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An integrated multi-scale approach to restoring a degraded secondary forest ecosystem: A case study in the Changbai Mountains, northeastern China

Lin Qi[a], Fuqiang Zhao[a,*], Jing Sun[b]

[a] CAS Key Laboratory of Forest Ecology and Management, Institute of Applied Ecology, Chinese Academy of Sciences, Shenyang 110016, China

[b] Key Laboratory of Agricultural Remote Sensing (AGRIRS), Ministry of Agriculture/Institute of Agricultural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing 100081, China

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ABSTRACT

Large-scale forest degradation has led to a drastic alteration of forest landscapes worldwide with severe consequences for human well-being and ecosystem services. The extent and spatial composition of forests within a landscape mosaic play a crucial role in processes and functions ranging from stand to landscape scales. A fundamental task for forest landscape restoration is the identification of potential forest types and species for restoration. In this study, we demonstrated how to restore and manage a degraded secondary forest accounting stand condition while simultaneously targeting optimal landscape structure and function. First, we identified 14 native primary forest types that correspond to different topographies in the study area with data from previous studies. Then, we extracted topography data from a digital elevation model and forest inventory. Combining the topography data with the native primary forest types, we identified the forest types for restoration in each forest sub-compartment. However, some sub-compartments had multiple alternative. Based on the landscape structure analyses, the optimal arrangement of forest types for restoration in the landscape was determined. Combined landscape restoration target and potential forest types for restoration of each sub-compartment, the locations and the species for restoration were determined. This study provides a significant baseline for forest restoration and increase restoration effects.

1. Introduction

Natural forest degradation is one of the most serious human disturbance that threatens the environment and ecosystem health (Foley et al., 2007). Currently, only one-fifth of the world's original forest cover remains in relatively undisturbed large tracts (Bryant et al., 1997). Because of forest degradation, environmental problems including soil erosion, loss of biodiversity, and loss of forest products (such as timber) have occurred, and natural hazards are occurring with increased frequency (Wenhua, 2004; Foley et al., 2007; Bullock et al., 2011). Consequently, forest degradation has severely threatened human environments and health, preventing economic progress (Lamb et al., 2005). Governments, scientists, and interested members of the public have realized that there is an urgent need to restore degraded forest ecosystems after decades of intensive logging, building, mining, etc. (Tuten et al., 2015; Charron and Hermanutz, 2016). To ensure that multiple forest functions can be maintained, forest restoration has become the third core component of various forest management strategies. However, effective ecological restoration is a matter of not only prohibiting commercial logging in relict forests or planting trees in barren lands but also following principles that include ecological integrity, long-term sustainability, and operability (Della Sala et al. 2003; Yu et al., 2011a).

Scientists and related governmental sectors implement great efforts to develop theories and techniques to promote degraded forest ecosystem restoration (Cummings and Reid, 2008; Aerts and Honnay, 2011; Zipper et al., 2011). Useful restoration knowledge and practices have been advanced (Margules and Pressey, 2000; Tuten et al., 2015). Recently, most of forest restoration were implemented at stand scale, expecting to provide several forest products or services. Some of these projects promote, or even compel to plant trees. However, due to lack of consideration on varied habitats acquirements and the connection between the restored forest ecosystem and its adjacent ecosystems, some forest ecosystems degraded again in a few years after the restoration. Although some forest restoration seems to be successful, whether these "successful restoration activities" at the site scale are truly beneficial at the landscape level is still unclear. Effective forest restoration actions face both local and land scape constraints. Restored forests may loss

* Corresponding author.
E-mail address: zhaofuqiang@iae.ac.cn (F. Zhao).

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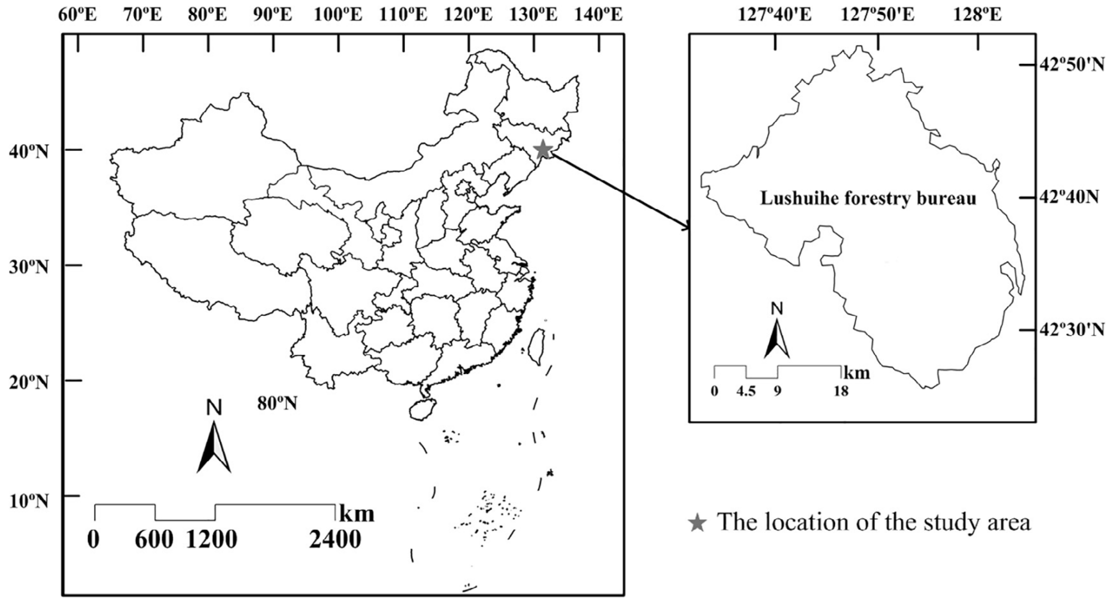


Fig. 1. Study area.

long-term sustainability if the impact of its adjacent ecosystems were not considered. And forests may become more fragmented at the landscape level even though the structure and function of the target ecosystem were well designed at the stand scale (Halme et al., 2013). Many studies demonstrate that both local and landscape factors are equally important in restoration and should be incorporated in restoration projects and programmes. However, extensive research at the stand level is already available, while few studies also consider the integration of the landscape scale.

In contrast to forest restoration at a stand scale, forest landscape restoration (FLR) seeks to regain ecological structure and function, conserve biodiversity, and enhance human well-being at a landscape scale (de Souza Leite et al., 2013). This approach aims to become a management option, integrating efforts to restore multiple functions at a landscape scale (Dudley et al., 2005). Integrating forest restoration actions with desirable objectives at the landscape scale is considered a more robust way to restore both degraded forests and the surrounding degraded landscape (Lamb et al., 2012; Menz et al., 2013). Despite global efforts and ambitious targets for such attempts to gain divers goals at different scales, there are as yet no general and effective solutions for linking planning at a landscape scale and implementation at an ecosystem scale. The main reason is that most plans for forest landscape restoration projects made “top-down” policies or decisions at a larger scale, in which landscape structure, regional ecosystem services are the primary concern. On the other hand, the implement of forest landscape restoration is a “bottom-up” process, which focus on restoring several specific ecosystems to gain target ecosystem structure and function, and the **planned** landscape structure. As a result, there are two challenges in forest restoration at the landscape: 1) How to identify the target structure for ecosystem restoration under a landscape perspective. 2) how to identify the degree of the forest degeneration, and the needed species and its quantity for restoration.

To explore the solution to the mentioned challenges, we conducted a case study in the Changbai Mountains. The Changbai Mountains, located in north-eastern China, contain the largest continuous forest area in contemporary China. The dominant forest type is the broadleaved Korean pine mixed forest. These temperate forests are important timber providers, while they are also well-known for their high species richness and distinctive composition (Dai et al., 2011). Forest harvesting in this region began in the 1950s. Clear-cutting was the primary method for timber harvesting in this region. After nearly a half century of extensive timber harvesting, large areas of natural forest were destroyed, timber resources were in decline, and the structure of the remaining forest had become unsustainable (Yu et al., 2011b). Since the 1980s, local forestry bureaus have started to adopt selective logging to balance timber production and resource protection. Since that time, forests and plantations over the whole area have been classified as either commercial production forests or forests with socio-ecological benefits as an overall forestry policy (Zhao et al., 2011). Although both large-scale planning using a top-down approach and stand scale restoration using a bottom-up approach were implemented, areas of degraded natural forests still increased sharply.

In this study, we try to address this problem by testing a new restoration approach that considers stand conditions based on recent-historic forests in combination with an assessment of several potential forest landscape structure indexes to identify potential restoration plans at multiple scales in the Changbai Mountains.

1) Use the native primary forest as potential communities for restoration at the stand scale based on topography and stand condition.
2) Develop the optimal arrangement of restored forest communities based on the landscape structure indexes.
3) Map the management implementation (the location, management methods, and intensity) for forest workers at the stand scale.

2. Methods

2.1. Study area

The study area is on lands of the Lushuihe Forestry Bureau located on the northern slope of the Changbai Mountains in north-eastern China (42°24′–42°49′N, 127°29′–128°02′E, Fig. 1). The area is characterized by a temperate continental climate, with long, cold, windy winters and short, moist summers. Soil type in the study area is dark brown forest soil, with variation in soil moisture and soil depth. The native natural vegetation is broadleaved Korean pine mixed forest, dominated by Korean pine (*Pinus koraiensis*), Amur linden (*Tilia amurensis*), Manchurian ash (*Fraxinus mandshurica*), and Mongolian oak (*Quercus mongolica*). Secondary forests, which originated from primary forests that have been affected by various logging practices, including naturally regenerated birch forest and larch or fir plantations following clear logging, and high intensity selective logged primary forest, constitute a high percentage of this area.

2.2. Data collection

In this study, data include 1) previous literature on the Changbai Mountains, 2) a digital elevation model (DEM) map, and 3) forest inventory data were used to obtain the information described in the next sections.

2.2.1. Potential primary forest ecosystems to restore in the study area and their habitat requirements

To identify potential primary forests and their habitat requirements, we conducted a literature review. The literature included forestry inventory data, historical documents and research papers on the forests in the Changbai Mountains. All native primary forest should be in late successional stage, historical or currently exist in Changbai Mountains. All native primary forests were identified and recorded, as well as their species composition (dominant species and their total stock percentages) and habitat requirements, including elevation, slope, slope position, aspect, soil type, soil depth and soil moisture.

2.2.1.1. Current forest composition and stand conditions of the study area. The current forest composition of the study area including dominant species and their total stock percentages were derived from state forest inventory data, where the fundamental unit is the sub-compartment. The inventory data also contain stand condition data such as soil depth and moisture, position and aspect of each sub-compartment. The location of all the sub-compartments was presented in a digitized forest sub-compartment map (FSCM).

2.2.1.2. Topography data of the sub-compartments of the study area. The aspect, slope and elevation of each sub-compartment were extracted from digital elevation model (DEM).

2.3. Data analysis

2.3.1. Identify the community for restoration at an ecosystem scale based on stand condition

To identify the potential forests for restoration in each sub-compartment, we assumed that native primary forests require a specific combination of stand condition variables (in some instances, several native primary forests may have similar habitat requirements). By comparing the stand condition of each sub-compartment to native primary forest habitat requirements, we can identify one or more potential forests for restoration in each sub-compartment (Fig. 2). We extracted a set of environmental and topographic variables from the DEM, FSCM and forest inventory data. The variables were 1) elevation (m), 2) slope (degrees), 3) aspect accounting for north-south and east-west gradients, 4) the topographic position and 5) soil depth and soil moisture.

2.3.2. Mapping the optimal arrangement of restored sub-compartments based on the balance of landscape structure indexes

Because one sub-compartment may be suitable to the growth of more than one native primary forests, we simulated all the possible combinations of these potential native primary forests. We used ArcGIS to map all the scenarios and convert the data to raster. Then, we used *fragstats* 3.3 to assess integrality, landscape diversity, contagion, and connectance of all the scenarios by calculating the following indexes:

1) Integrality = 1/splitting index (SPLIT)

$$\text{SPLIT} = \frac{A^2}{\sum_{i=1}^{m}\sum_{j=1}^{n} a_{ij}^2}$$

a_{ij}: Area (m^2) of patch ij.
A: Total landscape area (m^2).

2) Shannon's diversity index (SHDI)

$$\text{SHDI} = -\sum_{i=1}^{m}(P_i \bullet \ln P_i$$

P_i: Proportion of the landscape occupied by patch type (class) i.
3) Contagion (CONTAG)

$$\text{CONTAG} = \left[1 + \frac{\sum_{i=1}^{m}\sum_{k=1}^{m}\left[(P_i)\left(\frac{g_{ij}}{\sum_{k=1}^{m} g_{jk}}\right)\right]\bullet\left[\ln(P_i)\left(\frac{g_{jk}}{\sum_{k=1}^{m} g_{jk}}\right)\right]}{2\ln(m)}\right]$$

P_i: Proportion of the landscape occupied by patch type (class) i.
g_{ik}: Number of adjacencies (joins) between the pixels of patch types (classes) i and k based on the *double-count* method.
4) M: number of patch types (classes) present in the landscape, including the landscape border, and if present connectance index (CONNECT)

$$\text{CONNECT} = \left[\frac{\sum_{j\neq k}^{n} C_{ijk}}{\frac{n_i(n_i-1)}{2}}\right]$$

C_{ijk}: Joining between patch j and k (0 = unjoined, 1 = joined) of the corresponding patch type (i), based on a user-specified threshold distance.
n_i: Number of patches in the landscape of the corresponding patch type (class).
All these indexes were standardized, and in equal importance with each other. Patches in all four indexes > 0.5 were selected as candidates.
5) Identify the severity of the forest degradation and mapping the management implementation indication

To identify severity of the forest ecosystem degradation, we compared the composition of the current forests to that of the target native primary forests selected for the forest sub-compartments. Then, we mapped the species needed and their quantities to restore every forest stand.

3. Results

3.1. Potential native primary forests for restoration

We identified 14 potential native primary forests for restoration. These forests were distributed along an elevation from 400 to 2100 m, including one broadleaved deciduous forest, one coniferous forest and twelve mixed forests. Forest types A, B, C, D require their own unique habitats, while types E, F, G, and H, I, J, K, and L, M, N can partly share their habitats with each other. Forest types D – N were all dominated by Korean pine but with varied percentages and accompanying species. Except for type A, which cannot be used to produce timber, all the identified forests can be used for both conservation and timber production (Table 1).

The results of the literature review also showed that the forest type, species composition of the identified native forests was strongly correlated with geographical condition such as elevation, slope angle, position and aspect. That is because in the study area, forest type and species composition were mostly determined by stand condition, including temperature, soil moisture, soil depth, these factors were further determined by geographic condition. The temperature was mainly determined by election, soil moisture was mainly determined by the position and aspect, and the soil depth was mainly determined by slope angel and position. As a result, the forest type and species composition were determined by the different combination of geographical factors.

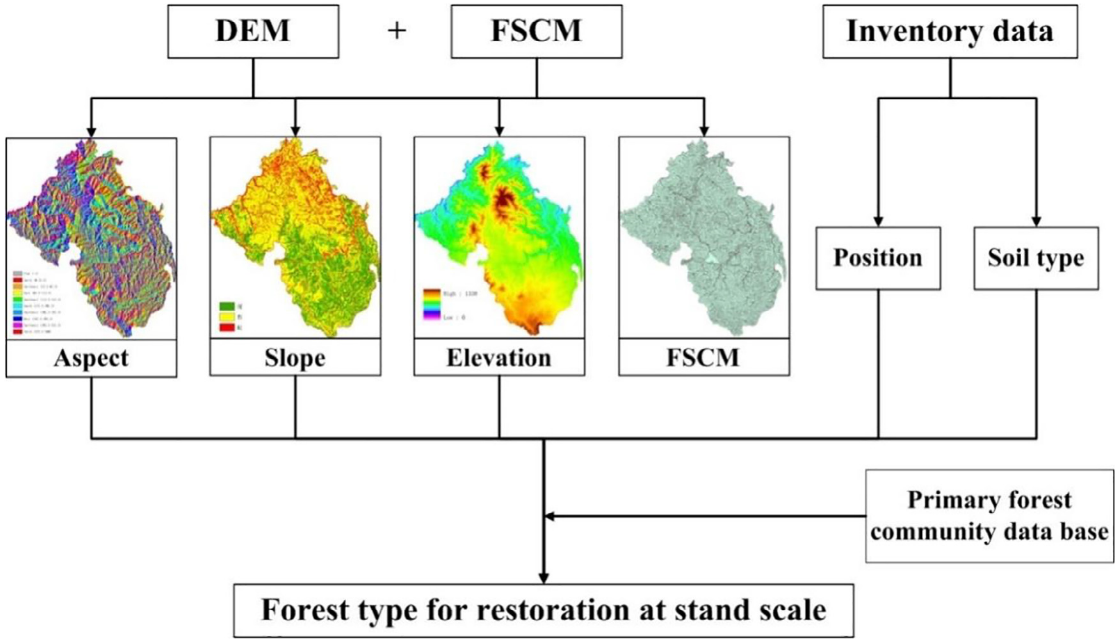


Fig. 2. Framework of identifying the community for restoration at an ecosystem scale based on stand condition. DEM: Digital elevation model; FSCM: Forest sub-compartment map.

3.2. Forests for restoration of each degraded stand

There were 7725 sub-compartments (stands) in the study area, including 7198 forested sub-compartments and 527 for other land-use types. After analysing the stand condition of all the forest compartments, we identified all potential native primary forests to restore each sub-compartment. In the 7198 forested compartments, 1955 sub-compartments, which account for 27.5% of the total, were suitable for only one restoration candidate. In addition, 817 sub-compartments have 2 restoration candidates, accounting for 11.4% of the total; 1056 sub-compartments have 3 restoration candidates, accounting for 14.7% of the total; 2117 sub-compartments have 4 restoration candidates, accounting for 29.4% of the total; and 1251 sub-compartments have 5 restoration candidates, accounting for 17.4% of the total (Fig. 3). The sub-compartment coverage of forest H was higher than that of the others, and almost all sub-compartments were suitable for restoration to sedge-Mongolian oak-Korean pine forest. Only 5 sub-compartments were suitable for the growth of forest A (Fig. 4).

3.3. Optimal spatial arrangement of potential forest development types (PFDT) at the landscape scale

Within the 14,282 potential generated patches, 12 were with all the selected standardized indexes (1/SPLIT, SHDI, CONTAG, and CONNECT) > 0.5. We selected the patch with highest mean value and lowest SD as the optimal patch (standardized INTEGRALITY = 0.601, standardized SHDI = 1.000, CONTAG = 0.872, and CONNECT = 0.884). In this patch, forest H covered 22.68% of the forested area, follow by forests C, D, K, I, B, J, A, F, and E, which covered 20.08%, 15.58%, 9.10%, 8.08%, 5.90%, 0.35%, 0.06%, 0.04%, and 0.02% of the forested area, respectively (Fig. 5).

3.4. Forest management map

The comparison of current forest composition with the optimal potential patch showed that most the stands required species composition management (artificial regeneration or thinning). In 15.8% of the sub-compartments, the proportion of Korean pine should be reduced, while 42.3% of sub-compartments needed low intensity regeneration, and 25.1% of the sub-compartments required high intensity regeneration; 32.2% of the sub-compartments needed thinning of Amur linden, while 37.2% of the sub-compartments required low intensity regeneration. No artificial regeneration of Mongolia oak was required; however, 41.0% of the sub-compartments needed thinning of Mongolia oak; 0.34% of the sub-compartments were not suitable for the growth of Manchurian ash but have been artificially regenerated pure Manchurian ash plantations. In addition, 23.0% of the sub-compartments were proper habitats for Manchurian ash but had inadequate proportions of Manchurian ash; spruce in 24.2% of the stands needed thinning, and in contrast, 47.6% of the stands should be artificial regenerated with fir (Fig. 6).

4. Discussion

By using this multi-scale restoration approach, we identified the optimal spatial arrangement of the targeted stands that achieve better landscape structural and functional synergies, while indicating the restoration location and management required. These results support traditional approaches such as selection of restoration forest type based on stand conditions combined with targets to benefit landscape structure and functions by using an integrated planning approach. We achieved this result by combining existing tools and methods. However, several uncertainties and simplifications substantially influence large-scale modelling and landscape restoration planning. These factors included limited data availability, the underlying modelling assumptions and the understanding of ecological processes at a multi-scale.

4.1. Multiple restoration objectives at a multi-scale

Setting targets for forest restoration is essential to verifying the success of the restoration (Stanturf et al., 2012). The proposed approach is based on the idea of integrating stand-scale restoration activities with landscape-scale decision making. Consequently, we set two levels of targets for forest restoration: at the stand level, the target was to restore the current forest community to a native primary forest community that was adapted to the stand condition; at the landscape level, the target was to select the optimal spatial arrangement of these forest stands with higher landscape connectance, diversity, and lower fragmentation.

Table 1
Community composition, habitat requirements and potential usage of native primary forest in the Changbai Mountains. Data source was listed in the appendix.

Communities	Elevation	Position	Slope	Aspect	Dominant species and their percentages	Usage
Subalpine *Betula ermanii*forest (A)	1800–2100	V/F/H	G/M/S	Southern/Northern	0.8 *Betula ermanii*	C
Betula ermanii-spruce-fir forest (B)	1600–1800	V/F/H	G/M/S	Southern/Northern	0.3 *Betula ermanii* + 0.3 *Picea asperata* + 0.3 *Abies fabri*	C
Dark coniferous forest (C)	1400–1600	V/F/H	G/M/S	Southern/Northern	0.4 *Picea asperata* + 0.4 *Abies fabri*	C/T
Moss-spruce- fir- Korean pine forest (D)	1000–1500	F	–	–	0.3 *Pinus koraiensis* + 0.2 *Abies fabri* + 0.2 *Picea asperata* + 0.1 *Betula platyphylla* + 0.1 *Larix olgensis* Henry	C/T
Shrub-*Tilia amurensis*-Mongolian oak-Korean pine forest (E)	800–1200	H	G/M/S	Southern/Northern	0.4 *Pinus koraiensis* + 0.3 *Tilia amurensis* + 0.2 *Quercus mongolica*	C/T
Shrub-*Manchurian walnut*-*Ulmus laciniata*-Korean pine forest (F)	800–1201	V/H	G	Southern/Northern	0.3 *Pinus koraiensis* + 0.2 *Juglans mandshurica* + 0.2 *Ulmus laciniata*	C/T
Shrub- *Fraxinus mandshurica*-*Tilia amurensis*-Korean pine forest (G)	800–1202	F/H	G	Southern/Northern	0.4 *Pinus koraiensis* + 0.2 *Tilia amurensis* + 0.1 *Betula costata* + 0.1 *Fraxinus mandschurica* + 0.1 *Picea asperata*	C/T
Sedge- Mongolian oak-Korean pine forest (H)	650–1000	H	G/M/S	Southern	0.5 *Pinus koraiensis* + 0.2 *Tilia amurensis* + 0.2 *Quercus mongolica* + 0.1 *Betula costata*	C/T
Fern-Spruce- Fir- Korean pine forest (I)	600–800	V	–	–	0.3 *Pinus koraiensis* + 0.2 *Abies fabri* + 0.2 *Picea asperata* + 0.2 *Fraxinus mandschurica* + 0.1 *Ulmus davidiana*	C/T
Ural false spiraea-*Ulmus davidiana*-*Fraxinus mandshurica*-Korean pine forest (J)	600–800	V	–	–	0.3 *Pinus koraiensis* + 0.2 *Fraxinus mandschurica* + 0.2 *Ulmus davidiana* + 0.1 *Tilia amurensis* + 0.1 *Betula costata*	C/T
Moss-Korean pine forest (K)	600–800	V/H	G/M/S	Southern/Northern	0.3 *Pinus koraiensis* + 0.2 *Tilia amurensis* + 0.2 *Fraxinus mandschurica* + 0.1 *Abies fabri*	C/T
Carpinus cordata-fir-Korean pine forest (L)	400–700	F/H	G/M/S	Northern	0.3 *Pinus koraiensis* + 0.2 *Tilia amurensis* + 0.1 *Picea asperata* + 0.1 *Betula costata*	C/T
Carpinus cordata-Mongolian oak-Korean pine forest (M)	400–701	H	G/M/S	Southern	0.4 *Pinus koraiensis* + 0.3 *Quercus mongolica* + 0.1 *Tilia amurensis* + 0.1 *Betula costata*	C/T
Carpinus cordata-*Tilia amurensis*-Korean pineforest (N)	400–702	F/H	G/M	Northern	0.4 *Pinus koraiensis* + 0.3 *Tilia amurensis* + 0.1 *Betula costata* + 0.1 *Quercus mongolica*	C/T

V: Valley; H: Hillsides; F: Flat; G: Gentle; M Moderate; S: Steep; C: Conservation; T: Timber producing.

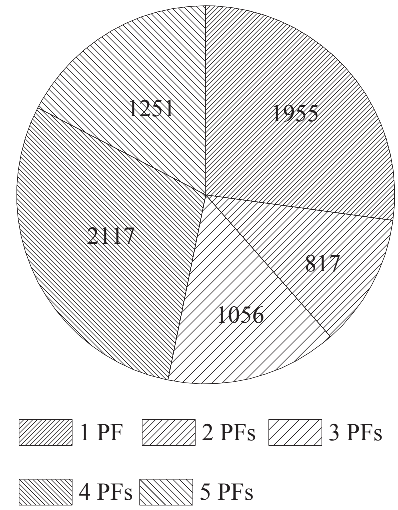


Fig. 3. Numbers of candidate potential forest types of each sub-compartment for restoration. PF(s): Potential forest type for restoration.

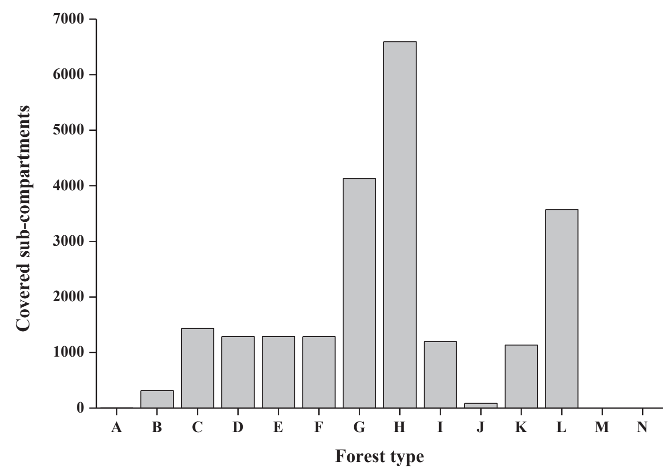
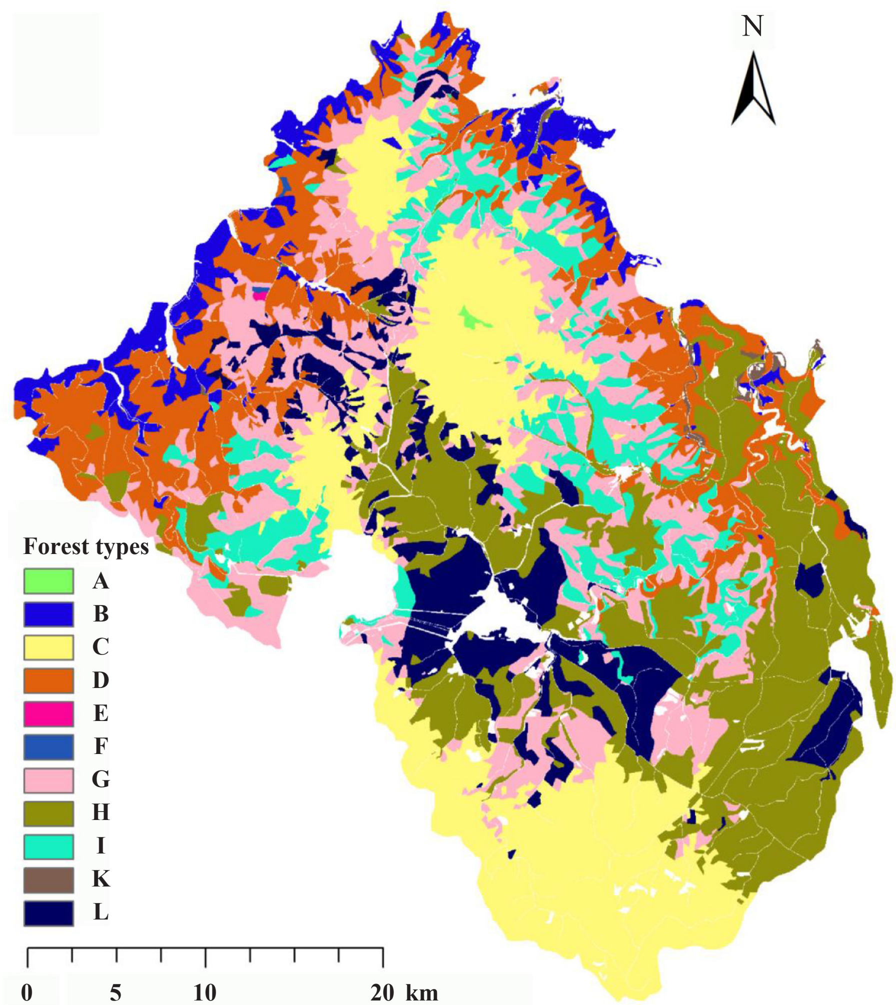


Fig. 4. Covered sub-compartment of each potential forest type. A: Subalpine *Betula ermanii* forest; B: *Betula ermanii*-spruce- fir forest; C: Dark coniferous forest; D: Moss-spruce-fir-Korean pine forest; E: Shrub- *Tilia amurensis*-Mongolian oak-Korean pine forest; F: Shrub-Manchurian walnut- *Ulmus laciniata*-Korean pine forest; G: Shrub-*Fraxinus mandshurica-Tilia amurensis*-Korean pine forest; H: Sedge- Mongolian oak-Korean pine forest; I: Fern-spruce-fir-Korean pine forest; J:*Ural falsespiraea-Ulmus davidiana- Fraxinus mandshurica*-Korean pine forest; K: Moss-Korean pine forest; L:*Carpinus cordata*-fir-Korean pine forest; M: *Carpinus cordata*-Mongolian oak-Korean pine forest; N:*Carpinus cordata-Tilia amurensis*-Korean pine forest.

Site-level forest restoration “is an intentional activity that initiates or accelerates recovery of an ecosystem with respect to its health, integrity and sustainability” (Jose et al., 2007). This type of restoration involves more than planting trees because its goal is more than simply to revegetate, but rather, site-level forest restoration includes specific goals for the composition and structure of the forest, an approach dominated by restoration to past conditions, as exemplified by reference stands (Margaret et al., 1997; Lindbladh et al., 2007). Based on abundant results from previous studies on the natural variability of the structure of natural forests across Changbai Mountains, we identified 14 original forest types as the targets for stand level forest restoration in different habitats. However, we still lack a full understanding of the interaction among different disturbances and the long-term cumulative effects of disturbance in forest ecosystems, and little research on the mechanisms underlying the forest structure and function dynamic of disturbed forest ecosystems have been conducted in China. Therefore,



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we only analysed the differences on species composition between the degrade stand and target native primary forest, did not involve indicating dynamic of the restored forests by using mean DBH of current forests. Similarly, there has been little research on how to accelerate the recovery of ecosystem structures from secondary forests to old-growth forest features. Further research and monitoring data on the dynamic of disturbed forest structure and function can enable us to predict the restoration process and provide quantity of restored species and technic accurately. Additionally, the goal of forest restoration is restoring not only a continual structure of the forest landscape but also multiple ecosystem services that the forest ecosystem provides. A lack of relevant studies limited us from integrating ecosystem functions and services (e.g. carbon fixing, forest products providing) into the process of restoration. Further studies on the dynamics of forest ecosystem functions and services during the restoration process are urgently needed.

Forest landscape restoration is a decision-making process and not simply a series of treatments that cover large areas (Lamb et al., 2005). This type of restoration involves choices about where and how restoration is undertaken by considering the location and connection of restored sites and their surroundings and the contribution of the restored sites to landscape integrity and diversity (Dudley et al., 2005). In this study, we only presented the optimal spatial arrangement of the target forest community map, which was generated by balancing 4 indexes with equal in weight that described landscape structure as our goal at the landscape level. However, the proposed method could be expanded to include various goals such as carbon stock, endangered species conservation, timber production or other ecosystem services by integrating relevant models in future research. Managers can also balance different weights for each goal they want to achieve by use the proposed method.

4.2. Decision support for feasible implementation plans

Finding ways to implement restoration at large or landscape scales is a challenge of FLR. To decide what type of restoration and how to restore is a difficult task (Emborg et al., 2012) because making decisions at a landscape scale is largely a “top – down strategic management” approach where governments set objectives and decide the goals at the landscape scale. In contrast, implementing restoration at the stand scale is often a “bottom – up tactical management” approach related to how to restore a degraded stand or forest ecosystem (Lamb et al., 2012). Restoration efforts may fail if these two processes were not well linked. In this study, we use stand condition as the key linkage between these two processes. By combining the targeted forest composition with the targeted landscape structure, we demonstrate that both targets can be achieved together. In the proposed method, designating the targeted landscape structure and function is determined by the selection of thresholds or weighted importance of the parameters, which is based on the needs of the managers. In this study, we used the balance of 5 standardized landscape indexes with equal importance as a simple and consistent rule for testing the integration of several targets as used in previous studies targeting restoration. Once the decisions on the targeted forest composition and its location were made, the proposed approach compares the structure and composition of the target

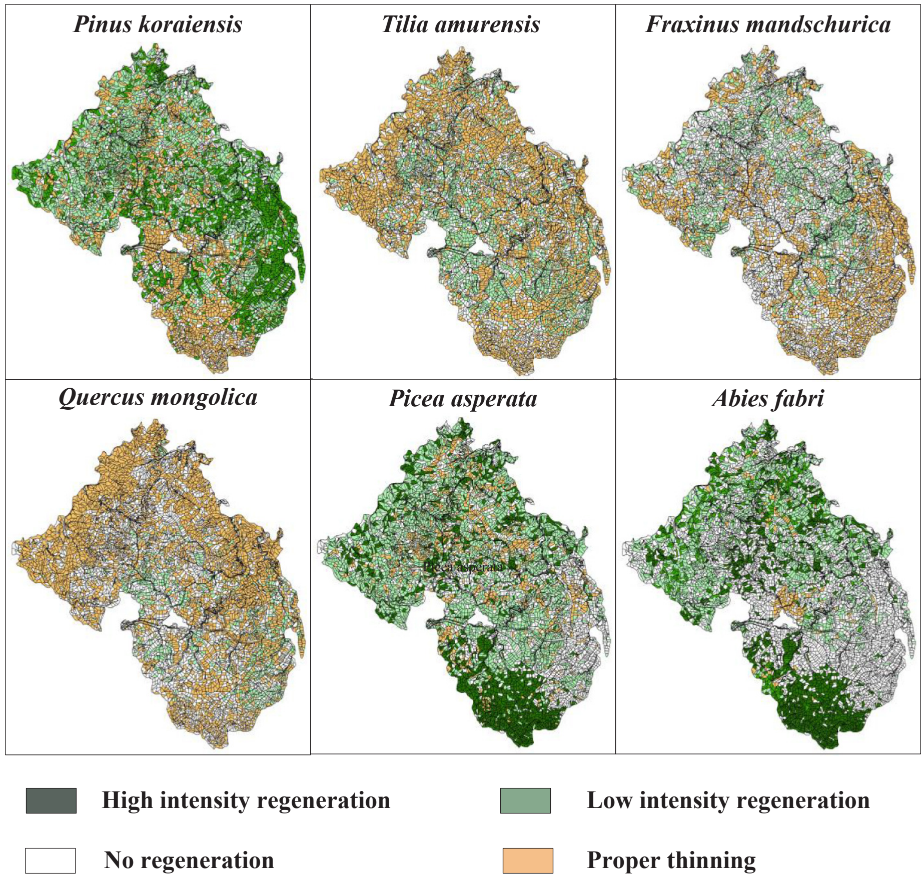

Fig. 6. Forest management map.

with the current forest structure at the same location, then the species and the quantity of species that need to be regenerated are determined and relevant maps are generated. Hence, two main uncertainties may occur in this process. First, some uncertainties relate to the selection of thresholds and definition of targets and goals. Moreover, some of the goals may contradict each other; for example, it is hard to gain maximum landscape integrity and maximum landscape diversity in one scenario, because landscape diversity usually increases with landscape integrity decrease. Second, some uncertainties relate to the ecosystem recovery process. Both uncertainties require a further understanding of ecological processes.

The methodology still needs to be tested, but it can be an easy and fast way to prioritize areas for restoration actions with the goal of providing multiple ecosystem services. We recognize that our study is only a starting point that may help develop different types of strategies for local areas. In addition, it will be necessary to expand our approach to include a wider range of potential functions of forest types. The identification of beneficiaries and the consideration of the specific local and regional demands remain a critical task for estimating and optimizing the benefits, i.e., services that multifunctional FLR might attain. However, ecosystems contain numerous functions that are crucial for their own maintenance. Restoring these functions might be the only reliable way to increase ecosystem services. It remains therefore important to further investigate the critical places within landscapes where FLR might contribute to enhancing multiple functions and the self-sustaining capacity of forests.

In the management map, recommendations on forest composition adjustments based on each dominant species were provided at a stand scale. By comparing the management strategy of the study area, the recommendations provided seem to be appropriate. For example, decreasing the proportion of Korean pine was suggested in most of the forests used for seeding trees conservation with exorbitant proportions of Korean pine. However, without data on the age structures of populations, we can only provide an estimate of the degree of intensity with which the species should be thinned or regenerated. Accurate management intensity can be suggested until data on age structure density are available and stand-scale growth models are integrated.

Despite the above simplifications and limitations, this study attempted to establish guidance for degraded forest ecosystem restoration that involved an integrated multi-scale approach. This guidance can be used in other areas for designing forest restoration plans based on area conditions.

5. Conclusion

With this study, we proposed an integrative approach of current-optimal forest patterns with multiple-scale forest restoration that can be useful for supporting decision making to untangle conflicting goals and easily model and visualize spatial consequences of different decisions. We emphasize the inclusion of habitat-based targeted forest type selection. This approach might provide an important bridge from stand-level implementation of actions to landscape decision-making processes.

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Appendix A. Supplementary data

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