on field survey was preferably accepted.

The development of multi-purpose silviculture for the LPs

We have confirmed that the single-species composition of LPs is the key to induce the problems such as lower soil fertility, reduced water-holding capacity and acidification of surface runoff water in LPs. Therefore, the development of multi-purpose silviculture for LPs is urgent for the management practice of LPs. Transforming LPs into larch-broadleaf mixed forests (LBMFs) at a large spatial scale is one of the most frequent measures for the development of multi-purpose silviculture. Approximate three-quarter of LPs are distributed in mountain regions, which are the head sources of many rivers. Thus, water conservation is one of the most important ecological functions (Wang et al. 2008). Additionally, considering the importance of slope in site conditions, i.e. in areas with similar precipitation and temperature, slope is the crucial topographic factor influencing the water conservation and timber production of plantations (Wang et al. 1992), we mapped the LPs in Northeast China according to the slopes. According to the Law of the People's Republic of China on Water and Soil Conservation (The Standing Committee of the National People's Congress of the People's Republic of China 2010), water and soil conservation measures should be taken in areas with a slope greater than 5°, and reclamation is forbidden where the slope is greater than 25°. Thus, the areas of LPs were divided into three regions (i.e. Sub-Region-I, II, III) according to slope and management aims (Fig. 7). A relevant and up-to-date management planning of LPs in Northeast China was designed based on the spatial pattern of LP with age-classes.

Sub-Region-I: timber production area

Sub-Region-I was the timber production area with an area of 0.72 million ha, i.e. 27.6% of the LP area in Northeast China, where the slope was less than 5°. In the 2010s, the areas of young LP, middle-aged LP, near-matured LP and mature LP were 3.38×10^5, 2.60×10^5, 8.86×10^4 and 3.34×10^4 ha, respectively. The productivity of LP in this region was relatively high according to field data, as well as its site condition was convenient for management practices. Therefore, an intensive management should be implemented, primarily aiming to produce timber. Nevertheless, previous research has found that soil carbon and nitrogen were significantly lower in the soil of LPs than in the adjacent secondary forests (Yang et al. 2012). To sustain the productivity of LPs in this area, several optimized management countermeasures should be applied.

Relieving nutrient depletion and promoting nutrient accumulation

First, introduction of self-fertilizing species could relieve nutrient depletion, including native leguminous grass and shrub species (e.g. *Vicia cracca*, *Medicago sativa*, *Lespedeza bicolor*, etc.), and non-leguminous tree species with the ability of nitrogen fixation (e.g. *Alnus japonica* and *Alnus fruticosa*) (Wang et al. 2014). Second, proper cutting and thinning managements are useful to improve timber production. One example showed that extending the interval and keeping the branches, leaves and barks in the forest stand when harvesting could reduce the nutrient output of LPs (40.7%) (Yan et al. 2014). Another typical example showed that a thinning pattern (reserving 3 lines of trees and cutting 3 lines of trees) used in young LP, middle-aged LP and near-matured LP could provide significantly higher volume, more abundant biodiversity in shrubs and herbs, and more soil organic carbon, than was found in stands either managed without cutting or by another thinning pattern (reserving 2 lines and cutting 2 lines) (Yin et al. 2013). Third, fertilization [e.g. $(NH_4)_2HPO_4$] in LPs where with high productivity and convenient transportation is also an effective management measure.

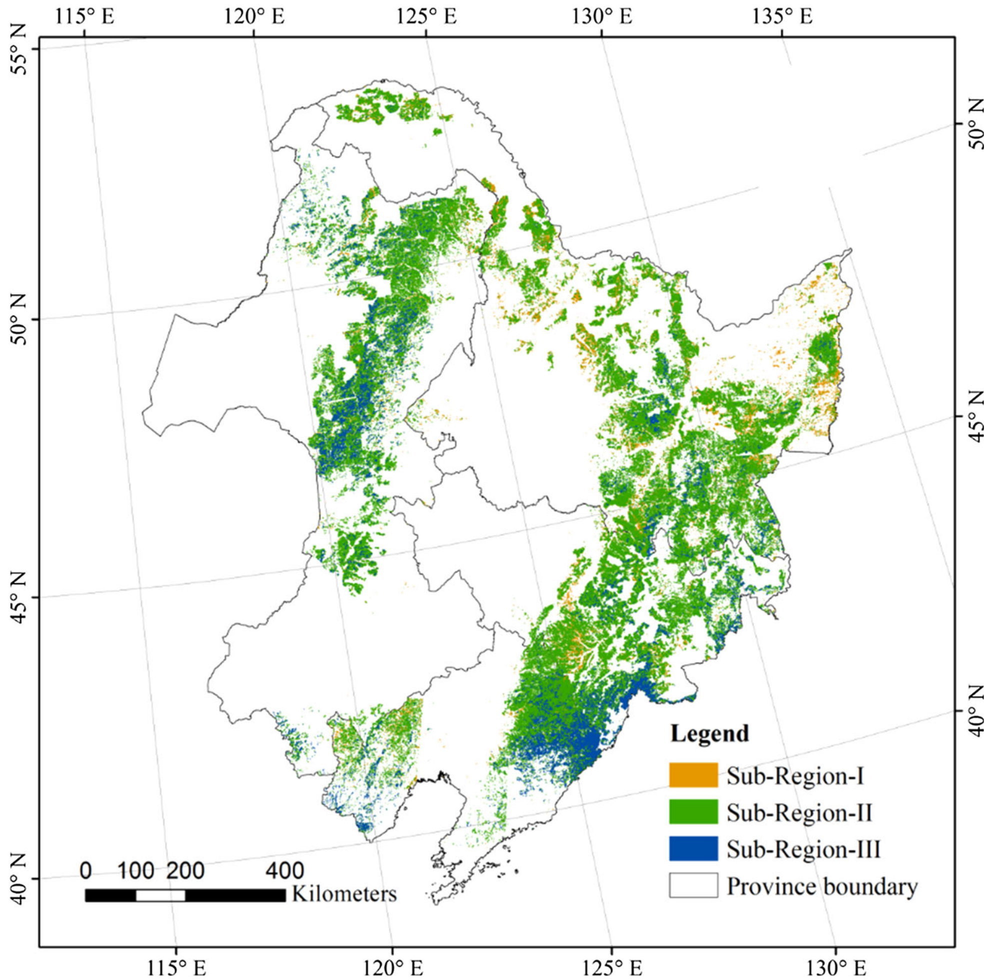

Fig. 7 The major function regionalization of larch plantations. Sub-Region-I: Timber production area. Sub-Region-II: The area maintaining both timber production and water conservation. Sub-Region-II-1: The area for LPs with the seed source of broadleaved tree species. Sub-Region-II-2: The area for LPs without the seed source of broadleaved tree species. Sub-Region-III: Water conservation area

Adjusting the stand and landscape structure

First, different *Larix* species should be planted in mixture to maintain the timber productivity. It has been proved that different *Larix* species can use different forms of nitrogen, and one *Larix* species can greatly benefit from other one if they are mixed planted (Guo et al. 2016). Second, broadleaved tree species or evergreen coniferous tree species (e.g. *Pinus koraensis*) plantation forests should be created surrounding the pure LPs to increase the patch density and landscape diversity, further to improve the system stability of plantation forests (Huang 2015).

Sub-Region-II: area for both timber production and ecological function

Sub-Region-II was the area for maintaining both timber production and ecological functions (particularly water conservation) with an area of 1.79 million ha, i.e. 68.6% of the LP area in Northeast China, where slope ranged from 5° to 25°. In the 2010s, the areas of young LP, middle-aged LP, near-matured LP and mature LP were 8.41×10^5, 5.19×10^5, 2.79×10^5 and 1.51×10^5 ha, respectively. In order to improve the ecological functions, the LPs in this area should be transformed into LBMFs. Whether there are the seed sources of broadleaved tree species is the key to transforming the pure LPs into LBMFs (Zhu et al. 2008, 2010; Yan et al. 2013). The mosaic plantation/secondary forest pattern is the main landscape in Northeast China. The relative position between LPs and the broadleaved secondary forests determines whether there are seed sources of broadleaved tree species in LPs (Yan et al. 2013). According to Yan et al.'s research (Yan et al. 2013), if LPs locating at the down slope of adjacent secondary forests in the same aspect, the seed sources of broadleaved tree species can easily invade into the LPs by wind or gravity effect (Yan et al. 2013, 2016b); if not (e.g. LPs distribute at the upslope position), the seed sources of broadleaved tree species can hardly invade into the LPs. The patch size of LPs is another factor to influence seed source of broadleaved tree species in LPs. If the patch size of LPs is large enough, the seed source of broadleaved tree species could not invade into the inner areas of LPs. Approximate 1.24×10^6 ha LPs distribute at the down slope position, most of which with small size of patch is around secondary forests (Yan et al. 2013). In contrast, the LPs without adjacent secondary forests (including a few LPs distributed at the down slope position, and 5.52×10^5 ha LPs distributed at the up slope position) could be induced to LBMFs by artificial regeneration. Thus, the LPs in Sub-Region-II were divided into two subparts (Sub-Region-II-1, Sub-Region-II-2) according to whether there is an adjacent seed source of broadleaved tree species. The further countermeasures of two subparts were given.

Sub-Region-II-1: area for LPs with seed source of broadleaved tree species

Sub-Region-II-1 was the area for LPs distributed at the down slope position. Broadleaved seeds could invade into LPs in this area, thus after thinning (according to forest age) LPs could be transformed to LBMFs by natural regeneration from seeds of broadleaved tree species (Yan et al. 2013, 2016b).

Sub-Region-II-2: area for LPs without the seed source of broadleaved tree species

Sub-Region-II-2 was the area for LPs located at the upslope position and distributed far away from the seed dispersal distance of broadleaved tree species (e.g. LPs with large patch). No seeds of broadleaved tree species could invade into LPs in this area (Yan et al. 2013), thus the LPs in this area should be transformed to LBMFs by artificial regeneration. For example, in a mountainous area (located in Liaoning Province, China), seed sowing (e.g. *Juglans mandshurica* and *Fraxinus mandshurica*) or seedling planting (intermediate shade tolerant species: *Acer mono* and *Fraxinus mandshurica*, shade intolerant species: *Quercus mongolica* and *Juglans mandshurica*) was feasible after implementing thinning in pure LPs (Gang et al. 2015; Yan et al. 2016a).

Sub-Region-III: ecological function area

Sub-Region-III was ecological function zone with an area of 0.10 million ha, where the slope was greater than 25°. In the 2010s, the areas of young LPs, middle-aged LPs, near-matured LPs and mature LPs were 3.92×10^4, 2.56×10^4, 2.02×10^4 and 1.76×10^4 ha, and the area of upslope position and downslope position were 2.89×10^4 and 7.38×10^4 ha, respectively. Fragile ecological environment, serious soil erosion and poor ability of water conservation are the main ecological problems in this region (Dong et al. 2007; Xi et al. 2009; Yang et al. 2012; Xu et al. 2013). The LPs in this region cannot be used for providing timber. Therefore, the LPs in this region should be protected or induced into LBMFs by natural or artificial regeneration to improve the ecological services. Several details need to be paid attention, e.g. neither clear cutting nor intense thinning should be implemented in this region, only over-matured wood and dead wood can be cut in this region, and human disturbances should be as less as possible.

Conclusions

In this study, man–machine interactional interpretation and change detection together with large-scale field survey were used to discriminate LPs from natural larch forests, and the spatial distribution and the ages of LPs in Northeast China were determined with accuracies that are higher than 86%. The methods were effective at a large regional scale. However, uncertainties still remained due to the low qualities of remote sensing images and high similar texture and spectral between some LPs and natural larch forests. Regionalization of LPs was conducted based on the topography conditions (i.e. slopes) where LPs are located. Consequently, LPs were divided into three Sub-Regions: timber production area (Sub-Region-I, slope less than 5°), production and ecological function area (Sub-Region-II, slope ranging from 5° to 25°) and ecological function area (Sub-Region-III, slope greater than 25°). Aiming to improve or maintain the productivity and ecological functions of LPs, previous studies of multi-purpose silviculture in forest stands were used to guide the development of regional forest management strategies adapted to the different types of LPs. This study may provide some new insights into the tending measures on the LP management practices.

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Compliance with ethical standards

Conflict of interest statement The authors declare that they have no conflict of interest.

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