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# Improving landscape connectivity for the Yunnan snub-nosed monkey through cropland reforestation using graph theory

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ABSTRACT

Habitat fragmentation is a threat to biodiversity because it restricts the ability of animals to move. Maintaining landscape connectivity could promote connections between habitat patches, which is extremely important for the preservation of gene flow and population viability. This paper aims to evaluate the landscape connectivity of forest areas as it relates to the conservation of the Yunnan snub-nosed monkey (*Rhinopithecus bieti*), an emblematic and endemic endangered primate species. Specifically, this study seeks to model ways to improve connectivity via cropland reforestation scenarios which incorporate graph theory and genetic distances. The connectivity improvement assessment is performed at two nested scales. At the regional scale, the aim is to quantitatively assess the gain in connectivity from different reforestation scenarios, in which croplands are replaced by different kinds of forest habitats. At the local scale, the goal is to prioritize and to locate croplands based on the gain in connectivity that they would provide if they were reforested. The results indicate that the four reforestation scenarios have different impacts on connectivity; the fourth scenario, in which reforestation is accomplished with plant species that provide optimal monkey habitat, yields the greatest increase in connectivity (+24% versus less than +2% for the others). Prioritization of the 1482 cropland patches shows that the 10 best patches increase connectivity from 0.04% to 9.1% as the isolation threshold distance increases. This kind of graph theoretic approach appears to be a useful tool for connectivity assessment and the development of conservation measures for species impacted by human activities.



## 1. Introduction

Human activities generate land use and cover change (LUCC) that may significantly affect natural habitats and, consequently, species viability (Foley et al., 2005). Since the beginning of the 20th century, the acceleration of LUCC has resulted in habitat loss for species of high conservation value, and this acceleration has been particularly strong in China over the last two decades, leading to a reduction in natural habitats (Liu, Zhuang, Luo, & Xiao, 2003). Many studies have focused on the impacts of urbanization on the environment (Liu, Wu, & Shen, 2000), the conversion of natural habitats to cropland also has important consequences, such as pollution, biodiversity loss and habitat fragmentation (Millennium Ecosystem Assessment, 2005). Habitat fragmentation is a landscape-level spatial process that generates patch-level consequences such as a decrease in habitat patch size and an increase in patch isolation (Fahrig, 2003), and this process is considered a major threat to species viability because it reduces landscape permeability to wildlife movements and gene flow (Cushman, McKelvey, Hayden, & Schwartz, 2006; Forman and Alexander, 1998). The maintenance and/or improvement of landscape connectivity, which facilitates the movement of animals among resource patches (Taylor, Fahrig,

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Henein, & Merriam, 1993), is thus a major issue facing the preservation of population viability, especially for species that depend on large habitats or on a high degree of connectivity between habitats. The distribution and the survival of primates, for instance, are directly influenced by landscape integrity and connectivity (Anzures-Dadda & Manson, 2007; Arroyo-Rodríguez & Fahrig, 2014).

Over the last decade, many studies have focused on improving and restoring landscape connectivity for species conservation (Bodin & Saura, 2010; Briers, 2002; Clauzel, Bannwarth, & Foltête, 2015; Dalang and Hersperger, 2012; Etienne, 2004; Hodgson et al., 2011; McRae, Hall, Beier, & Theobald, 2012). Among the methods used, network analysis based on graph theory is one of the most promising because it offers an interesting compromise between the amount of input data and information about ecological processes (Urban & Keitt, 2001; Calabrese & Fagan, 2004). Graph-based methods are used to model the ecological networks of species, generally to represent the trophic interactions between species in an ecosystem. Here, we use graph modelling to represent the spatial connectivity between habitat patches of a single species, which allows us to analyse both the structural and functional aspects of landscape networks by integrating species behaviour. A graph is a set of nodes corresponding to the habitat patches of a given species that are connected by links representing potential movements between patches (Galpern, Manseau, & Fall, 2011). Landscape graph analysis is often used to quantify potential connectivity by means of connectivity metrics (Foltête, Clauzel, & Vuidel, 2012), to identify the most important landscape elements (patches or corridors) for preserving connectivity (Baranyi, Saura, Podani, & Jordán, 2011; Bodin & Saura, 2010; Crouzeilles, Lorini, & Grelle, 2013; Erős, Schmera, & Schick, 2011; Jordán, Báldi, Orci, Rácz, & Varga, 2003; Saura & Rubio, 2010) or to test different scenarios to improve connectivity. This last goal can be achieved by increasing the size or the quality of existing habitat patches or corridors (Etienne, 2004) or by creating new habitat patches or corridors through landscape restoration (Benedek, Nagy, Rácz, Jordán, & Varga, 2011; Clauzel, Deng, Wu, Giraudoux, & Li, 2015; García-Feced, Saura, & Elena-Rosselló, 2011; Zetterberg, Mörtberg, & Balfors, 2010; Hodgson et al., 2011; McRae et al., 2012).

The aim of this paper is to improve the connectivity of forest networks by proposing different reforestation scenarios, and we use a method that combines graph theory and genetic distances to model the landscape network of a given species. The analysis is focused on the connectivity of high-altitude coniferous forests in Yunnan (China), which have a high value in biodiversity (Yang, Tian, Hao, Pei, & Yang, 2004). The restoration of this ecosystem could benefit to many species living in this habitat, especially the Yunnan snub-nosed monkey (*Rhinopithecus bieti*). This primate species is an important conservation target because of its endemism and the critical size of its population, which is fragmented into 15 groups. Indeed, the species is highly threatened by growing urbanization and, most importantly, the conversion of forests for cropland, which causes habitat fragmentation and isolation (Xiao, Deng, Cui, Zhou, & Zhao, 2003). Some studies (Li, Xue, Wu, Li, & Giraudoux, 2014; Wong, Li, Xu, & Long, 2013) have highlighted the importance of preserving or restoring the corridors between habitat patches to enable monkey movements.

The present study focuses on improving the quality of potential snub-nosed monkey corridors by proposing different reforestation scenarios, which are focused solely on croplands located in the corridors because their restoration is considered easier and more feasible compared to other land cover types. The analysis is conducted at two nested scales, regional and local, that are recognized as important to the distribution and abundance of monkeys (Anzures-Dadda & Manson, 2007). At the regional scale, this research assessed the improvement in connectivity under our cropland reforestation scenarios as differentiated by the type of forest plant species selected for use. At the local scale, we prioritized the cropland patches according to the gain in connectivity that they would provide if they were reforested and to consequently identify the best locations for creating new habitat patches. The results are a useful guide for the implementation of conservation measures, such as habitat restoration, for the Yunnan snub-nosed monkey and, more generally, for threatened species with discrete distributions due to habitat fragmentation.

## 2. Materials and methods

### 2.1. Materials

#### 2.1.1. Study area

The study area (Fig. 1) is located in northwest Yunnan Province in the Three Parallel Rivers region (between 29.020N, 98.038 E in the north and 25.053N, 99.022 E in the south), which is one of the most ecologically significant areas of China in terms of biodiversity, and covering approximately 17000 km$^2$ across four counties in Yunnan (Deqin, Weixi, Lanping, and Lijiang). The elevation of the study area varies from 1200 m to 5500 m with the northern part being higher (3900 m on average compared to 2900 m in the southern part). Land cover varies greatly between the north and south; the northern part is dominated by subalpine coniferous forest while the southern part contains mixed coniferous and broadleaf forest. In addition, land cover in the south is more fragmented due to a higher density of human activities, such as infrastructure and intensive agriculture.

#### 2.1.2. Study species

The Yunnan snub-nosed monkey is one of the most endangered animal species endemic to China. It lives in inaccessible mountains between 1800 m and 4513 m, one of the most extreme environments for any non-human primate (Long, Zhong, & Xiao, 1996), and its habitat consists in an archipelago of high-altitude coniferous forest patches (Fig. 1) (Li, Yang, & Xiao, 2006; Wang, Xue, & Xia, 2011; Xue, Li, Wu, & Zhou, 2011). The population is approximately 2500 individuals living in 15 isolated groups (12 groups in Yunnan and 3 groups in Tibet) (Wong et al., 2013), and the number of individuals in a single monkey group ranges between 50 and 200 (Long et al., 1996). The main areas of occupancy are the Baima Mountains (groups 6–10) and the Laojun Mountains (groups 11 and 12). Since the 1950s, suitable habitats (dark coniferous forest, mixed coniferous and broadleaf forest, and oak patches) have been decreased by over 30%, and the average patch size has been reduced from 15.6 km$^2$ to 5.4 km$^2$ (Xiao et al., 2003). Due to this reduction in suitable habitats, it is difficult for species to move among resource patches, but it can also prevent genetic exchange between populations, making the species more vulnerable to extinction. (Xiao et al., 2003; Li et al., 2014; Liu et al., 2009).

During the day, the snub-nosed monkey spends most of its time feeding, moving and resting. According to several surveys (Kirkpatrick, Long, Zhong, & Xiao, 1998; Ren, Li, Long, Grüter, & Wei, 2008; Ren, Li, Long, & Wei, 2009), the daily travel distance varies between 350 m and 3000 m with an average of approximately 1500 m, but dispersal events are not well known, especially in terms of the coverage of extreme distances (Grueter, 2003).

#### 2.1.3. Land cover data

Land cover data were obtained from a supervised classification on SPOT-5 images (Institute of Forest Inventory and Planning, Yunnan, 2012) with ground-truthing by the Conservation Information Centre of The Nature Conservancy's China programme. All data were geo-corrected in ERDAS 9.2 with a root-mean-square (RMS) error <1.