Changes in the spatial and temporal pattern of natural forest cover on Hainan Island from the 1950s to the 2010s : implications for natural forest conservation and management

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The study of the past, present, and future state and dynamics of the tropical natural forest cover (NFC) might help to better understand the pattern of deforestation and fragmentation as well as the influence of social and natural processes. The obtained information will support the development of effective conservation policies and strategies. In the present study, we used historical data of the road network, topography, and climatic productivity to reconstruct NFC maps of Hainan Island, China, from the 1950s to the 2010s, using the random forest algorithm. We investigated the spatial and temporal patterns of NFC change from the 1950s to the 2010s and found that it was highly dynamic in both space and time. Our data showed that grid cells with low NFC were more vulnerable to NFC decrease, suggesting that conservation actions regarding natural forests need to focus on regions with low NFC and high ecological value. We also identified the hot-spots of NFC change, which provides insights into the dynamic changes of natural forests over time.

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Abstract

The study of the past, present, and future state and dynamics of the tropical natural forest cover (NFC) might help to better understand the pattern of deforestation and fragmentation as well as the influence of social and natural processes. The obtained information will support the development of effective conservation policies and strategies. In the present study, we used historical data of the road network, topography, and climatic productivity to reconstruct NFC maps of Hainan Island, China, from the 1950s to the 2010s, using the random forest algorithm. We investigated the spatial and temporal patterns of NFC change from the 1950s to the 2010s and found that it was highly dynamic in both space and time. Our data showed that grid cells with low NFC were more vulnerable to NFC decrease, suggesting that conservation actions regarding natural forests need to focus on regions with low NFC and high ecological value. We also identified the hot-spots of NFC change, which provides insights into the dynamic changes of natural forests over time.

INTRODUCTION

Human activity is the dominant cause of contemporary environmental change worldwide (Lewis & Maslin, 2015). Land use by humans is a major component of the long-term anthropogenic global changes that have defined the "Anthropocene" as a new epoch of geologic time (Ellis et al., 2013; Dirzo et al., 2014; Lewis & Maslin, 2015). The study of land use and land cover change was initially dominated by monitoring and modelling of the ecological impacts of major land cover changes, such as deforestation and desertification, on the natural system (Lambin & Geist, 2006). However, research of land cover change has now become more integrative, focusing on both the drivers and impacts of land change, including a wider range of interacting processes. Understanding the drivers, state, trends and impacts of different land cover change in combination with the social and natural processes might help to reveal the effects of land system changes on the socio-ecological system and consequently develop effective conservation strategies.

The decrement of natural forest is an important environmental issue in the tropical environment, since these forest harbour exceptional biodiversity, providing important ecosystem services that support the livelihood of local communities (Myers et al., 2000; Sodhi et al., 2006; Page, Rieley & Banks, 2011; Arima, 2016). The study of the past, present, and future state and dynamics of the tropical natural forest cover (NFC) changes might help to better understand the manner of deforestation and fragmentation as well as the influence of social and natural processes. The obtained information will support the development of effective conservation policies and strategies, especially in areas with rapid forest decline (Romijn et al., 2015). The

52 first comprehensive assessment of global forest resources was reported by Zon & Sparhawk

53 (1923), the Food and Agriculture Organization (FAO) of the United Nations has carries out

54 regular assessments (Forest Resources Assessments; FRA) at intervals of five or ten years since

55 1948 (MacDicken, 2015). Although the FRA data are only partially accurate (Grainger, 2008),

56 they shed light on NFC changes at a global scale (MacDicken, 2015). though not at a local scale,

57 mainly because the mechanisms of NFC changes are more complicated than those reported in

58 previous studies (Lambin, Geist & Lepers, 2003). Remote sensing by satellites has been used to

59 tracking NFC since 1972 (Grainger, 2008). Hansen et al. (2013) developed a dataset of high-

60 resolution global maps and assessed forest cover change from 2000 to 2012 using satellite data

61 with a spatial resolution of 30 m. These results depict a globally consistent and locally relevant

62 record of forest change. However, little is known about the long-term historical distribution of

63 NFC prior to the 1970s (Liu & Tian, 2010). Overall, it is essential to assess the historical

64 distribution of NFC at a specific spatial scale (Miao et al., 2013) in order to explore the

65 underlying mechanisms (Goldewijk, 2001; Goldewijk et al., 2011) and create more effective

66 conservation policies.

67   Previous studies used biophysical (e.g. topography and climate) and socio-economic data

68 (e.g. population density, road networks, migration, urban extension, and gross domestic product)

69 to reconstruct the long-term historical distribution of NFC (Millington, Perry & Romero-

70 Calcerrada, 2007; Arima et al., 2008; Miao et al., 2013; He, Li & Zhang, 2014). However, these

71 variables are only valid in regions with abundant historical data. Of the variables, roads have

72 long been considered an important driver of deforestation in many tropical countries, because of

73   their high availability and strong correlation with NFC (Arima et al., 2005; Arima et al., 2008;

74   Gaveau et al., 2009; Freitas, Hawbaker & Metzger, 2010; Cai, Wu & Cheng, 2013; Walker et al.

75   2013; Li et al., 2014; Arima et al., 2016; Hu et al., 2016). Multiple studies have focused on the

76   effect of roads on NFC, but only a few of them have used the temporal and spatial dynamics of

77   road networks for studying the distribution of NFC (Perz et al., 2007; Perz et al., 2008; Ahmed et

78   al., 2013; Newman, Mclaren & Wilson, 2014).

79   Hainan is the largest island in the Indo-Burma biodiversity hotspot and harbours high levels

80   of biological endemism (Myers et al., 2000). Natural forest initially covered almost the entire

81   island, but NFC has now decreased to less than one quarter, mainly in the central mountainous

82   area of the island, owing to the intensive exploitation and deforestation since the 1950s (Lin et al.,

83   2015). Although the NFC changes in Hainan have been previously reported, limited information

84   is available regarding the distribution of NFC over time, which is important to better understand

85   the dynamics of wildlife communities (Brook et al., 2006), especially of some endangered

86   species (e.g. Hainan Gibbon; Xu et al., in press). The deforestation of Hainan Island has led to a

87   series of grave ecological consequences (e.g. large floods, landslides, and drought) that

88   threatened the local communities and decreased the overall environmental quality (Wang et al.,

89   2014). Thus, understanding the spatial and temporal dynamics of NFC is crucial to evaluate the

90   environmental quality and restore forest ecosystems that important services to the local residents.

91   Here, we used historical road maps and environmental variables to simulate and document

92   the temporal and spatial dynamics of NFC on Hainan from the 1950s to the 2010s. First, we

93   fitted a random forest (RF) model to simulate the distribution of NFC with road-related and

94   environmental variables in 1975, 1995, and 2012. Next, we used the random forest model to

95   reconstruct the NFC at a 20-years intervals from the 1950s to the 2010s. Based on our data, we

96   aimed to: (1) explore the effect of the road network on NFC changes and (2) identify changes in

97   the distribution of NFC from the 1950s to the 2010s.

98

MATERIAL and METHODS

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Study area

100

101   This study was carried out on Hainan Island, an area of approximately 33,900 km^2 located

102   in south China (Fig. 1). The island has a central mountainous region with a maximum elevation

103   of 1,867 m (Fig. 1) and is flat in the northern and coastal regions. The climate is tropical with

104   warm and humid weather. The average annual temperature ranges from 16°C in January to

105   27.5°C in July. The annual rainfall is over 1,600 mm (Francisco-Ortega et al., 2010) and

106   unevenly distributed both between the rainy and dry season and across the island. Rainfall

107   mainly occurs in eastern Hainan Island (Wenchang, Qionghai, Wanning, Lingshui, and Sanya

108   Counties) due to typhoons from the Pacific Ocean. The western part of the island is characterized

109   as dry, while the eastern part is humid (Xu et al., in press).

110   Prior to 1950s, the forest area on Hainan Island was largely natural, since the number

111   ofcoconut and rubber plantations was limited island (Chen, 1948), whereas the non-forest area

112   was mainly farmland. The natural forest area decreased considerably owing to logging for timber,

113   rubber plantations, and residential expansion, with NFC reached a minimum in the 1980s. In

114   response to this dramatic NFC loss, the Hainan Provincial Government established a natural

115   forest logging ban in 1994 (Standing Committee of Hainan Provincial People 's Congress, 1993;

116   Zhang, Uusivuori & Kuuluvainen, 2000).

Distribution of natural forest

118   In this study, arboreal forest, shrub land, and open woodland were considered as natural

119   forest based on the standards of the National Forest Inventory of China (SFA PRC, 2004). The

120   distribution of natural forest in 1975 was obtained from 93 topographical maps of Hainan Island

121   and digitised using ArcInfo 9.3. (ESRI, 2008; see Appendix 1 for more details). These maps

122   incorporated different types of land uses and outlined the distribution of arboreal forest, shrub

123   land, and open woodland. The distribution of natural forest in 1995 and 2012 was reproduced

124   from maps of the 5th and the 8th National Forest Resources Inventory of China

125   (http://www.forestry.gov.cn/gjslzyqc.html). Three datasets of the historical natural forest

126   distribution were primarily produced by aerial photography and validated by field observations.

127   Field investigation data of 1997/1998 and 2012/2013 (Xu et al., in press) were used to estimate

128   the accuracy of natural forest distribution in 1995 and 2012 (Fig. S1). To enhance data

129   consistency, the NFC distribution in the 1970s, 1990s and 2010s was combined using the

130   'Simplify polygon' function in ArcInfo 9.3. (ESRI, 2008).

131   We established a 5 × 5 km grid cell system for model simulations. First, Hainan Island was

132   divided into 5 × 5 km grid cells, and those with a land area less than 50% were excluded to

133   minimise the bias of low NFC. A total of 1360 grid cells were used for further analysis. Next, we

134   overlaid the polygons of natural forest in 1975, 1995 and 2012 with the grid cells, and the

135   proportion of natural forest was considered as the NFC of grid cell. The obtained NFC datasets

136   were used as a response variable in model simulations.

Variables correlated with NFC

138   We investigated three main categories of variables with a potentially high correlation with

139   NFC: (1) topography, such as slope (SLO, °) and elevation (ELE,m), which indicate

140   difficulty in accessibility and historical exploitation (Teixeira et al., 2009); (2) climatic potential

141   productivity (CPP, Kg • hm^{-2} • a^{-1}), which   indicates the potential of forest loss due to crop

142   farming (Pongratz et al., 2008); and (3) road network, which indicates the scale and intensity of

143   socio-economic impact on NFC (Arima et al., 2005; Walker et al. 2013; van der Ree, Smith &

144   Grilo, 2015; Arima et al., 2016).

145   Digital elevation data (approximately 90 × 90 m resolution) were obtained from the

146   Consortium for Spatial Information (http://www.cgiar-csi.org/data/srtm-90m-digital-elevation-

147   database-v4-1). The slope map was created based on changes in elevation between adjacent

148   pixels of the digital elevation data. Data on the climatic potential productivity (approximately 1 ×

149   1 km resolution) were obtained from the National Earth System Science Data Sharing

150   Infrastructure (http://www.geodata.cn/index.html). The SLO, ELE, and CPP of each grid cell

151   were calculated by averaging all cells (1 × 1 km or 90 × 90 m) such that their centroid fell within

152   each 5×5 km grid cell.

153   Historical data of the road network were obtained from maps and digital databases

154   published prior to 2013 (Table S2). Maps were digitised using ArcInfo 9.3.(ESRI, 2008) and

155   assigned to a 20-year interval. Due to differences in the mapping scale of traffic maps, the Rural

156   road was designated as the lowest level road, whereas Expressway, Highway, Simply-built

157   highway, and Cart road were designated as roads with relatively higher levels (Table S2). Based

158   on the function and surface material of various roads, we classified these roads into two classes

159   in the 1950s, 1970s, 1990s and 2010s: main road (Expressway, Highway, and Simply-built

160   highway) and secondary road (Cart road and Rural road).

161   Four road-related variables: including the sum of road length (SRL, km km^{-2}), the distance

162   from the grid cell centroid to the nearest road (DNR, km), the number of nodes of road network

163   (NON, ea km^{-2}), and the mean node degree (MND, *ea* km^{-2}; the mean number of roads connected

164   to each node), were calculated in each grid (Table S3) to represent the density and configuration

165   of the road network in the 1950s, 1970s, 1990s, and 2010s.

166   **Reconstruction of the historical NFC from the 1950s to the 2010s**

167   Prior to the reconstruction of the historical NFC, we tested the predictive performance of

168   four modelling techniques, including the generalized linear model (GLM), generalized additive

169   model (GAM), artificial neural networks (ANN) model, and random forests (RF) model. We

170   used the normalised mean square error (NMSE) to compare the predictive performance of the

171   four models in simulating the NFC of each 5×5 km grid cell (Appendix 5). NMSE is a relative

172   measure, estimating the overall deviation between predicted and measured values and also a unit-

173   less measure in the interval [0,1]. The modelling technique with the lowest value of NMSE has

174   the highest predictive performance. The RF model showed the lowest NMSE among the four

175   models and consequently, was used for reconstructing the historical NFC from the 1950s to the

176   2010s (Table S4).

177   The RF model (Iverson et al., 2008) is characterized by insensitivity to multicollinearity,

178   steadiness across unbalanced datasets, accuracy in predicting the effects of multiple explanatory

179   variables (Breiman, 2001; Culter et al., 2007), higher efficiency in large datasets than that of

180   traditional machine-learning techniques, suitability in demonstrating the nonlinear effect of

181   variables, modelling complex interactions among variables, and robustness to   outliers (Li,

182   2013; Breiman, 2001; Culter et al., 2007). In the present study, we fitted the RF model to

183   associate the NFC data of each grid cell with SLO, ELE, CPP, and main and secondary road

184   networks related indicators (SRL, DNR, NON, and MND) in the 1970s, 1990s, and 2010s. Next,

185   we used the obtained RF model to reconstruct the historical NFC of each grid cell at 20-year

186   intervals from the 1950s to the 2010s, according to the topography, climate, and road network

187   data in a specific period. We assumed that topography and climate did not change significantly

188   over a relatively short time and therefore used the same SLO, ELE, and CPP in all the assessed

189   time periods (1950s-2010s, 1950s-1970s, 1970s-1990s, and 1990s-2010s). The methodological

190   sequence describing the input data, the modelling and validation approaches, and the generation

191   of predictions is shown in the Fig.2.

192   Overall, we investigated the historical, temporal, and spatial dynamics of NFC on Hainan

193   Island from the 1950s to the 2010s. We first applied simple linear regression to explore the

194   relationship between each road-related indicator and the NFC change rate of each grid cell in the

195   four assessed time periods. We used adjusted R^2 to estimate the explanatory power of each road-

196   related indicator in the simple linear regression model. The variation partition was also applied to

197   compare the effects of main roads vs. secondary roads on NFC change. Simple linear regressions

198   with the combined effect of the four road-related indicators of main road and secondary roads

199   were used to estimate the variation partition of different road types in the four assessed time

200   periods.

201   All analyses were conducted in R 3.2.3 (R Development Core Team, 2016) using the 'mgcv'

202   (Wood, 2011), 'caret' (Kuhn, 2016), 'randomForest' (Liaw & Wiener, 2002), 'DMwR' (Torgo,

203   2011) packages.

204   **Hot-spots analysis**

205   To quantify the degree of deforestation, the Getis-Ord Gi* statistic was computed to

206   measure the degree of spatial clustering of a local sample and its difference from the expected

207   value using the sum of the differences between values in the local sample and the mean, and is

208   standardized as a Z score (Scott & Warmerdam, 2005). The Z score reveals the spatial clustering

209   of features with either high or low values. To test the significance of the Z score the value within

210   a specific confidence level were compared. Positive Gi* values represent clusters that are greater

211   than the mean (reforestation Hot-spots), whereas negative Gi* values represent clusters that are

212   lower than the mean (Deforestation Cold-spots; Getis & Ord, 1996; Cohen et al. 2011). This

213   statistic represents the frequency of a hotspot relative to the number of input deforested points

214   covered the area. To identify spatial clustering patterns of NFC changes at 20-year intervals, hot-

215   spots analysis was performed using Getis-Ord Gi* statistics (Mitchell, 2005) with the 'Hot Spot

216   Analysis' function in ArcInfo 9.3. (ESRI, 2008).

217   The Getis-Ord Gi* was calculated as follows:

218

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \overline{X} \sum_{j=1}^{n} w_{i,j}}{s \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j} \right)^2 \right]}{n-1}}}$$

219   where x_j is the attribute value for feature j, $w_{i,j}$ is the spatial weight between feature i and j,

220   and n is equal to the total number of features. The G_i^* statistics is a Z score and thus, no further

221   calculations are required.

RESULTS

The temporal and spatial dynamics of NFC

224   NFC changes at 20-year intervals from the 1950s to the 2010s are shown in Fig. 3. We also

225   calculated the total NFC to explore the temporal dynamics of NFC from the 1950s to the 2010s.

226   The trend of total NFC indicated a considerable decrease from 41.4% in the 1950s to 24.2% in

227   the 2010s (Fig. 4; R^2=0.99, p=0.004).

228   In the 1950s, most grid cells with NFC >50% were identified in the central mountainous

229   regions, whereas those with NFC <20% were identified in the coastal regions (Fig. 3). The grid

230   cells with NFC⩽20% showed a significant increase from 433 to 839 from the 1950s to the

231   2010s (Fig. 3), whereas their distribution gradually shifed from the coastal regions to the

232   mountainous regions (Fig. 3). The grid cells with NFC > 50% mainly distributed in the central

233   and southern mountainous region, but showed a significant decrease from 544 to 286 from the

234   1950s to the 2010s (Fig. 3). These results revealed that that the natural forest decrease and also

235   fragmentized from the 1950s to the 2010s.

236   We used the slope of site-specific relationships between NFC and its change rate over time

237   to identify the dynamic change patterns of NFC. The slopes were positively correlated from the

238   1950s to the 2010s., indicating that a lower NFC tended to correspond to a higher rate of NFC

239   decrease (Fig. 5; F=122.3, $p<2.2\times10^{-16}$). Assessing the pattern of NFC change rate revealed that

240   most grid cells with low NFC change rate were distributed in the mountainous areas

241   (Jiangfengling, Yinggeling, and Wuzhishan mountains), whereas most grid cells with high NFC

242   change rate were distributed in the Qiongbei Platform (Fig. 5). Hot-spots analysis from the 1950s

243   to the 2010s showed that NFC decrease mainly occurred in the platform area, whereas NFC

244   increase occurred in the mountainous region (Fig. 6). However, NFC also increased in

245   Wenchang County, although this area is flat and well developed. When assessed at 20-year

246   intervals, the distribution of hot-spots with decreased NFC was observed to be shifted from the

247   eastern regions to the western regions of Hainan Island (Fig. 6).

248   **Dynamics of road expansion**

249   The density and configuration of the main road network markedly changed with the time

250   from the 1950s to the 2010s. The mean SRL of main roads increased from 0.11 km km^{-2} in the

251   1950s to 0.45 km km^{-2} in the 2010s (Table 1). The standard deviation of SRL of main roads also

252   increased, indicating that the distribution of main roads became more heterogeneous across the

253   grid cells. The mean DNR decreased from 0.30 km in the 1950s to 0.04 km in the 2010s (Table

254   1). The standard deviation of DNR also decreased, indicating that the spatial distribution of main

255   roads markedly increased. The average value of NON and MND of main roads increased from

256   the 1950s to the 2010s (Table 1), revealing that the configuration of the road network became

257   more complicated across the grid cells. The standard deviation of NON of main roads increased

258   from 0.04 ea km^{-2} to 0.23 ea km^{-2} from the 1950s to the 2010s, whereas the standard deviation of

259   MND of main roads had slightly decreased from 0.05 ea km^{-2} to 0.04 ea km^{-2}, revealing that the

260   configuration of the main road network became more complex and the spatial pattern of main

261   road was uneven across the grid cells.

262   The SRL of secondary roads increased from 0.18 km km^{-2} in the 1950s to 0.36 km km^{-2} in

263   the 1970s, but remained stable after the 1970s. The NON and MND of secondary roads also

264   showed the same trend both clearly increase in the 1950s to 1970s, but remained stable after

265   the 1970s (Table 1). The DNR of secondary roads had decreased from 0.11 km in the 1950s to

266   0.05 km in the 1970s, whereas only slightly changed after the 1970s. The standard deviation of

267   the four road-related indicators showed that the secondary road network markedly changed in for

268   the 1950s to 1970s, but remained stable after the 1970s (Table 1). The density and configuration

269   of the secondary road network markedly changed from the 1950s to 1970s, whereas it changed

270   only slightly after the 1970s (Table 1).

271   Both the main road and secondary road network obviously developed from the 1950s to the

272   2010s: however, the construction processes were faster in the former than the latter. Overall, the

273   density and configuration of the road network was higher and more complex after nearly 60

274   years of construction.

275   **Effects of different road expansion on NFC change**

276   The change of SRL of main roads explained 11.20% ($p < 0.001$) of the variance in NFC

277   change from the 1950s to the 2010s and was also the strongest indicator in the other three

278   assessed time periods (1950s-1970s, Adjusted R^2 = 14.22%, p < 0.001; 1970s-1990s, Adjusted

279   R^2 = 20.73%, p < 0.001; and 1990s-2010s, Adjusted R^2 = 4.89%, p < 0.001; Table 2). In the

280   1950s-2010s, the overall variation partition of main roads (Adjusted R^2 = 23.40%; p < 0.001) in

281   the simple linear regression was much higher than the secondary roads (Adjusted R^2 = 13.30%; p

282   < 0.001). The change of main roads also explained a higher degree of the variance than the

283   change of secondary roads in the other three assessed time periods. These results indicated that

284   the main road network had a more significant effect on deforestation than the secondary road

285   network from the 1950s to the 2010s.

286   In the 1990s-2010s, the adjusted R^2 of the main road network decreased from 25.2% to 5.10%

287   (Table 2), whereas that of the secondary road network decreased from 8.99% to 0.12% (Table 2),

288   showing that the association between the road network and deforestation weakened with time.

289   However, the main road network still showed linkage stronger association with NFC change than

290   the secondary road network (5.10% vs. 0.12%).

291

DISCUSSION

NFC reduction and fragmentation

294   Our results demonstrated that the total NFC of Hainan Island decreased significantly from

295   the 1950s to the 2010s (Fig. 4), and the distribution of grid cells with NFC < 20% increased in

296   the mountainous regions and thus became more vulnerable to deforestation (Fig. 5). These

297   patterns are consistent with those reported in other tropical regions, in which natural forest

298   deforestation is always accompanied by fragmentation (Pimm, 1998; Laurance et al., 1998;

299   DeFries et al., 2005). Natural forest that is severely fragmented shows small patches of natural

300   forest that are highly vulnerable to clearing (Stickler et al., 2013; Taylor, 2013). We also

301   observed that the grid cells with NFC > 50% were located in areas with a high altitude and steep

302   slope (Fig. 3), in which mechanisation and accessibility are limited (Freitas, Hawbaker &

303   Metzger, 2010; Hu et al., 2016). Most nature reserves on Hainan Island were similarly

304   distributed in the mountainous regions with high altitude and steep slope (Lin et al., 2015).

305   Although some grid cells located in some mountainous regions showed a moderately high degree

306   of recovery (Fig. 5), most of them with NFC >50% was shrank and fragmented.

307   Natural forest fragmentation is a major issue in tropical environments, since the spatial

308   arrangement and geometric configuration of fragments can impair ecological processes. Six

309   general fragmented patterns have been recognised at the global scale in previous work (Geist &

310   Lambin, 2002; Mertens & Lambin, 1997) , of which five are observed in the Amazon tropical

311   forest—rectangular, fishbone, radial, dendritic, and 'the stem of the rose' (Arima et al., 2005).

312   Road network architecture plays a critical role in shaping forest fragmentation patterns in the

313   Amazon (Arima et al., 2005; Soares-Filho et al. 2006; Walker et al. 2013). We also revealed that

314   the road network expansion explained more than 30% of natural forest deforestation and

315   fragmentation on Hainan Island from the 1950s to the 2010s (Table 2; Fig. 5). When the road

316   network was overlaid by grid cells with high NFC (Appendix 6; Fig. S2), we found that the

317   dominant fragmented pattern of Hainan Island natural forest was radial and dendritic. Unlike the

318   Amazon, road construction combined the complex topography determined the pattern of natural

319   forest landscape on Hainan Island (Fig. 1). Thus, forest fragmentation patterns on the Hainan

320   Island were highly affected by road construction and topography.

321   Our analysis showed that hot-spots with decreased NFC mainly occurred in the Qiongbei

322   Platform (Fig. 5), following a dynamic spatial distribution pattern from east to west, whereas

323   hot-spots with increase NFC occurred in Wenchang County (Fig. 5), an area that is flat and well

324   developed with a frequent typhoon occurrence during the summer. The local residents preserved

325   some small patches of natural forest around the villages and buildings, known as "geomantic

326   forest", as a protecting shield against the severe weather events.

Effect of road network on natural forest deforestation

328   Road-related indicators are not the actual drivers of NFC decrease, but they play a role in

329   natural forest dynamics through land-use changes and deforestation (Freitas, Hawbaker &

330   Metzger, 2010; Newman, McLaren & Wilson, 2014). The development of roads and road

331   networks is strongly correlated with the economic growth and is associated with the ecological

332   disturbance and natural forest degradation (Wilkie et al., 2000; Laurance, Goosem & Laurance,

333   2009). In tropical forests, roads have a low direct effect on habitat loss, but a high indirect effect

334   on the spatial patterns of deforestation (Fearnside, 2008), since they facilitate accessibility,

335   resource extraction, and human activities (Selva et al., 2011; Hu et al., 2016). Our results were

336   consistent with those of previous studies that also reported the significant effect of road networks

337   on natural forest deforestation in tropical regions (Perz et al., 2007; Gaveau et al., 2009; Freitas,

338   Hawbaker & Metzger, 2010; Cai, Wu & Cheng, 2013; Li et al., 2014; Arima et al., 2016; Hu et

339   al., 2016). We demonstrated that road-related indicators played a substantial role in determining

340   the deforestation of NFC in Hainan. The SRL of main roads was one of the strongest variables

341   associated with NFC change dynamic in the four assessed time periods(Table 2). However, the

342   power of road network in explaining the NFC reduction weakened over time, in both main and

343   secondary roads, probably revealing the underlying socio-economic processes of road expansion

344   itself (Perz et al., 2007).

345   The influence of road networks on deforestation is associated to population migration and

346   various socio-economic events. Large populations moved to Hainan Island, since it is area rich in

347   natural resources (Yan, 2008). After the foundation of People's Republic of China in 1949, the

348   economy became a key element in the national strategic plan. Both agriculture and forest

349   farming developed rapidly, and large agricultural populations migrated to Hainan Island under

350   the conduct of the national government. In the 1960s and 1970s, the 'sent-down youth'

351   movement influenced the social activity and increased migration to Hainan. In the 1950s-1970s,

352   roads were constructed for accessing land and timber resources and thus, the main road and

353   secondary road network was markedly associated to natural forest deforestation (Table 2). In

354   1988, Hainan Island was established as a provincial agency and Economic Development Zone,

355   leading to another population migration event, mainly of urban population. In the 1970s-1990s,

356   roads were built for accessing land resources and linking major cities and towns; thus, the main

357   road network had a stronger influence on deforestation than the secondary road network (Table

358   2). In the early 1990s, the industrial structure of Hainan Island was transformed and upgraded.

359   The tertiary industry, especially tourism, became the core of economic development, changing

360   the functions of road construction. Additionally, the Hainan Provincial Government established a

361   natural forest logging ban in 1994 in response to the sharp decline in NFC (Standing Committee

362   of Hainan Provincial People 's Congress, 1993). Consequently, the association between the road

363   network and deforestation weakened in 1990s-2010s (Table 2).

364   Deforestation was more affected by the main road network than the secondary road network

365   in the four assessed time periods (Table 2). Population was the most important factor affecting

366   NFC on Hainan (Zhang, Uusivuori & Kuuluvainen, 2000; Lin & Zhang, 2001). The main road

367   network of Hainan Island includes expressways, highways, and simply-built highways built or

368   funded by the national or provincial governments for geopolitical purposes, especially for

369   connecting major cities. The secondary road network includes cart roads and rural roads built or

370   funded by the city and county governments for supporting local livelihoods, connecting

371   communities, and accessing land and other natural resources. The construction of main roads

372   improves the connectivity of major cities, supports urbanisation (Perz et al., 2008), and thus,

373   highly increases deforestation. The construction of secondary roads also promotes deforestation,

374   but in a smaller scale than that of main roads (Fig. S2).

375   **Implications for natural forest conservation and management**

376   Our study provided significant information for natural forest conservation and management.

377   At a global scale, ecosystems decline and become fragmented (Saunders, Hobbs & Margules,

378   1991; Fischer & Lindenmayer, 2007), and thus, the small natural forest patches represent large

379   elements of tropical natural forest (Tulloch et al., 2016). Theoretical and experimental studies

380   have highlighted the importance of conserving large contiguous natural forest patches for

381   maintaining biodiversity (Bender, Contreras & Fahrig, 1998; Mortelliti et al., 2014).

382   Consequently, conservation actions have mainly focused on preserving large contiguous forest

383 patches and not relatively small fragmented forest patches (Ovaskainen, 2002; Tulloch et al.,

384 2016). Small fragmented forest patches contribute to short-term and long-term indigenous

385 species persistence; enhance the biodiversity in human-dominated fragmented landscapes

386 (Turner & Corlett, 1996); positively affect the diversity of forest bird and mammal species, forest

387 plant species, and migratory animals as well as the persistence of meta-populations (Laurance,

388 1994; Warkentin, Greenberg & Salgado Ortiz, 1995; Jacquemyn, Jan Butaye & Hermy, 2001);

389 act as refuges for plant and animal species; and help conservationists to launch a final attempt to

390 rescue endangered species   that may serve as sources of natural forest reconstruction (Turner &

391 Corlett, 1996). In Hainan, small natural forest patches are formed from the fragmentation of

392 larger contiguous natural forest patches. Those small natural forest patches are isolated and

393 always have an area less than 10 ha in Hainan. Those small natural forest patches are always

394 located at the edge of large contiguous natural forest in the mountainous region or around the

395 villages in the flat region, and provide important ecosystem services for local residents. For

396 example, the "Geomantic forest" in Wenchang and Qionghai counties is an example of small

397 natural forest patches- with typical tropical forest structure, but high plant diversity (Yang & Wu,

398 2002), distributed in the Lingnan region that includes the modern Chinese provinces of Jiangxi,

399 Hunan, Guangdong, Guangxi, and Hainan. The Geomantic forest is related to the Fengshui

400 Theory, which includes historical and cultural features of ecological significance, and provides

401 important ecosystem services such as water and soil conservation as well as protection against

402 severe weather events (Cheng, He & Liu, 2009). Due to this forest, the NFC of Wenchang

403 county increased from the 1950s to the 2010s (Fig. 5). Thus, the protection of small natural

404 forest patches is important, and long-term data need to be used for developing effective

405 management with specific conservation objectives. Regions with low NFC tend to be more

406 vulnerable in natural forest loss (Fig. 5). The natural forest loss and fragmentation patterns are

407 dynamic on Hainan (Fig. 6). Our results showed that the spatial and temporal change patterns of

408 NFC could be accurately assessed using historical data (Newman, McLaren & Wilson, 2014).

409 Thus, conservationists and decision-makers need to evaluate natural forest changes and develop

410 effective management actions (Margules & Pressey, 2000). On Hainan Island, regions with low

411 NFC, but high ecological value (Yangshan region in Haikou city; the Geomantic forest in

412 Wenchang city; Fig. 3) located in flat areas that are well developed and have high population

413 density, are more vulnerable than natural forest within the nature reserves. Thus, conservation

414 frameworks and forest restoration projects are needed to preserve or recover the natural forest.

415 The NFC in the mountainous region increased in the past 60 years; however, regions with

416 high NFC are vulnerable to fragmentation due to the expansion of the road network in some

417 remote regions in the mountains (Fig. S2). The south-central mountainous region of Hainan

418 Island is a biodiversity hotspot (Myers et al., 2000) and thus, a priority area for conservation in

419 China (Ministry of Environmental Protection of the People 's Republic of China, 2011).

420 Monitoring the natural forest in using remote sensing and drones could help in protecting the

421 natural forest and predict any future changes (Paneque-Gálvez et al., 2014).

422

423 **CONCLUSIONS**

424 This study used historical data to reconstruct NFC maps in order to better understand the

425   spatial and temporal change patterns. The road network was identified as an important factor of

426   forest loss and fragmentation of tropical forests. Although the exact distribution of natural forest

427   was not depicted, we found that the dominant fragmented pattern of Hainan Island natural forest

428   is radial and dendritic.

429   Our study showed that: (1) low NFC corresponds to a high rate of NFC decrease as well as

430   highly dynamic spatial and temporal change patterns of NFC; (2) the road network significantly

431   affected NFC, whereas topography affected deforestation by influencing the road network

432   construction pattern; and (3) the effect of road network on NFC was related to population

433   migration and socio-economic events, and the main road network had a stronger relation to

434   deforestation than the secondary road network.

435   Deforestation and fragmentation still occur in Hainan, and public concern remains

436   pronounced in recent years. Thus, it is crucial to better understand implications of deforestation

437   on biodiversity conservation, as well as the driving forces of deforestation. Conservation efforts

438   must focus on small natural forest patches using new technologies (e.g. remote sensing and

439   drones) that will improve monitoring and data collection.

440   Although our model was incomplete, since it only included topography, climate and road

441   network data, it revealed the spatial and temporal change patterns of NFC on Hainan Island.

442   Future modelling studies need to build an improved model, combining historical, natural, and

443   socio-economic factors that will help to better understand the underlying mechanisms of NFC

444   change patterns.

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Figure 1

Location and topography of Hainan Island, China.

JFL, Jianfengling Mountain; BWL, Bawangling Mountain; YGL, Yinggeling Mountain; WZS, Wuzhishan Mountain; DLS, Diaoluoshan Mountain.

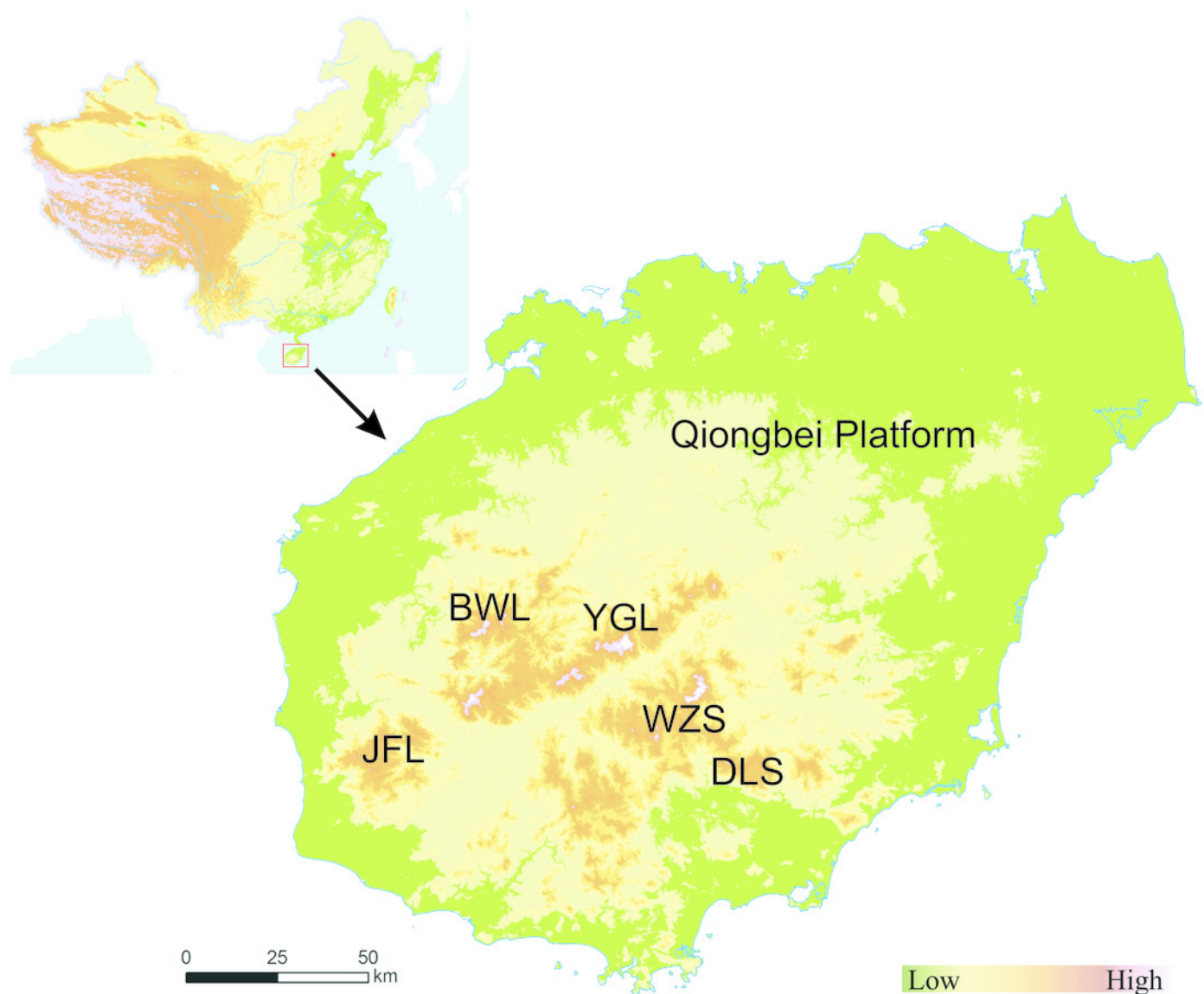



Figure 2

Flowchart showing the methodological sequence describing the input data, the modelling and validation approaches, and the generation of predictions.

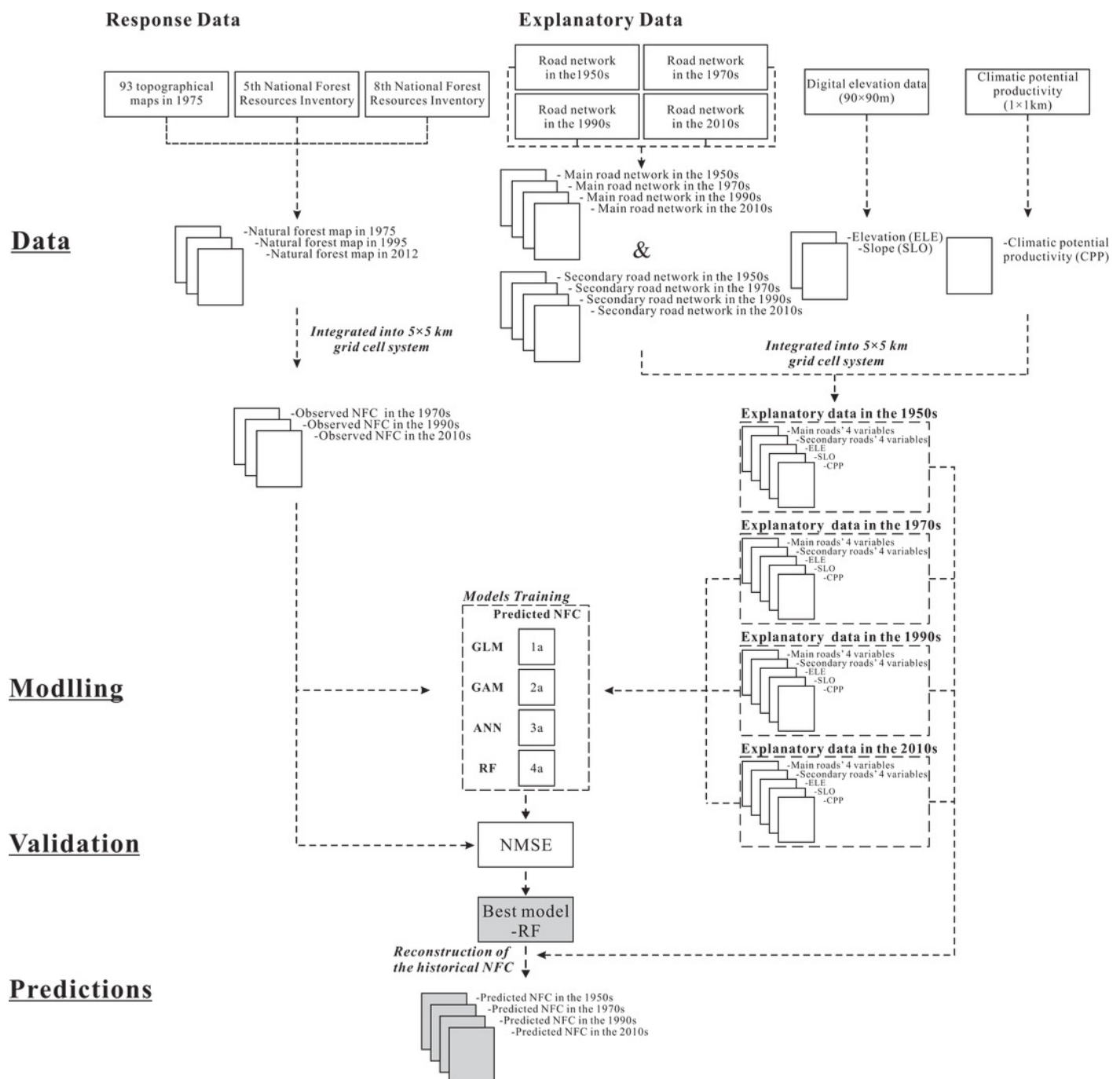



Figure 3

Distribution patterns and histogram statistics of natural forest cover (NFC) in the 1950s (A), the 1970s (B), the 1990s (C) and the 2010s (D) on Hainan Island.

Natural Forest cover (NFC,%)

| ≤ 10 | 10.1-20 | 20.1-30 | 30.1-40 | 40.1-50 | 50.1-60 | 60.1-70 | 70.1-80 | 80.1-90 | 90.1-100 |

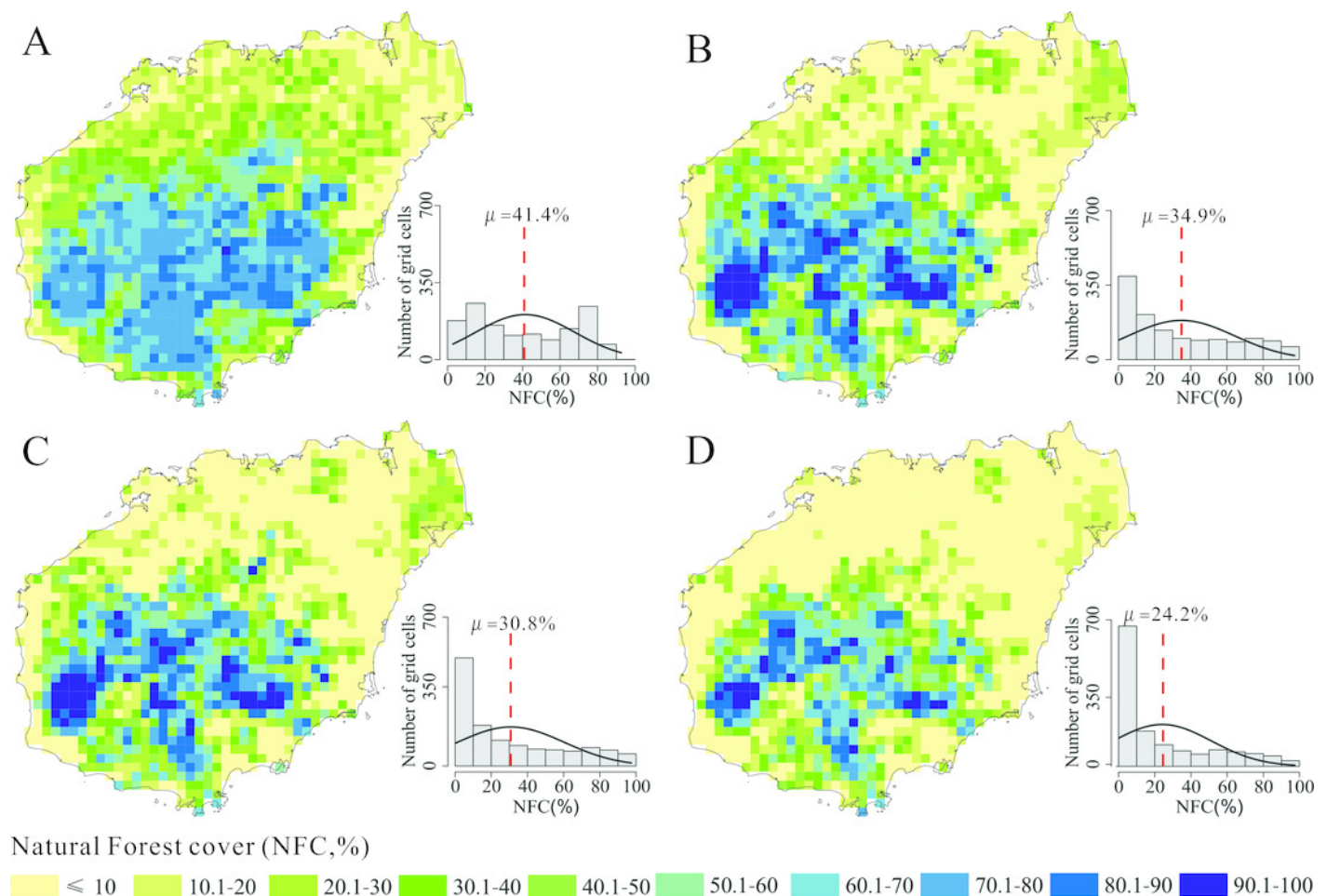



Figure 4

Trend of total natural forest cover (NFC) from the 1950s to the 2010s on Hainan Island.

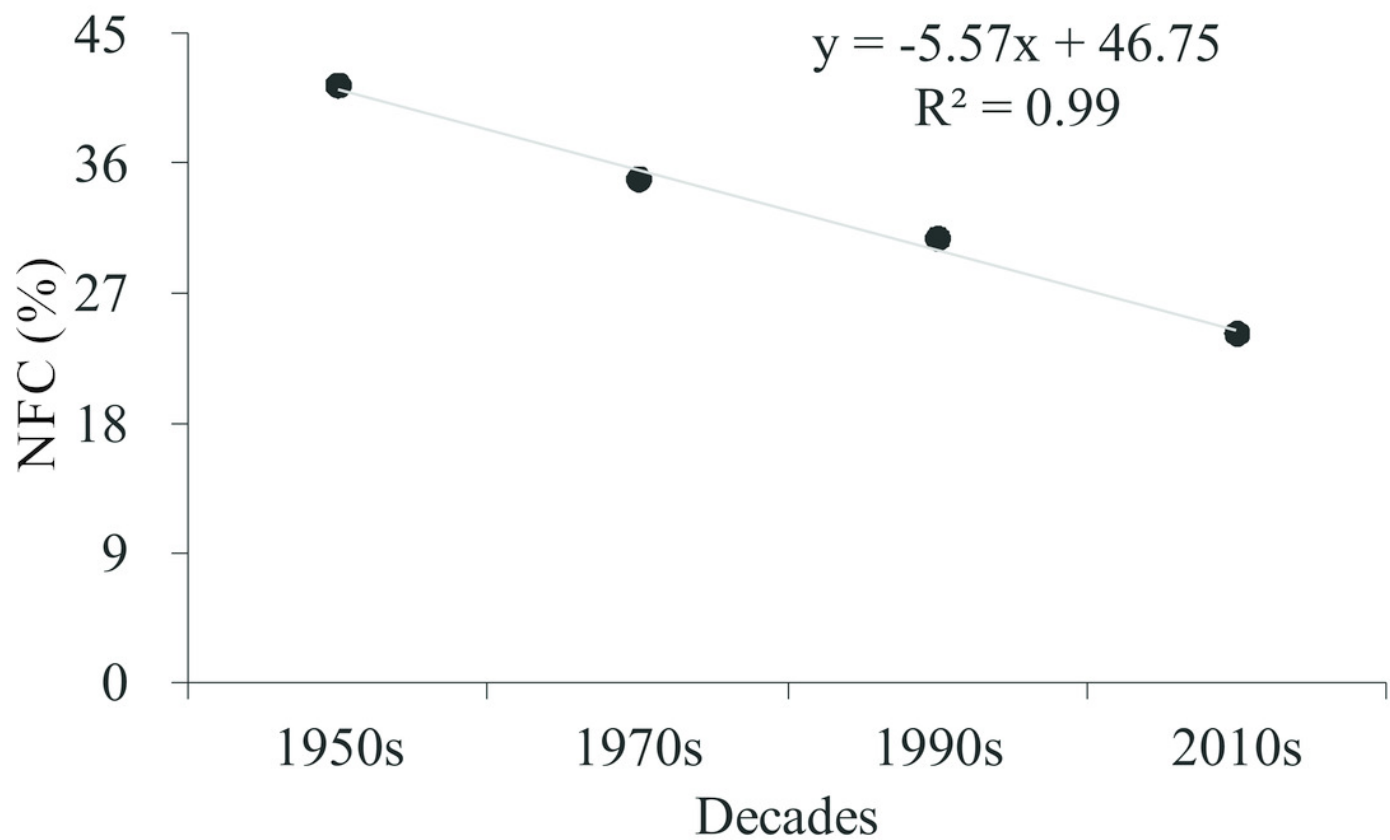



Figure 5

The site-specific relationships between NFC and its change rate (A), and the distribution pattern of change rate (B) from the 1950s to the 2010s.

Green represents high NFC (≥60%) in the 1950s and had NFC increased from the 1950s to the 2010s; Red represents low NFC (≤20%) in the 1950s and had NFC decreased from the 1950s to the 2010s.

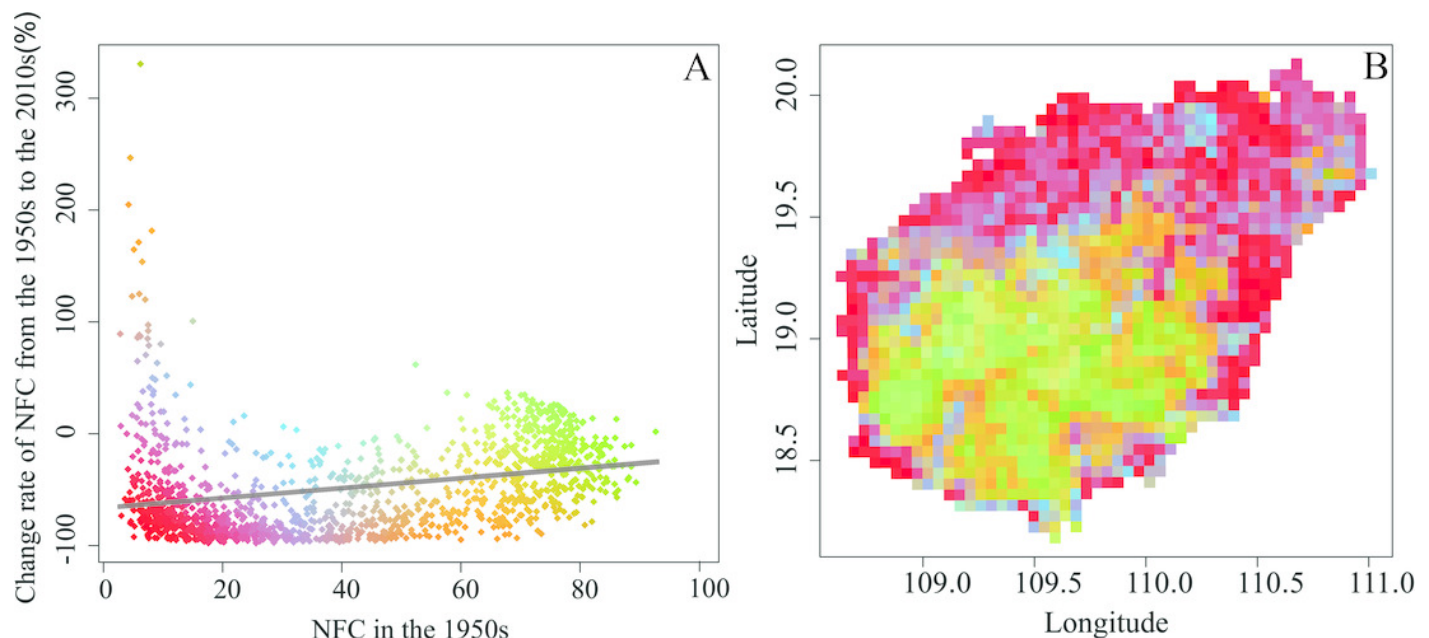
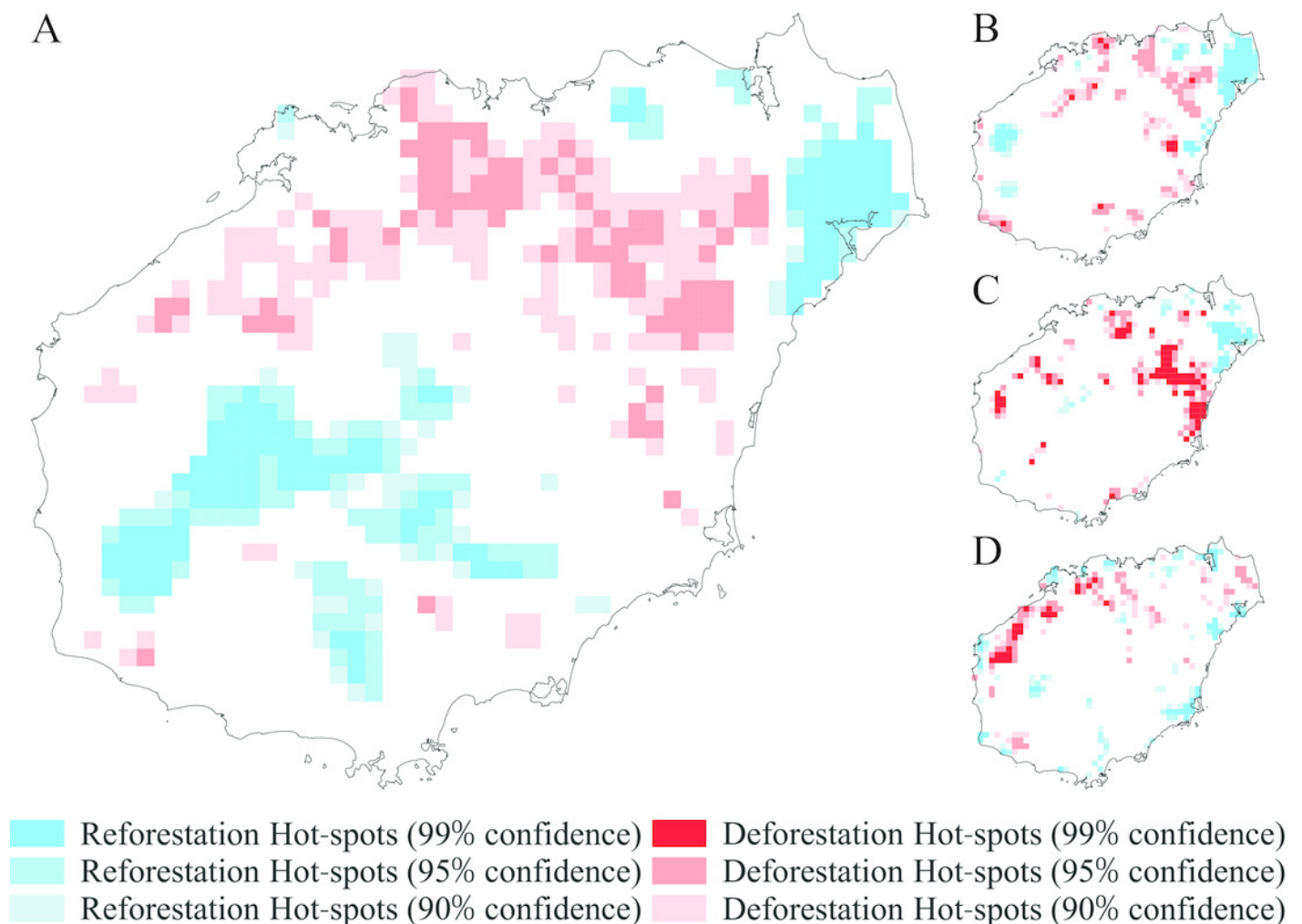



Figure 6

Hot-spots of natural forest cover (NFC) decrease and increase in four assessed periods: 1950s-2010s (A), 1950s-1970s (B), 1970s-1990s (C), and 1990s-2010s (D) on Hainan Island.

Changes in road-related variables of main and secondary roads from the 1950s to the 2010s on Hainan Island.

Data are the means and standard deviation of all grid cells. SRL, sum of road length (km km^{-2}); DNR, distance from the grid cell centroid to the nearest road (km); NON, number of nodes of road network (ea km^{-2}); MND, mean number of roads connected by each node (ea km^{-2}).

1 **Table 1**

		1950s	1970s	1990s	2010s
SRL	Main road	0.11±0.17	0.23±0.22	0.27±0.24	0.45±0.27
	Secondary road	0.18±0.18	0.36±0.23	0.36±0.23	0.36±0.23
DNR	Main road	0.30±0.29	0.09±0.08	0.08±0.08	0.04±0.04
	Secondary road	0.11±0.11	0.05±0.05	0.05±0.04	0.05±0.04
NON	Main road	0.01±0.04	0.09±0.20	0.11±0.20	0.20±0.23
	Secondary road	0.03±0.06	0.23±0.21	0.23±0.21	0.23±0.21
MND	Main road	0.02±0.05	0.04±0.04	0.05±0.04	0.07±0.04
	Secondary road	0.03±0.05	0.05±0.03	0.05±0.03	0.05±0.03

The explanatory power (Adjusted R^2, %) of the change of road-related indicators in a simple linear regression model.

SRL, sum of road length; DNR, distance from the grid cell centroid to the nearest road; NON, number of nodes of road network; MND, mean number of roads connected by each node. The p value represents the significance level of the relationship between NFC change rate and change of road-related indicators. *, significant at $p < 0.05$; **, significant at $p < 0.01$; ***, significant at $p < 0.001$.

1   **Table 2**

Change of road-related indicators		Change of NFC in the 1950s–2010s		Change of NFC in the 1950s–1970s		Change of NFC in the 1970s–1990s		Change of NFC in the 1990s–2010s	
Type of road	Indicators	Adjusted R^2	p value	Adjusted R^2	p value	Adjusted R^2	p value	Adjusted R^2	p value
Main road	Change of SRL	11.20	< 0.001***	14.22	< 0.001***	20.73	< 0.001***	4.89	< 0.001***
	Change of DNR	11.07	< 0.001***	0.27	0.031*	5.97	< 0.001***	0.45	0.007***
	Change of NON	4.83	< 0.001***	4.37	< 0.001***	19.03	< 0.001***	1.76	< 0.001***
	Change of MND	5.59	< 0.001***	8.31	< 0.001***	7.35	< 0.001***	2.30	< 0.001***
	Overall	23.40	< 0.001***	17.67	< 0.001***	25.20	< 0.001***	5.10	< 0.001***
Secondary road	Change of SRL	0.32	0.021*	0.14	0.089	0.36	0.015*	< 0.01	0.613
	Change of DNR	7.14	< 0.001***	5.26	< 0.001***	<0.01	0.801	0.32	0.021*
	Change of NON	5.11	< 0.001***	2.26	< 0.001***	<0.01	0.932	0.01	0.422
	Change of MND	0.22	0.045*	1.11	< 0.001***	<0.01	0.505	0.01	0.605
	Overall	13.3	< 0.001***	8.99	< 0.001***	0.31	0.085	0.12	0.228
Main road & Secondary road		30.7	< 0.001***	22.5	< 0.001***	26.0	< 0.001***	5.4	< 0.001***