Demography of threatened tree species in Vietnam

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Demografie van bedreigde boomsoorten in Vietnam
(met een samenvatting in het Nederlands)

Động thái quần thể các loài cây bị đe dọa ở Việt Nam
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To Ha and Duy

Contents

Chapter 1

General introduction

Forest status in the tropics

Tropical forests are characterized by a very high plant diversity: covering less than 10% of the land areas, they posses more than 50% of all known plant species on earth (Wilson 1995, Mayaux et al. 2005). In a single ha of these forests, as many as 300 tree species can coexist (Gentry 1998b), although a large difference may occur between continents and regions (Givnish 1999, ter Steege et al. 2000). Yet, during the past decades, tropical forests have severely declined, with around 6 million ha lost and more than 2 million ha visibly degrading each year (Achard et al. 2002). The main causes for the loss of tropical forests are agricultural expansion, over-harvesting, development of plantations, mining operation, industry, urbanization and road building (Geist & Lambin 2002). As a result, an unknown, but large number of species has become extinct, while many others run the risk of extinction (Frankham et al. 2002, World Conservation Union 'IUCN' 2006). Among tropical areas, South-East Asia has the highest relative rate of deforestation (Achard et al. 2002, Brook et al. 2006), also is facing a serious problem of species extinction (Sodhi et al. 2004, IUCN 2006).

Tropical forests in Vietnam

Three quarters of Vietnam is composed of hills and mountains, which was originally covered by tropical forests (Trung 1998). Being a venue of plant species emigrated from three flora areas: the Himalaya-Yunnam-Guizhou flora in the North-West, the India-Myanmar flora in the West, and the Malaysia-Indonesian flora in the South and South-East, Vietnam harbours a very high number of plant species (Trung 1998, Chan et al. 1999, Lap 1999) (for details see Chapter 2). Nevertheless, due to many reasons, such as rapid changes in land use, over-harvesting and long wars, the forests of Vietnam have severely declined, both in quantity and quality (Dang et al. 2001, for details see Chapter 2). Consequently, many species of Vietnam run the risk of extinction (Nghia 2005), of which around 150 are critically endangered and vulnerable (IUCN 2006). As threatened tree species often occur in small and isolated populations (Ministry of Science, Technology and Environment 'MSTE' 1996, cf. Ouborg 1993), they are very vulnerable to local extinction due to demographic stochasticity or lack of genetic variation (Menges 1992; Lande 1993; Oostermeijer et al. 2003). On the other hand, tropical trees are often slow-growing, long-lived species, taking a long time to reach the age of reproduction (Chambers et al. 1998, Fichtler et al. 2003, Laurance et al. 2004), and this makes it difficult to determine whether the population is growing or declining in size (Kwit et al. 2004). It is therefore necessary to carry out a demographic study for these species in order to decide on actions before they have declined below the critical level.

The context of this study

In this dissertation, a demographic study of six threatened tree species was carried out in four protected areas in Vietnam: *Annamocarya sinensis* and *Parashorea chinensis* in Cuc Phuong National Park, *Calocedrus macrolepis* and *Manglietia fordiana** in Ba Vi National Park, *Dacrydium elatum* in Bach Ma National Park, and *Pinus kwangtungensis* in Hang Kia – Pa Co Nature Reserve. The status and distribution of the six species are presented in Chapter 3. The four protected areas are briefly described below.

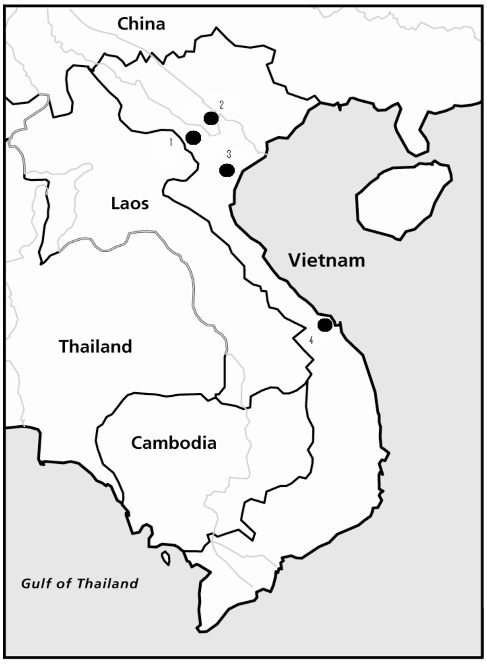

Figure 1
Location of four protected areas in Vietnam: Hang Kia – Pa Co Nature Reserve (1), Ba Vi National Park (2), Cuc Phuong National Park (3), and Bach Ma National Park (4).

Ba Vi National Park

Ba Vi NP is located in Ha Tay province (21°N, 105°E, Fig.1), about 50 km north-west of Ha Noi. Covering 12,023 ha, the Park includes low to middle high mountains, and is surrounded by plains. The climate in the region is characterized by an average precipitation of 2600 mm y^{-1}, an average annual temperature of 23°C and a pronounced cold and dry season from November to March (Forest Technique and Science Association of Vietnam 'FTSA' 2001). The natural forests occur at altitudes

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*: Some scientists call it *Manglietia hainanensis,* but we prefer the name *Manglietia fordiana* as *Manglietia hainanensis* is conspecific with *Manglietia fordiana* (Liang & Nooteboom 1993).

above 600 m above sea level (a.s.l.), but not at lower elevation due to a long period of overexploitation and agricultural practice (FTSA 2001). The natural forests are very diverse in species and structure, and can be distinguished into three main types at increasing elevation: Tropical evergreen broad-leaved rain forests, Subtropical evergreen broad-leaved rain forests, and Subtropical evergreen broad-leaved and coniferous forests (FTSA 2001)

The buffer zone of the Park is inhabited by 47,000 inhabitants of whom nearly half belong to ethnic minorities. Most local people are poor as their incomes are mainly derived from forests and poor practice of agriculture (FTSA 2001).

Bach Ma National Park

Bach Ma NP covers 22,030 ha in Central Vietnam (16°N, 105°E, Fig.1). Due to a complex terrain, the annual precipitation of the region strongly varies among places, ranging from 3000 in the lower parts to over 8000 mm yr^{-1} at altitudes above 700 m a.s.l., with the rainy season from September to February (FTSA 2001, Keo 2003). The average temperature in the rainy season is around 20ºC compared to 25ºC in the dry season (FTSA 2001). The Park has two main patterns of forests in relation to elevation. The evergreen tropical forest covers areas below 900 m of which around 2700 ha are considered intact forests, but the rest is secondary forest as a result of a long time of overexploitation and wars. From 900 m a.s.l. to the highest mountain (1450 m a.s.l.), there is evergreen subtropical forest (FTSA 2001, Keo 2003)

There are more than 63,000 inhabitants living in the buffer zone of the Park, and most of them are King People. The main incomes of the inhabitants are from agriculture and forest products. Their standard of living is in general very low (FTSA 2001).

Cuc Phuong National Park

The Park is located on the boundary intersection of three provinces: Hoa Binh, Ninh Binh and Thanh Hoa (20°N, 105°E, Fig.1). Its area is 22,200 ha. The average elevation of the Park is from 300-400 m, while the peak (May Bac) reaches to 648 m a.s.l. (Thu & Can 1999). The climate of the region is characterized by an average annual temperature of 21°C, and the average rainfall of 2150 mm y^{-1}. Most the rainfall falls in the summer, from March to November (FSTA 2001). Three main types of the forests can be distinguished in the Park (FSTA 2001). The forests covering the valleys and foot hills are characterized by 3 layers of tree species, a layer of shrubs and a layer of fern and grass. The forests on mountain slopes include 2 layers of tree species and 1 layer of shrubs. The forests at the top of mountains have only two distinct layers: a layer of small tree species and shrubs, and the under storey.

There are more than 50,000 inhabitants living in the buffer zone of the Park, and most of them are ethnic minorities. Their main livelihoods are agricultural practice, and extraction of forest products from the park. The standard of living of the local people is very low (FTSA 2001).

Hang Kia - Pa Co Nature Reserve

The Reserve comprises 7,091 ha in the high mountain area of Hoa Binh province (20°N, 104°E, Fig.1). With an average altitude of 1200 m a.s.l., the Reserve has a complex terrain of limestone mountains alternated by valleys (Hoa Binh Community 'HBC' 1993, Nghia 2000). The Reserve lies in the subtropical climate zone, characterized by two pronounced seasons: hot and cold. The average temperature of the hot season (March – September) is around 20°C as against 3 to 10°C for the cold season. The average rainfall is 1900 mm y^{-1}, and most falls in the hot season (HBC 1993).

The Reserve has more than 4,000 inhabitants living in the core, and 6,000 others living in the buffer zone. Most local people are ethnic minorities, whose standard of living is very low compared with other regions of the country (HBC 1993). Particularly, most people living in the core are H-Mong, whose livelihoods are mainly based on shifting cultivation, and forest extraction. They are now experimenting with permanent agriculture, but still extract products from the forests (HBC 1993).

The present study

This research project formed part of the Tropenbos International - Vietnam Programme in cooperation with Utrecht University and the Forest Science Institute of Vietnam.

Tropenbos International (TBI) is a non-governmental organization funded by the Dutch Government. The main objective of TBI is to improve conservation status and sustainable use of tropical rain forests by generating and developing applicable methodologies and making these locally available. TBI also aims to strengthen the local research capacity of the tropical countries by cooperation and training. To do so, TBI has carried out multi-disciplinary research programmes in cooperation with research institutions, government agencies and other stakeholders of tropical countries, e.g. Guyana, Colombia, Suriname, Ghana, Indonesia, and Vietnam (for details see the website: www.tropenbos.org).

Tropenbos International - Vietnam (TBI – Vietnam) was established in 2001 with the main research site is in Central Vietnam. The main activities of TBI - Vietnam are to support the establishment of the National Forest Research Strategy of Vietnam. It also helps to generate and disseminate information, methodologies and technologies in support of the conservation and sustainable use of Vietnamese forests. The results thereof are subsequently supported to be transferred into policy and practical forest management. In addition, TBI - Vietnam supports to build research capacity in the forestry sector by providing short and long training programmes, both in the country and overseas (for details see the website: www.tropenbos.org).

The Forest Science Institute of Vietnam (FSIV) is the main research institution on forestry of Vietnam. Its main tasks are to organize and implement research on forestry ranging from ecology, silviculture, forest industry, and forest economics to forestry organization and management. It is also responsible for post-graduate training and international research cooperation on forestry (for details see the website: www.fsiv.org.vn).

In 2002, within the framework of the TBI – Vietnam activities, the Department of Plant Ecology and Biodiversity, Utrecht University, and the Forest Science Institute of Vietnam started intensive cooperation on plant ecological training and research, resulting in several cooperation projects. In 2003, one of these cooperation projects, named: "Generating and disseminating knowledge on conservation and use of Vietnamese tree species" started running with the funding partly supported by TBI – Vietnam, Utrecht University and the Forest Science Institute of Vietnam. This dissertation is a result of this cooperation project.

Objectives of this study

The objectives of the study are:

1. to analyse the demography of six threatened tree species in four protected areas in Vietnam;
2. to project the future prospects of these six species, given current status and dynamics of remaining populations;
3. to propose conservation and restoration measures for the six study species;
4. to evaluate the effects of matrix dimension on model output.

Outline of the thesis

This thesis addresses the demography of six threatened tree species in four protected areas in Vietnam. It includes six chapters, which are briefly presented below:

Chapter 2 describes the general setting, presenting short descriptions of geography, climate, landscapes and soil types in Vietnam. Also, the forest status is described, pointing out the causes of forest degradation and its consequences to the flora and threatened tree species. In addition, the system of protected areas in Vietnam and their roles in conservation are discussed.

Chapter 3 analyses the demography of six threatened tree species in Vietnam. A demographic field study in four protected areas provides the basic data for constructing matrix models, which are used to project the population performances of the six species and to determine the most important life stages for the population growth rates. Based on these results, conservation measures are suggested.

Chapter 4 uses population viability analysis (PVA) to project the development of the study populations in the future. By applying stochastic matrix models, the development of study populations under the influence of the environmental and demographic stochasticity is estimated and discussed.

Chapter 5 analyses methods to estimate tree ages using matrix models. By comparing tree ages obtained from annual rings with those obtained from matrix models, suitable matrix dimensions for estimating ages, population growth rates and elasticity are discussed.

Chapter 6 summarizes the main results of the thesis and provides a general discussion.

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Note: * The initial titles in Vietnamese were translated into English.

Chapter 2

Vietnamese forestry, biodiversity and threatened tree species

With M.J.A. Werger & N.H. Nghia

Introduction

A successful conservation strategy requires a good understanding of the natural and social conditions and their relations to the strategy's objectives. This is particularly important for the tropical countries, where the forests are very diverse in species and complex in structures, but being lost at an alarming rate (Wilson 1988, Whitmore 1997, Sodhi et al. 2004). Tropical countries, on the other hand, have among the world' highest population (people) growth rates, which are the most crucial underlying cause of deforestation (Laurance 1999, Wright & Muller-Landau 2006).

In this chapter, we present several natural conditions of Vietnam, a tropical country located in South-East Asia. We also discuss the plant biodiversity, forest status, protected areas and the relationship among people, forests and threatened tree species with recommendations for a better conservation.

Geographical location

Vietnam is located in Southeast Asia, sharing boundaries with China (1400 km) in the North, with Laos (2067 km) and Cambodia (1080 km) in the West and having the East Sea in the East. The country has a total land area of 330,991 square km, and stretches over 3,200 km between the latitudes of 8°30' and 23°22' N, and between the longitudes of 102°10' and 109°24' E (Thao 1998, Lap 1999). Three quarters of the country is composed of hills and mountains with the highest peaks reaching over 3,000 m above sea level (a.s.l.) (Government of the Socialist Republic of Vietnam and the Global Environment Facility Project 'GoVN' 1994, Nhat 2001).

The country is S-shaped in outline. It has two wide deltas, one in the south along Mekong River and one in the north along the Red River. The Middle of the country is almost completely occupied by the Truong Son Range, there being only a narrow strip of coastal plains (Thao 1998, Lap 1999). The Truong Son Range is divided into the North and the South of Truong Son by the Hai Van Pass. The Central Highlands lie at the South of the Middle, sharing boundaries with Cambodia in the west, with Southern Truong Son in the East and with the South-east region in the South (Soil

Science Association of Vietnam 'SSA' 1996). At its narrowest point in the Middle, the country is only 50 km across, while at its widest in the North, it is about 600 km. Most of the country drains directly into the East Sea, but the western parts of the Central Highlands drain into the Mekong basin of Cambodia and then into the East Sea (GoVN 1994, Trung 1998).

Climate

Vietnam basically has a tropical climate as it lies inside the Northern Tropical Zone. However, due to a varying monsoon regime and a complex terrain, the climate of Vietnam differs with latitude and altitude (Trung 1998, Lap 1999).

Sunshine regime

Situated in the Northern Tropical Zone, Vietnam receives a great amount of sunshine, though it differs from the South to the North. Each year, the South receives around 2000 to 3000 hrs of sunshine with mean cumulated intensity of 160 kcal cm^{-2} yr^{-1}, while the North has only 1400 to 2000 hrs and an intensity of between 110 to 140 kcal cm^{-2} yr^{-1} (Toan 1998, Lap 1999). Due to the complex terrain, the sunshine regime also differs per area. For instance, the North-East and Northern Truong Son Range annually receive around 1600 to 1800 hrs, while the South-East receives around 2600 to 3000 hrs (Lap 1999).

Monsoons

Three monsoonal systems affect the rainfall pattern in Vietnam. From September to April, the winter monsoon originating from Siberia, blows over a huge continental area (China), carries cold and dry air that causes cold and dry weather in the North of Vietnam (Toan 1998, Trung 1998, Lap 1999). This wind may also reach Vietnam via the East Sea, and then carries humidity from the sea, and produces drizzle in the North from December to January (Trung 1998). From May to October, there are two monsoonal systems affecting the country. The South-west Pacific monsoon blows to the country via Cambodia and Laos. When meeting the Truong Son Range, it causes a lot of rainfall in the west of the Range, but dry and hot weather in the East, particularly from June to August. The provinces of the Middle are strongly affected by this monsoon (Trung 1998, Lap 1999). In contrast, the South-east monsoon from the East Sea brings a lot of rainfall to the whole country. This monsoon may mitigate the unfavourable effects of the South-west monsoon as it brings a cool and rainy weather (Lap 1999).

Apart from the three monsoons mentioned above, the country is under the influence of typhoons bearing from the East Sea from July to November. The typhoons often bring strong wind and heavy rains, and may cause a severe flooding along the coastline, particularly in the middle of the country (GoVN 1994, Thin 2000, Nhat 2001).

Temperature

The temperature of Vietnam is generally high, but varies with seasons, latitudes and altitudes.

In the winter, the North and the Northern Middle (as far south as the Hai Van Pass) are cold as they are affected by the winter monsoon. However, the rest of the country does not have the winter weather due to the weak influence of this wind. The mean temperature of the coldest month (January) in Ha Noi (the North) is 16.4°C, Hue (the Middle) 19.7°C, but in Hochiminh City (the South) it is still 25.8°C (Table 1) (Trung 1998, Lap 1999).

Table 1. Monthly mean temperature of areas throughout the country (*°C*)

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Lang Son	13.3	14.3	18.2	22.1	25.5	26.9	27.0	26.6	25.2	22.2	18.3	14.8
Ha Noi	16.4	17.0	20.2	23.7	27.3	28.8	28.9	28.2	27.2	24.6	21.4	18.2
Vinh	17.6	17.9	20.3	24.1	27.7	29.2	29.6	28.7	26.8	24.4	21.6	18.9
Dong Hoi	19.0	19.3	21.7	24.9	28.0	29.7	29.7	29.1	27.0	24.8	22.4	19.9
Quang Tri	19.4	20.4	22.6	25.6	28.1	29.4	29.5	29.0	27.1	25.1	23.2	20.8
Hue	19.7	20.9	23.1	26.0	28.3	29.3	29.4	28.9	27.1	25.1	23.1	20.8
Da Nang	21.3	22.4	24.1	26.2	28.2	29.2	29.1	28.8	27.3	25.7	24.0	21.9
Quy Nhon	23.0	23.8	25.3	27.2	28.8	29.6	29.7	29.8	28.2	26.6	25.3	23.7
Phan Thiet	24.7	25.2	26.5	27.9	28.3	27.7	26.9	27.0	26.8	26.7	26.3	25.3
HCM City	25.8	26.7	27.9	28.9	28.3	27.5	27.1	27.1	26.8	26.7	26.4	25.7
Ca Mau	25.1	25.8	26.8	27.9	27.7	27.3	27.1	27.0	26.9	26.7	26.3	25.5

Source: Lap (1999)

In summer, however, the temperature does not differ much throughout the country. The mean temperature of the hottest month in Ha Noi (July) is 28.9°C, Hue (July) 29.4°C, and Hochiminh City (April) 28.9°C (Tabe 1) (Trung 1998, Lap 1999). There is a drop of about 0.5°C with every 100 m increase in altitude (Toan 1998, Lap 1999). From example in the South between 1000 and 1800 m altitude the mean annual temperature drops from 20°C to 15°C and the same happens between 700 and 1600 m in the North. Between these altitudes the mean temperature of the coldest month is below 15°C, and the lowest temperature in this month may be as low as 0°C

Table 2. Rainfall in areas throughout the country *(mm/rainy days)* (Lap 1999)

	I	II	III	IV	V	VI	VII	VIII	IX	X	XI	XII
Lang Son	24/7	41/10	53/12	96/12	165/13	200/15	258/17	255/17	164/13	79/8	34/6	23/6
Ha Noi	19/8	26/11	44/15	90/13	188/14	240/15	288/16	318/17	265/14	131/9	43/7	23/6
Quang Tri	157/15	66/12	66/12	58/9	110/10	81/7	80/8	110/8	436/15	621/19	491/20	281/18
Hue	161/16	63/11	47/10	52/9	82/10	117/9	95/8	104/10	473/16	796/21	581/22	297/19
Quy Nhon	65/12	32/6	24/4	32/4	63/7	61/6	55/5	59/7	245/15	463/20	423/20	170/18
Nha Trang	47/10	17/4	32/4	33/5	55/8	49/8	43/8	51/8	167/15	324/18	374/18	167/14
Vung Tau	2/1	1/1	5/1	33/3	188/5	206/18	213/20	178/19	214/19	215/16	69/7	23/4
HCM city	14/2	4/1	11/2	50/5	218/18	312/22	294/23	270/22	327/23	266/21	117/12	48/7
CanTho	12/2	2/1	10/1	50/3	177/14	206/17	227/18	217/18	273/19	277/18	155/11	41/5

(Trung 1998). From 1600 to 2600 m in the South and from 1600 to 2400 m in the North the annual mean temperature drops from 15°C to 10°C, and in the coldest month the temperature is less than 10°C with the minimum temperature below 0°C. At higher altitudes, it is cold throughout the year, and there is sometimes snow in the winter (Trung 1998).

Rainfall

In general, Vietnam has a high annual rainfall and it varies with latitude, altitude and seasonally. The annual rainfall of Ha Noi (the North Delta) is 1676 mm yr^{-1}, Hochiminh City (the South Delta) 1931 mm, and Quy Nhon (a delta of the Middle) 1692 mm yr^{-1} (Table 2, Lap 1999). The high mountains, which trap monsoons, often have a high rainfall, such as Sapa (Hoang Lien Son Mountains) 2833 mm yr^{-1}, and Hon Ba (Truong Son Mountains) 3751 mm yr^{-1} (Lap 1999). Particularly at Bach Ma (Truong Son Mountains) the annual rainfall is very high: more than 8000 mm yr^{-1} at higher 700 m a.s.l. (FTSA 2001, Keo 2003). In contrast, areas behind these mountains may have little rainfall. For instance, Phan Rang (edge of the southern Truong Son) has only 653 mm yr^{1} and Ky Son (edge of the northern Truong Son) has 643 mm yr^{-1} (Lap 1999).

The rainfall in Vietnam is concentrated in a rainy season that comprises about 70 to 80% of the precipitation of the whole year. The rainy season lasts from May to November in the North, the Central Highlands and the South, and from August to February in the Middle (Lap 1999). On the other hand, the dry season is often characterized by some periods of no rain (Trung 1998, Lap 1999).

Humidity

The humidity of Vietnam is high as the country receives high annual rainfall, and the North is often more humid than the South (Trung 1998). The humidity of the North is around 80 to 85%, while the South is about 78 to 83%. In the North, the most humid period is from March to April (87%) and the driest period is from November to December (81%). In the South, the humidity is high (82% - 88%) in the rainy season (May to October), and dry (70% - 80%) in the dry season (February to April). The Middle is a combination of the North and the South, it is dry (73% - 82%) from May to July, and humid (86% - 91%) from August to April (Trung 1998, Lap 1999).

Climate zones

In short, Vietnam has 3 main kinds of climate in 3 main zones through the country (SSA 1996, Thao 1998, Lap 1999).

- *The Northern climate:* From the boundary between Vietnam and China to the Ca River there is a tropical monsoon climate with 4 distinct seasons. The summer is hot and rainy, the winter is cold and dry (SSA 1996, Thao 1998, Lap 1999).

- *The Middle climate:* From the Ca River along the Truong Son Range to Mui Dinh (except the Central Highlands) there is also a tropical climate, which is a combination of the Northern and the Southern climate. In this zone the rainy season comes late (from August to November). This zone is also strongly affected by the hot and dry South-west monsoon, and by the typhoons from the sea (SSA 1996, Thao 1998, Lap 1999).

- *The Southern climate:* The South Delta, the Central Highlands and the Edge of Southern Truong Son have a typical tropical climate. In this zone the temperature is high all the year round, and it has only the dry and the rainy seasons, in which the rainy season occupies more than 90% of the total annual rainfalls (SSA 1996, Thao 1998, Lap 1999).

Apart from the 3 main climate zones above, Vietnam also has both subtropical and temperate climates as one third of the country is mountainous with altitudes of above 500 m a.s.l. (Trung 1998, Lap 1999, Thin 2000). The areas from 1000 to 1800 m a.s.l. in the South and from 700 to 1600 m a.s.l. in the North are under the influence of a subtropical climate. The region has a low annual temperature and a distinct winter. From 1800 to 2600 m a.s.l. in the South and from 1600 to 2400 m a.s.l. in the North there is a humid temperature climate. It is very cold in winter, but cool in summer, and the minimum temperature may be as low as 0°C. At still higher altitudes, there is a cold temperature climate, and it is cold all year round. There is sometimes snow in winter (Trung 1998).

Geology, terrain and soils

Geology

The geology of Vietnam is under the influence of 2 main land blocks, the Indonesian Land Block covering the South, the Middle and an edge of the North-west (Muong Te and Dien Bien Phu), while the Southern Chinese Land Block affected the North to the Ma River (Thao 1998).

In the North rock from the Cambric to Mesozoic eras is widely distributed, while pre-Cambric rock only occurs along the Red River. Under the North Delta the rock is Neogenic and is covered by recent alluvium (Thao 1998, Lap 1999).

The rest of the country is divided geologically into two parts. From Tam Ky - Phuoc Son to the North the rock is mainly Paleozoic and Mesozoic. The South, however, mostly has pre-Cambric rock. In the Central Highlands (which belong to the South), there was strong of volcanic activity at the end of the Neogen Period, and from this result the fertile red soils in these areas (Thao 1998).

Apart from the sedimentary rocks discussed above, magmatic rock is widely distributed (particularly Granite) from North to South. They are mainly pre-Cambric, but also Paleozoic, Mesozoic and Kainozoic. Pre-Cambric granite is common in the East of the Central Highlands and some other areas of the Middle such as Quang Ngai, Binh Dinh provinces. Mesozoic and Kainozoic granite occur throughout the country (Thao 1998, Lap 1999).

Terrain

The terrain of Vietnam is complicated and varies from the North to the South and from the West to the East (Thao 1998, Lap 1999). According to Lap (1999), Vietnam has five main kinds of terrain: Hills and mountains, Karstic landscapes, valleys and hollows, alluvial plains and coastal areas, and they show a complicated distribution throughout the country.

- *North-western Zone:* This area contains the Hoang Lien Son Range, which is an extension of the Chinese Hengduan Mountains and constitutes the highest part of the country. It is a large area, including the provinces of Ha Giang, Tuyen Quang, Yen Bai, North-western Ha Tay, Hoa Binh, Lai Chau, Son La, western Ninh Binh and Thanh Hoa (Nhat 2001). The topography is very complex as it ranges from very high and steep mountains, highlands and hills to valleys and hollows (Lap 1999, Thin 2000). The mean altitude of the mountain ranges is around 2000 m a.s.l. The main direction of the mountain ranges is from north-west to south-east (SSA 1996).

- *North-eastern Zone*: Sharing boundaries with the Hoang Lien Son Range and the Red River Delta, the topography of this area is less complex than the North-western Zone, as it includes mainly low mountains alternating with hills, valleys and plains. The altitude of the zone decreases gradually from the north-west to the south-east (SSA 1996, Nhat 2001). The mountains and hills of the region were formed like an arc, in which mountains from the border (Vietnam – China) converge towards the Tam Dao Mountains. This type of topography increases the capacity of receiving the influence of the winter monsoon from China (SSA 1996).

- *Red River and Mekong River Deltas*: These Deltas were filled up by Quaternary sediments from the Red and Mekong River. The terrain of these regions is generally simple as it is low and flat. There are several depressions such as Nam Ha, Ninh Binh (in the North), Dong Thap Muoi and U Minh (in the South), and also several higher tongues of land made up by alluvial deposits (Lap 1999).

- *Northern Truong Son Zone:* From the Ca River to the Hai Van Pass runs the Northern Truong Son Range in the Middle of the country. The range includes high mountains with steep slopes in the east, and gentle slopes in the west (SSA 1996, Lap 1999). There are also narrow plains with alternating depressions and sand dunes. These plains are strongly separated from one another by mountainous spurs where the Truong Son Range reaches the sea (Lap 1999).

- *Southern Truong Son Zone:* Beginning at Hai Van Pass and sharing a boundary with the Central Highlands, the Southern Truong Son Range extends along the coastline and then to the East Sea in Binh Thuan province (SSA 1996, Lap 1999). The topography of the region is complex with high and steep mountains, narrow plains and sand fields, again separated by spurs of the Truong Son Mountains (SSA 1996).

- *Central Highlands:* From the borders with Laos and Cambodia in the west to the Southern Truong Son Range in the east, the Central Highlands comprises the highlands of Kon Tum, Dac Lac, Da Lat, Lam Dong and Snaro (SSA 1996). The altitude of the Central Highlands ranges from 500 m a.s.l. (Kon Tum) to more than 2000 m (Da Lat). However, the terrain of the Central Highlands is general flat and simple, and it slopes gently from the north-east or the north to the south-west or the south (SSA 1996, Lap 1999).

Soils

Affected by a monsoon tropical climate and a complex topography, Vietnam has a diverse system of soil types, ranging from the Ferralsols distributed widely in mountains and hills, Luvisols in highlands, Fluvisols in deltas to Arenosols and the Salic Fluvisols in the coastal areas (Binh 1996, SSA 1996, Thao 1998, Lap 1999). However, several main soil types and their distribution can be classified as follows:

- *Plinthic Ferrasols:* Formed in a humid tropical climate, these soils occupy around 47% of the total land area of the country (Lap 1999). They occur from 8°5 N to 22°5 N and at altitude lower than 600 m (in the North), 800 m (in the Middle) and 1000 m (in the South) (Binh1996, Sam & Binh 2001). These soils are often acid, and reserved for forestry and agro-forestry production (Lap 1999).

- *Luvisols:* These soils cover of around 1% of the total land area, and occur in the Central Highlands, the South-east and in Karstic terrains in several provinces of the North such as Cao Bang, Hoa Binh, Son La and Lai Chau (Lap 1999).

- *Rhodic Ferralsols:* These soils cover around 2,680,000 ha of the total land area and occur mostly in the Central Highlands and some other provinces, e.g. Quang Tri, Nghe An and Thanh Hoa (Lap 1999).

- *Acrisols:* Compared with other kinds of soils, the Acrisols are unfertile as they were affected by a strong progression of leaching and erosion (Binh 1996, Lap 1999).

These soils cover around 7.5% of the total land area and mainly occur in the North and South deltas and the highlands (Lap 1999).

- *Humic Ferralsols:* These soils occur in low mountains of the country over around 10.25% of the total land area. These soils are often humid and fertile and to be the habitat of the evergreen forests (Lap 1999).

- *Fluvisols:* These soils occupy around 24% of the total land area of the country, and occur mainly in deltas and valleys (Binh 1996, SSA 1996, Lap 1999). These soils are very important for the country as they are the base for most cultivation and inhabitation of people (Lap 1999).

- *Salic Fluvisols:* These soils occur along the entire coastline of the country. The total area of these soils is around 4.4% of the total land area of Vietnam (SSA 1996, Lap 1999).

Biogeography

The basis of the flora of Vietnam and the whole of Indochina was laid a long time ago. Schmid (1962) and Vidal (1973) stated that many species of the Lycopodiales, Equisetalis and Pteridospermae occurred in the Paleozoic Era, when the land blocks of Annamia (in the North) and Sinien (in the South) emerged. In the late-Paleozoic and the Mesozoic Era, the flora contained species of the class of the Psilotophyta and particularly of the Cycadales (Schmid 1962). However, the present flora of Vietnam and Indochina developed mainly in the Kainozoic Era (Schmid 1962, Vidal 1973). During this period also many taxa immigrated into the area (Trung 1998).

Immigration of taxa from adjacent areas into Indochina and subsequent radiation of species was facilitated as the area lies on or near the contact zones of three major earth plates: the huge Eurasiatic plate with smaller, adjacent South China and Indochina plates, the Indian plate and the smaller, adjacent Birma-Siam plate, and the South-East Asian (Sunda) plate. Furthermore, the mainly North-South running mountain ranges facilitated the migration of taxa. The availability of different source floras and the occurrence of dispersal tracks make the Indochinese area plant geographically very interesting. The mixture of taxa with different geographic affinities, the evolution of new taxa in the area, and the persistence of geographically restricted, relic taxa add to its attractiveness (cf. Willis & McElwain 2002).

Basically, Vietnam's flora includes species from the Northern Vietnam-Southern China Flora (indigenous and endemic species), the Himalaya-Yunnan-Guizhou flora in the North-West, the India-Myanmar flora in the West, and the Malaysia-Indonesian flora in the South and South-East (Fig. 1) (Trung 1998, Chan et al. 1999, Lap 1999).

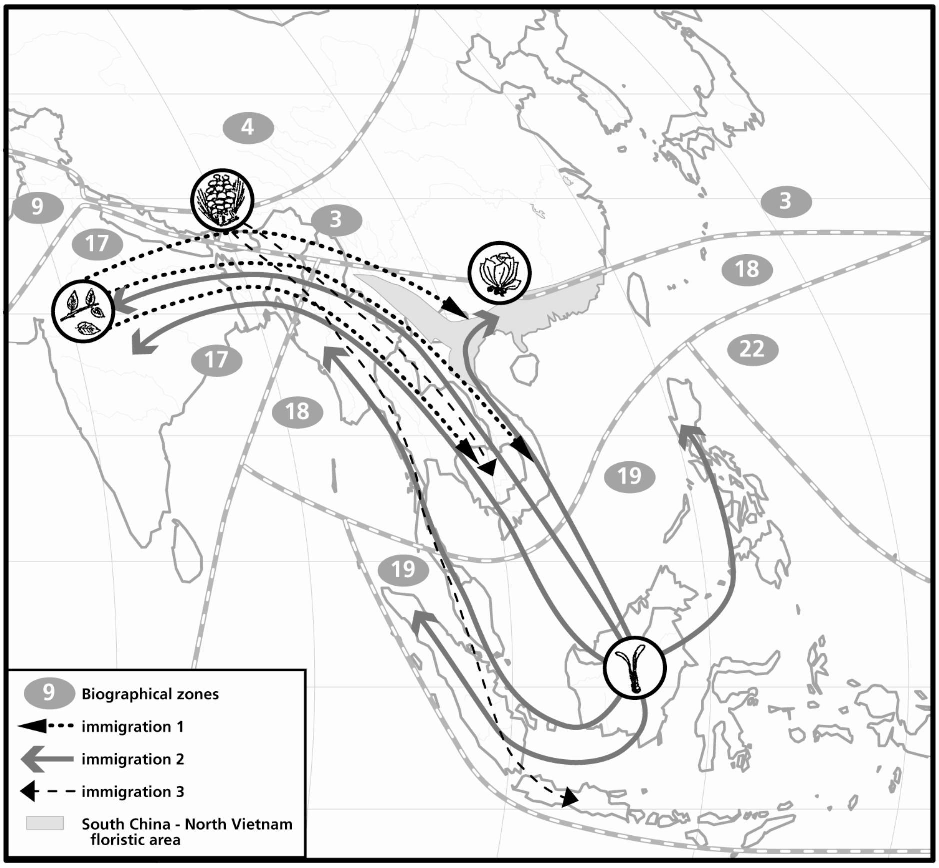

Figure 1. North Vietnam – South China floristic area and the immigration of plants from three nearby floras (from arrows 1-3) (Trung 1998).

The flora of Northern Vietnam-Southern China extends from Southern China to the Hai Van Pass (except in the North-west and the Truong Son Range). It consists of around 50% of the total species occurring in Vietnam, of which 40% evolved in Vietnam and 10% came from Southern China (Pocs 1965, Trung 1970, 1998). The Northern Vietnam-Southern China flora is integrated as the Northern Vietnam flora was almost similar to the Southern China flora from the Third Form to date (Trung 1998, Lap 1999). Many species-rich families belong to this flora, such as Lauraceae, Moraceae, Fagaceae, Leguminosae, Liliaceae, Betulaceae, Ebenaceae, Magnoliaceae, Annonaceae, Sterculiaceae, Sapindaceae, Meliaceae, Clusiaceae and several coniferous families, e.g. Cupressaceae and Taxodiaceae (Engler 1882, Schnell 1962, Good 1969, Trung 1998, Lap 1999, Willis & McElwain 2002).

It is estimated that around 10% of the total species of Vietnam originated from the Himalaya-Yunnan-Guizhou flora (Trung 1998, Lap 1999). Originating from the temperate zone, most immigrated species inhabited the high to middle high mountains of the North-West and the Truong Son Range to the latitude of 10°N (Lap 1999). Several taxa, however, extended further south and also to lower elevations, and as a consequence developed more subtropical and tropical species (Trung 1998). Many species in this group are Gymnospermae, such as *Pinus merkusii*, *Pinus kesiya*, *Keteleeria davidiana*, *Fokiena hodginsii*, *Calocedrus macrolepis*, *Tsuga yunnanensis*, *Abies pindrow*, *Cryptomeria japonica.* However, the deciduous broad-leaved species of the families Fagaceae, Betulaceae, Aceraceae, Oleaceae, Juglandaceae, Ericaceae and Vacciniaceae are also found in this region (Schnell 1962, Good 1969, Trung 1998, Lap 1999).

From the west, the India-Myanmar flora contributed around 14% of the total species number of the Vietnam's flora. Taxa with this affinity mainly occur in the North-West, the Truong Son Range and the Central Highlands of the country (Trung 1998, Lap 1999). The most common family in this group is Combretaceae with the genera Terminalia, Anogeissus, Finetia and Combretum. They drop their leaves in the dry season (Trung 1998). Also the species of *Lagerstroemia* (Lythraceae), *Tetrameles nudiflora* (Datiscaceae), and *Gossampinus malabaricus* (Bombacaceae) belong to this group (Good 1969, Trung 1998).

Around 15% of the flora of Vietnam has affinities to the Malaysia-Indonesian flora (Schnell 1962, Good 1969, Trung 1998, Lap 1999). In this group, the species of the Dipterocarpaceae (both evergreen and deciduous species) occur mainly in the Central Highlands and the Truong Son Range. The deciduous species can be found in the Central Highlands, where the climate has a distinct dry season, and the evergreen species occur in tropical humid forests (Lap 1999). However, Lap (1999) reported that the species may occur to as north as 20°N, and several species of Dipterocarpaceae, such as *Dipterocarpus tonkinensis*, occur in the evergreen forests in Phu Tho and Yen Bai provinces (the North).

Table 3. Elements of Vietnam's Flora (Pocs 1965, Trung 1998)

Elements	Contribution (%)
Endemic species (Southern Vietnam-Southern China Flora)	50
Himalaya-Yunnan-Guizhou Flora	10
India-Myanmar Flora	14
Malaysia-Indonesia Flora	15
Other tropical zones	7
Other temperature zones	3
Elsewhere	1
Total	100

Apart from the four floras mentioned above, the flora of Vietnam also includes species that arrived from other parts of the world. Pocs (1965) and Trung (1998) estimate their number at around 7% of its total species from other tropical zones, 3% from other temperate zones, and 1% from elsewhere (Table 3).

In plant geographical classifications all of Indochina including Vietnam and Thailand, are part of the Paleotropical Kingdom, the Indo-Malaysian Subkingdom, and the (Continental) South-east Asian Region (Schmithusen 1968, Good 1969, Walter & Straka 1970). Depending on the taxonomic classification favoured by the authors, the area has no or a few, small endemic families, but it contains more than 250 endemic genera, mostly small in species numbers and with a localized distribution (Good 1969, Takhtajan 1971).

Biogeographical zones of Vietnam are recognized on the basic of natural geography, topography and species composition of the region (GoVN 1994, Thin 2000). In general, 3 main biogeographical zones are distinguished: The first zone covers the North-West and the Truong Son Range (until the latitude of 10°N). In this zone, most plant species occurring in the mountains are of Himalaya-Yunnan-Guizhou flora affinity, while the species growing in lower areas are mostly of India-Myanmar flora affinity (Trung 1998). From the North-East to the latitude of 16°N we find a biogeographical zone, where most species belong to the endemic Southern Vietnam-Southern China floral element (Trung 1998). This zone is the habitat of *Erythrophloem fordii*, which is strictly endemic here (Trung 1998). However, in this zone we also find several species of Malaysia-Indonesian floral affinity (Lap 1999). From the South to the latitude of 18°N is the zone of Malaysia-Indonesian floral affinity. There are many species of Dipterocarpaceae occurring in this zone (Trung 1998).

Plant biodiversity

Table 4. Components of the flora of Vietnam (Thin 1997)

Phyla	Number of families	Number of genera	Number of species
Bryophyta	60	182	793
Psilotophyta	1	1	2
Lycopodiophyta	3	5	57
Equisetophyta	1	1	2
Polypodiophyta	25	137	669
Gymnospermae	8	23	63
Angiospermae	299	2175	299
Total	378	2524	11373
Endemic (%)	0	3	27.7

Vietnam possesses a very abundant and diverse flora, of which around 30% of its total species are endemic (Thin 1997, Trung 1998). Vietnam is estimated to have from 12,000 to 15,000 plant species, according to different scientists. GoVN (1994) reports that Vietnam has more than 12,000 plant species, of which 7,000 have been identified. In the 3 phyla Pteridophyta, Gymnospermae and Angiospermae 11,000 species belonging to 2500 genera were identified (Ly 1993). Subsequently, Thin (1997) indicates that Vietnam has 11,373 plant species, 27.7% of which are endemic, belonging to 2524 genera, 378 families and 7 phyla (Table 4). He also predicts that Vietnam may possess between 12,000 to 15,000 plant species (Thin 2000). Several floristic biodiversity centres in Vietnam, Laos and Cambodia have also been determined (Fig. 2).

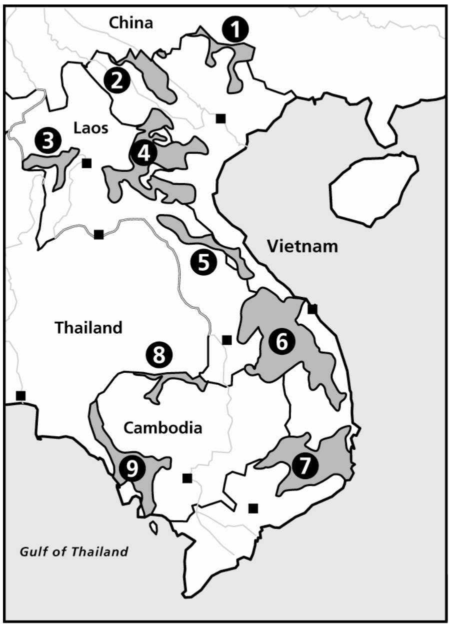

Figure 2. Floristic biodiversity centres (the number) in Vietnam, Laos and Cambodia (Schmid 1993).

Based on the potential use of the species, Chuyen et al. (1987) divide the flora of Vietnam into several utility groups:

- Group of timber species: 1200 species in 100 genera
- Group of species producing fibers for paper production: 100 species
- Group of species producing essential oils: 500 species
- Group of species producing fat oils: 260 species
- Group of species producing tannin: 600 species
- Group of species producing dyes: 200 species
- Group of medicinal plant species: 1000 species

However, the number of species in each group will probably increase as more research is carried out. For instance, Chi (1997) determines that there are 3200 medicinal plant species, rather than the 1000 species as given by Chuyen et al. (1987).

Table 5. Plant families with more than 100 species occurring in Vietnam (Thin 1997)

Family	Number of species in Vietnam	Family	Number of species in Vietnam
Orchidaceae	800	Arecaceae	125
Leguminosae	470	Melastomataceae	124
Euphorbiaceae	425	Moraceae	118
Poaceae	400	Caesalpiniaceae	118
Rubiaceae	400	Asclepiadaceae	113
Asteraceae	336	Polypodiaceae	113
Cyperaceae	303	Fagaceae	111
Lauraceae	246	Araliaceae	110
Acanthaceae	175	Zingiberaceae	109
Annonaceae	173	Rutaceae	108
Apocynaceae	170	Myrtaceae	107
Lamiaceae	145	Theaceae	101
Myrsinaceae	139	Araceae	100
Verbenaceae	131	Rosaceae	100
Scrophulariaceae	128	Urticaceae	100

Many plant families occurring in Vietnam are very rich in number of species. Thin (2000) describes 30 families with more than 100 species (Table 5). The author also distinguishes 20 families that are very abundant in the vegetation of Vietnam. They are: Acanthaceae, Araceae, Arecaceae, Asteraceae, Caesalpiniaceae, Dipterocarpaceae, Elaeocarpaceae, Euphorbiaceae, Fabaceae, Fagaceae, Lauraceae, Meliaceae, Moraceae, Myrtaceae, Rubiaceae, Rutaceae, Sapindaceae, Sterculiaceae, Urticaceae, Verbenaceae.

Main vegetation types

The vegetation of Vietnam has been studied and classified from the beginning of the last century (Chevalier 1918). Nevertheless, the number of types and rule by which the vegetation was classified have varied over time by scientists (e.g. Fig. 3 is one type of forest classification). The result of all such works was a range of vegetation

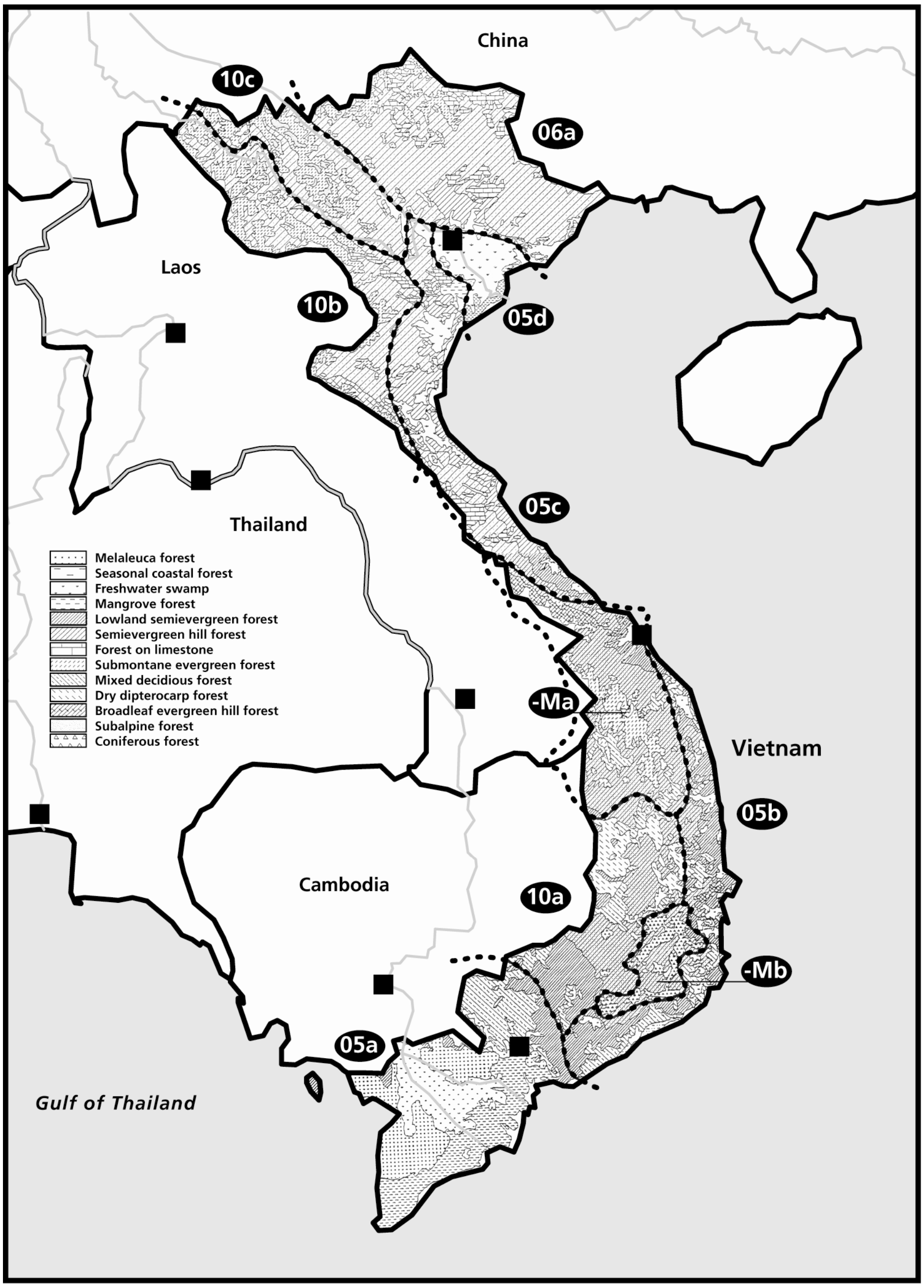

Figure 3. Original vegetation cover and bigeographical units (GoVN 1994). The biogeographical units include: North-East Vietnam (06a), Hoang Lien Son Mountain Range (10c), North Central Inidochina (10b), South Central Indochina (10a), Red River Delta (05d), North Annam (05c), South Annam (05b), Mekong Delta (05a), Central Truong Son Mountains (Ma), Da Lat Highlands (Mb), and Red River Delta (05d).

classifications for Vietnam with several overlapping and/or similar forest types identified. However, the main types of vegetation of Vietnam can be distinguished as follows:

Tropical evergreen broad-leaved forest

This kind of forest is found widely throughout the country at elevations below 700 m a.s.l. in the North and below 1000 m a.s.l. in the South (Chan & Dung 1992, Trung 1998). In the distribution area of this vegetation type the mean annual temperature ranges from 20 to 25°C. The annual precipitation is more than 1200 mm, with 2-3 dry months (with rainfall less than 50 mm per month) (Trung 1998). This forest type is very diverse and complex in structure with a great number of tree, vine, epiphyte and shrub species. It has 2-5 vegetation layers: a layer of emergents, the main canopy storey, the subcanopy layer, the shrub understorey and the forest floor layer. The emergents may reach up to 25-30 m in height (Chan & Dung 1992, Trung 1998).

Tropical semi-deciduous broad-leaved forest

The occurrence of this forest type is concentrated in Northern Vietnam and the Central Highlands at the same elevation as the tropical evergreen broad-leaved forest (Chan & Dung 1992, Linh 1996, Trung 1998). In the distribution of this vegetation type the mean annual temperature is 20 to 25°C, with the temperature of the coldest month 15-20°C. Annual rainfall is high, from 1200 to 2500 mm, but 4-6 months are considered dry, and 1 month usually has no rain at all (Trung 1998). The forest structure is also complex and diverse. Deciduous trees occupy about 25 to 75% of the timber trees in this forest type (Chan & Dung 1992, Linh 1996).

Tropical deciduous broad-leaved forest

This type is distributed naturally at an elevation of less than 700 m a.s.l. in the North and below 1000 m a.s.l. in the South. This kind of forest has a simple structure with 2 main layers of timber trees. The percentage of deciduous trees is estimated at more than 75% (Chan & Dung 1992). In these areas, the rainfall is low: it may be as low as 600 mm per year. The dry season may last from 4 to 6 months, with at least 1 month of no rain at all (Trung 1998).

Subtropical evergreen forest

This forest is distributed naturally at altitudes above 700m a.s.l. in the North and above 1000 m a.s.l. in the South (Chan & Dung 1992, Hung 1996). Occurring at high elevations, this type of forest is under the influence of subtropical climate. The mean annual temperature ranges from 15 to 20°C. The annual rainfall is still high, fluctuating from 1200 to 2500 mm (Chan & Dung 1992). Like temperate forest, the subtropical evergreen forest has a simple structure of 2 main layers of timber trees. The overall species richness is less than in the tropical evergreen forest (Chan & Dung 1992).

Limestone forest

This forest grows on the limestone substrate (calcareous soil), which extends over a large Karstic area of the North and a smaller area of Northern Middle of Vietnam (GoVN 1994, Truong 1996). The area of limestone forest is estimated at about 5.4% of the total forested land (Phon et al. 2001, Dung 2005). In fact, these forests are subtypes of the closed evergreen and semi-deciduous broad-leaved forests. The flora is diverse and includes a large number of coniferous and broad-leaved species (Chan & Dung 1992, Truong 1996, Dung 2005). Growing on infertile soil and under hard climatic conditions, the forest structure is simple, with 1-2 layers of slow-growing tree species (GoVN 1994, Truong 1996, Phuong 2000). This forest type has recently been severely degraded by uncontrolled logging, wildfire and slash and burn cultivation, and needs to be protected and reserved (GoVN 1994, Phon et al. 2001).

Coniferous forest

This forest occurs in the North and the Central Highlands, at elevations of over 1000 m a.s.l. where the climate is cool in summer and cold in winter (Chan & Dung 1992, Truong 1996). These areas are comparatively dry as annual precipitation is only from 600 to 1200 mm (Chan & Dung 1992). The dry season is long, lasting from 4 to 6 months, with 1 month without any rain (Trung 1998). The forest structure is often simple and the forest is dominated by 2 species, *Pinus merkusii* and *P. kesiya* (Chan & Dung 1992). However, more recently, large areas of plantations of *P. merkusii, P. kesiya, P. massoniana* and *P. caribaea* have been established at lower elevations (Truong 1996).

Mangrove forest

These forests grow in tidal areas along the coast of the country, especially in estuaries (Chan & Dung 1992, Sam et al. 2005). This type of forest is most prevalent in the South, but also occurs as shorter and simpler forest in the North (GoVN 1994). The structure of the forest is simple as it often has 1 layer (Chan & Dung 1992, Truong 1996). However, this type of forest has dramatically been destroyed and replaced by farming and land reclamation (GoVN 1994, Sam et al. 2005)

Bamboo forest

These forests are distributed throughout the country and emerge after harvesting of the natural forests or after slash and burn cultivation (Chan & Dung 1992). The total area of bamboo forests of Vietnam is estimated at 1,489,000 ha, of which 1,415,500 ha are natural bamboo forests (both monoculture and mixture) and 73,500 ha are plantations. The bamboo species of Vietnam are diverse as they contain about 29 genera and 140 species (Dung & Lam 2005). This type of forests occurs as pure patches or as mixtures with tree species (Lam 2005).

Forest status

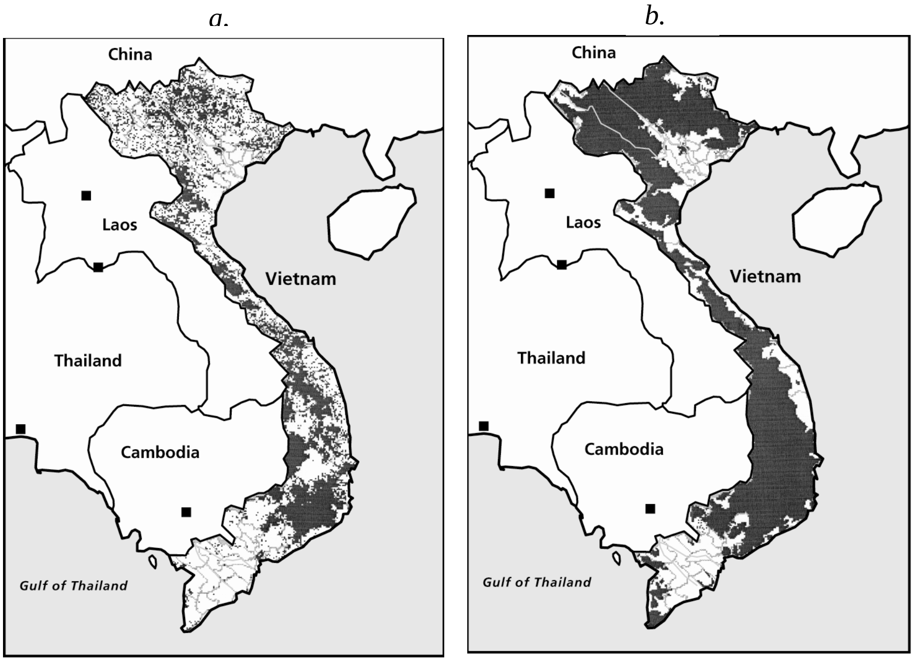

Figure 4. Forest cover of Vietnam in 1995 (a) and in 1943 (b) (Maurand 1943, FIPI 1995).

The forests of Vietnam have dramatically decreased during the last 60 years, even though they have slightly increased recently. Before 1945, when Vietnam was under French Colonial Rule, forests had heavily been harvested for timber, pole and also for rubber and coffee production (Dang et al. 2001). However, at that time the forest area was still high as it covered around 43% of the country' s area (Fig. 4) (Maurand 1943). From 1954 to 1975, the forests of Vietnam were severely damaged by the long war with the USA (the American war hereafter), overexploitation and shifting cultivation. By 1976, the total area of forests had been reduced to 11.2 million ha (covering 33.8% the country), of which only 10% were intact forests (Lung 2001, Nhat 2001). Sine 1976, more forests have still been destroyed for many reasons, such as overexploitation, shifting cultivation, and agricultural extension. As a result, the forest cover declined to an estimated 30% in 1985, and 28% in 1995 (Fig. 4) (Lung 2001). In 1998, the 5 Million ha Reforestation Program was launched with a target to plant 5 million ha of forests by 2010, restoring the forest cover to 43% (Forestry Department 2001). The program aims not only to reforest, but also to protect existing natural forests. As a result, the forest cover of Vietnam has gradually increased. In 2003, the forested area of Vietnam was 12,094,518 ha, of which 10,004,709 ha were natural forests and 2,089,809 ha were plantation forests, resulting in a forest cover of 36.1% (Hung 2004).

However, the quality of forests is still low as most of the forests are poor in timber volume and lack valuable species as a result of a long time of overexploitation and random logging (Thin 1997, Dang et al. 2001). It is reported that natural forests rich in timber resources cover only 1.4 million ha (13%) while poor and young forests comprise around 6 million ha (55%). The amount of plantation forests has sharply increased (Hung 2004), but the quality also still low. Most plantations are even age and to be established by exotic species (e.g. *Pinus* spp, *Eucalyptus* spp, *Acacia* spp). In general, the plantations have low growth rate (about 8-10 m^3 ha^{-1} $year^{-1}$), and they mainly support small and medium sized stems (Dang et al. 2001).

There are many reasons for the rapid loss of forests in Vietnam, but the American war played a major role (Quy 1985, Bouny 2006). From 1954 to 1975, the American Army used around 74 million liters of herbicides (Agent Orange) in order to defoliate dense forest areas (Quy 1985, Bouny 2006). Around 13 million tons of bombs (some what between two and four times the bombs' tonnage of the whole Second World War) were dropped on Vietnam, most of which severely impacted the forested areas (Quy 1985, Bouny 2006). As a result, more than 2 million ha of natural forests, of which 500,000 ha of closed upland forests and 30,000 ha of mangroves were completely destroyed (Westing 1971, Quy 1985, Truong 1996).

Overexploitation is also an important reason for the decrease in forest resources in Vietnam. During the American war, many large forest areas were heavily logged to support people and the war effort. Subsequently, to rebuild the country after the war, around 1.3-1.4 million m^3 of timber and 100,000 tons of bamboo were exploited annually (Nhat 2001). As a developing country with 80% of the population being farmers, Vietnam needs a huge amount of firewood. Annually, from 22 to 23 million tons of firewood are harvested (Dang et al. 2001, Nhat 2001). In addition, illegal logging is a serious problem as it has annually destroyed around 30,000 ha of forests in several last decades (GoVN 1994).

The population of Vietnam has increased quickly, and this has also a dramatic impact on the forests. At the beginning of the last century, the population of Vietnam was about 15 million. However, this number had doubled by 1940, in just 30-40 years. From 1960 onwards, the population has doubled every 25 years (Dang et al. 2001). In 1999, the population of Vietnam was 77,263,000 people, with a density of

233 people per sq.km, 5 times higher than the average density of the world (Toan 1998, Dang et al. 2001). Such a large population puts the forest under heavy pressure, not only through practices of shifting cultivation, but also by transforming forested land into agriculture production fields (Toan 1998, Nhat 2001).

The impact of shifting cultivation on forests may be sustainable if the local population density is low (Sam 1996, Nhat 2001). To produce enough food for self sufficiency, people just cultivate a limited area for a while, and then leave it for a reasonable time before going to use it again. So, the field has enough time to renew a cover and for the soil to rejuvenate, and people do not need to greatly extend the area for cultivation, so that they do not cause much further loss of forests. However, if the density of the population increases, the rate of forest destruction will exceed the rate of recovery (GoVN 1994, Nhat 2001). Forests therefore will be rapidly lost when the population density is extremely high, and people have to keep clearing new forests for cultivation of agricultural crops (Sam 1996).

Vietnam has several million people whose lives are based on shifting cultivation. In the North, around 1.4 million people are reported to practice shifting cultivation. The population densities of the mountainous areas are now very high, in many places up to100 people per sq.km (Dang et al. 2001). The government has introduced policies and encouraged rural people to convert to permanent agriculture. However, more attention should be paid to this point in order to better preserve the forests (Dang et al. 2001).

Transformation of forested land into agricultural fields has decreased the forest cover quickly as a huge number of people from the delta areas moved to live in mountainous areas (GoVN 1994). For instance, before 1975 around 1 million people of the North moved from the Red River delta (very high population density) to mountainous areas (Dang et al. 2001). From 1975 to 1995, the Central Highlands received around 650,000 people under the policy of a relocation scheme, as well as around 334,000 free moving people (Dang et al. 2001). The big movement of people has quickly changed the forests. They cleared forests to cultivate agricultural crops. They also uncontrollably harvested timber, firewood, food and other forest products. Particularly, in the Central Highlands and the South-East, large areas of natural forests have been cleared for planting industrial trees such as rubber and coffee. Along the coast line and estuaries of the country, especially in Minh Hai province (in the South), certain areas of mangroves have been cleared to form farms for shrimp production and other seafood (GoVN 1994, Nhat 2001).

Recently, the country has been moving towards a market-economy, which may have a negative impact on forests (Nhat 2001). To increase yield from forests and plantations, many exotic and hybrid species have been imported. These species may invade the habitat of the native forests, and also bring new pests and diseases, that may damage indigenous species (Nhat 2001, Socialist Republic of Vietnam 'SRVN' 2003).

Threatened tree species

The forests of Vietnam have severely degraded for over half a century, not only the area of forests, but also their quality. This had severe impacts on the flora of Vietnam as their habitat was fragmented and destroyed. According to the Ministry of Science, Technology and Environment 'MSTE' 1996), Vietnam has around 356 threatened tree species (in different degrees of endangerment) of which 337 are vascular plant species and 19 lower species. In his studies on the conservation of threatened tree species, Nghia (2005) classified a number of valuable trees, which are facing danger of extinction. This classification is given in Table 6.

Table 6. Levels of endangerment of valuable tree species in Vietnam, adapted from Nghia 2005 (Using categorization of IUCN 1997).

Vietnamese name	Latin name	Family	Threatened levels
Sơn huyết	*Melanorrhoea laccifera* Pierre	Anacardiaceae	CR C
Sơn đào	*Melanorrhoea usitata* Wall	Anacardiaceae	CR C
Sơn	*Toxicodendron succedanea* (L) Mold	Anacardiaceae	EN C
Thiết đinh	*Markhamia stipulata* Seem	Bignoniaceae	VU A cd
Trai lý	*Garcinia fagraeoides* S. Chev.	Clusiaceae	NT
Đỉnh tùng	*Cephalotaxus mannii* Hook. f.	Cephalotaxaceae	EN C
Bách xanh	*Calocedrus macrolepis* Kurz	Cupressaceae	EN D
Hoàng đàn	*Cupressus funebris* Endle	Cupressaceae	EW
Pơmu	*Fokienia hodginsii* Henry & Thomas	Cupressaceae	VU A cd
Tùng	*Tetrameles nudiflora* R.Br	Datiscaceae	EN A cd
Vên vên	*Anisoptera costata* Korth	Dipterocarpaceae	VU A cd
Dầu nước	*Dipterocarpus alatus* Roxb ex G.Don	Dipterocarpaceae	NT
Dầu cát	*Dipterocarpus chartaceus* Sym	Dipterocarpaceae	EN A cd
Dầu song nàng	*Dipterocarpus dyeri* Pierre ex Laness	Dipterocarpaceae	NT
Chò nâu	*Dipterocarpus tonkinensis* A. Chev.	Dipterocarpaceae	EN A cd
Dầu bao	*Dipterocarpus baudii* Korth	Dipterocarpaceae	EN D
Dầu mít	*Dipterocarpus costatus* Gaert.f.	Dipterocarpaceae	EN C
Dầu đọt tím	*Dipterocarpus grandiflorus* Blanco	Dipterocarpaceae	VU B

Dầu lông	*Dipterocarpus intricatus* Dyer	Dipterocarpaceae	LC
Dầu đồng	*Dipterocarpus tuberculatus* Roxb	Dipterocarpaceae	LC
Sao lá hình tim	*Hopea cordata* Vidal	Dipterocarpaceae	CR C
Săng đào	*Hopea ferrea* Pierre	Dipterocarpaceae	VU A cd
Sao đen	*Hopea odorata* Roxb	Dipterocarpaceae	NT
Kiền kiền	*Hopea pierrei* Hance	Dipterocarpaceae	VU A cd
Sao mạng	*Hopea reticulata* Tardieu	Dipterocarpaceae	CR C
Kiền kiền	*Hopea siamensis* Heim	Dipterocarpaceae	VU A cd
Chò chỉ	*Parashorea chinensis* H.Wang	Dipterocarpaceae	VU A cd
Chò đen	*Parashorea stellata* Kurz	Dipterocarpaceae	EN A cd
Chai lá cong	*Shorea falcata* Vidal	Dipterocarpaceae	VU A cd
Sến cát	*Shorea roxburghii* G.Don	Dipterocarpaceae	VU A cd
Cẩm liên	*Shorea siamensis* Miq	Dipterocarpaceae	LC
Chò chai	*Shorea guiso* (Blco) BL	Dipterocarpaceae	LC
Táu trắng	*Vatica odorata* (Griff) Sym	Dipterocarpaceae	VU A cd
Táu duyên hải	*Vatica mangachapoi* Blanco	Dipterocarpaceae	VU A cd
Táu mật	*Vatica cinerea* King	Dipterocarpaceae	VU A cd
Mun	*Diospyros mun* A Chev. ex Lecomte	Ebenaceae	CR A cd
Vạng tr ứng	*Endospermum chinense* Benth	Euphorbiaceae	VU A cd
Dẻ đỏ	*Lithocarpus ducampii* A.Chev.	Fagaceae	NT
Chò đãi	*Annamocarya sinensis* (Dode)j.Leroy	Juglandaceae	CR C
Mạy chấu	*Carya tonkinensis* Lecomte	Juglandaceae	CR C
Vù hương	*Cinnamomum balansae* Lecomte	Lauraceae	CR A cd
Xá xị	*Cinnamomum glaucescens* Drury	Lauraceae	CR A cd
Re hương	*Cinnamomum parthenoxylum* Meisn	Lauraceae	CR A cd
Kháo vàng	*Machilus odoratissima* Nees	Lauraceae	NT
Gõ đỏ, cà te	*Afzelia xylocarpa* (Kurz) Craib	Leguminosae	EN A cd
Trắc dây	*Dalbergia annamensis* A.Chev.	Leguminosae	EN A cd
Cẩm lai Bà Rịa	*Dalbergia bariensis Pierre*	Leguminosae	EN A cd
Trắc nghệ	*Dalbergia cochinchinensis* Pierre	Leguminosae	VU A cd
Cẩm lai vú	*Dalbergia mammosa* Pierre	Leguminosae	EN A cd
Sưa	*Dalbergia tonkinensis* Prain	Leguminosae	EN D
Xoay	*Dialium cochinchinensis* Pierre	Leguminosae	EN A cd

Lim xanh	*Erythrophloeum fordii* Oliv.	Leguminosae	EN A cd
Ráng ràng mít	*Ormosia balansae* Drake	Leguminosae	VU A cd
Gụ mật	*Sindora siamensis* Teysm. Ex Miq	Leguminosae	VU A cd
Gụ biển	*Sindora siamensis* var. maritima	Leguminosae	NT
Gụ lau	*Sindora tonkinensis* A. Chev.	Leguminosae	EN A cd
Giáng hương	*Pterocapus macrocarpus* Kurz	Leguminosae	VU A cd
Căm xe	*Xylia xylocarpa* (Roxb) Taub.	Leguminosae	VU A cd
Trai Nam Bộ	*Fagraea fragrans* Roxb	Loganiaceae	CR C
Mỡ Ba Vì	*Manglietia hainanensis* Dandy	Magnoliaceae	EN D
Lát hoa	*Chukrasia tabularis* A. Juss	Meliaceae	CR A cd
Vân sam Fansipăng	*Abies delavayi* Franchet ssp fransipanensis (Q.P.Xiang) Rushforth	Pinaceae	EN D
Du sam đá vôi	*Keteleeria davidiana* Beissn	Pinaceae	EN D
Du sam	*Keteleeria evelyniana* Master	Pinaceae	VU A cd
Thông Đà Lạt	*Pinus dalatensis* de Ferre	Pinaceae	NT
Thông hai lá dẹt	*Pinus krempfii* H. Lecomte	Pinaceae	VU A cd
Thông Pà Cò	*Pinus kwangtungensis* Chun ex Tsiang	Pinaceae	EN D
Thiết sam giả	*Pseudotsuga sinensis* Dode	Pinaceae	VU A cd
Thiết sam	*Tsuga chinensis* (Franchet) Pritzel ex Diels	Pinaceae	EN D
Trúc vuông	*Chimonobambusa yunnanensis* Hsueh et Zhang	Poaceae	CR D
Trúc hoá long	*Phyllostachys aurea* Carr. Ex A. et	Poaceae	CR D
Trúc đen	*Phyllostachys nigra* Munro	Poaceae	CR D
Trúc dây	*Ampelocalamus* sp.	Poaceae	CR D
Bạch tùng (Thông nàng)	*Dacrycapus imbricatus* (Blume) de Laub.	Podocarpaceae	VU A cd
Hồng tùng (H.D.giả)	*Dacrydium elatum* (Roxb.) Wall	Podocarpaceae	VU A cd
Kim giao Bắc	*Nageia fleuryi* (Hicke) de Laubenfels	Podocarpaceae	EN B
Kim giao Nam	*Nageia wallichiana* (Prest.) Kuntze	Podocarpaceae	VU A cd
Thông tre	*Podocarpus neriifolius* D.Don	Podocarpaceae	VU A cd
Thông tre lá ngắn	*Podocarpus pilgeri* Foxwonrthy	Podocarpaceae	VU A cd
Hồng quang	*Rhodoleia championii* Hook	Rhodoleiaceae	VU A cd
Sến mật	*Madhuca pasquieri* H.J.Lam	Sapotaceae	VU A cd

Dẻ tùng sọc trắng	*Amentotaxus argotenia* Pilg	Taxaceae	NE
Dẻ tùng sọc nâu	*Amentotaxus hatuyenensis* Hiep et Vidal	Taxaceae	EN D
Dẻ tùng Poalan	*Amentotaxus poilanei* Ferguson	Taxaceae	NE
Dẻ tùng Vân Nam	*Amentotaxus yunnanensis* Li	Taxaceae	NE
Thông đỏ	*Taxus chinensis* Pilger	Taxaceae	EN D
Thông đỏ	*Taxus wallichiana* Zucc	Taxaceae	CR C
Sa mu dầu	*Cunninghamia konishi* Hataya	Taxodiaceae	VU A cd
Thuỷ tùng	*Glyptostrobus pensilis* (Staunton) K.Koch	Taxodiaceae	CR A cd
Bách tán Đài Loan	*Taiwania cryptomerioides* Hataya	Taxodiaceae	CR D
Bách vàng	*Xanthocyparis vietnamensis* Farjon & Hiep	Taxodiaceae	EN D
Trầm hương	*Aquilaria crassna* Pierre ex Lecomte	Thymeleaceae	CR A cd
Dó giấy	*Wikstroemia balansae* (Drake) Gilg.	Thymeleaceae	VU A cd
Nghiến	*Burretiodendron tonkinensis* Kost	Thymeleaceae	EN A

Note: EW: Extinction in the wild
CR: Critically endangered (threatened level decreases from A to E)
EN: Endangered (threatened level decreases from A to E)
VU: Vulnerable (threatened level decreases from A to D)
cd: Conservation dependent
NT: Near threatened
LC: Least concern
NE: not evaluated

National Park and nature reserve system

To address the biodiversity threats due to habitat loss, Vietnam established a system of protected forests with the aim of protecting the main ecosystems represented in Vietnam, as well as the threatened and endemic species of flora and fauna and their habitats, and the valuable landscapes for culture, ecology and biodiversity (Tai 1995, SRVN 2003).

The first National Park (Cuc Phuong) was established in 1962 as an important point for forest protection and conservation in Vietnam (Thu 2002). Since then, the national park and nature reserve system of Vietnam has developed quickly. By the year 1986, Vietnam had established 87 protected areas, occupying 3.3% of the total area of the country (SRVN 2003). From 1986 onwards, more attention has been paid to forest protection and conservation and a large number of protected areas was established. By the year 2003, Vietnam had 126 areas of special purpose forests with total area of 2,541,675 ha (Table 7), occupying 7.7% of the total area of the country (Forest Department 2004).

Table 7. System of special purpose forests (Forest Department 2004)

Classification	Number	Area (ha)
National Parks	27	957,330
Nature reserve areas	49	1,283,209
Species/habitat management protected areas	11	85,849
Protected landscape or seascape areas	39	215,287
Total	126	2,541,675

The 4 kinds of special purpose forests (protected areas) have different purposes, and thus they differ in terms of importance for protection and conservation and also management level. Forest Techniques and Science Association of Vietnam (FSTA) (2001) defined the 4 kinds of protected areas as follows:

- *National Park:* An area on the mainland or in the sea that has not or only slightly been impacted by human activities. It contains rare, precious or endemic species or has popular landscapes at national or international levels. The objectives of establishing a National Park are to protect the ecosystem of threatened species, as they have important roles for the country and the world, and to provide facilities for scientific study and eco-tourism.
- *Nature Reserve:* A large area having typical ecosystems or containing populations of valuable species that need conservation. Nature Reserves are to protect and maintain ecosystems and floral and faunal species in their natural conditions. They aim also to provide for scientific research and environmental
- management. However, in contrast to National Parks, eco-tourism is limited in nature reserves.
- *Species/Habitat Management Protected Area*: A forest area established to protect, maintain and favor particular threatened species and their environment.
- *Protected Landscape or Seascape*: A protected landscape or seascape established to protect famous natural landscapes or national cultural properties. It is also to protect the natural beauty of forests, caves, waterfalls, sand dunes, coral islands and volcanic craters.

National parks are the most important for protection and conservation. In National Parks, activities such as logging, firewood and food collection, hunting or fishing are not allowed. In contrast, all these activities are allowed in the Protected Landscape or Seascape areas. In Nature Reserve Areas and Species/Habitat Management Protected Areas, several activities are allowed, as long as they are in harmony with the purpose of conservation of the area. The location, sizes and purposes of protected areas are specified in Table 8 (SRVN 2003).

Table 8. Protected areas and their objectives in Vietnam (SRVN 2003)

	Name of protected area	Location (provinces)	Area (ha)	Objectives
	Total		2,541,675	
I	*National Parks*		*957,330*	
1	Ba Be	Bac Can	7,610	Limestone forests, natural lakes in the mountains
2	Ba Vi	Ha Tay, Hoa Binh	12,023	Evergreen forests, *Calocedrus macrolepis*
3	Bach Ma	Thua Thien Hue	22,030	Evergreen forests, *
4	Bai Tu Long	Quang Ninh	15,738	Forests on the island, *
5	Ben En	Thanh Hoa	16,634	Evergreen forests, *Erythrophleum fordii*, *
6	Bu Gia Map	Binh Phuoc	26,032	Evergreen forests, *
7	Cat Ba	Hai Phong	15,200	Limstone forests, *Nageia fleuryi*, *
8	Cat Tien	Dong Nai, Lam Dong, Binh Phuoc	70,548	Evergreen forests, *
9	Con Dao	Ba Ria Vung Tau	19,998	Forests on the island, *
10	Chu Mom Ray	Kon Tum	56,621	Evergreen forests and semi-evergreen forests, *
11	Chu Yang Sing	Dak Lak	58,947	Evergreen forests, *
12	Cuc Phuong	Ninh Binh, Thanh Hoa, Hoa Binh	22,200	Limestone forests, *
13	Hoang Lien Son-Sapa	Lao Cai	29,845	Evergreen forests, *Abies fansipanensis*, *Tsuga dumosa*, *
14	Kon Ka Kinh	Gia Lai	41,780	Evergreen forests, *Fokienia hodginsii*, *
15	Lo Go Sa Mat	Tay Ninh	18,765	Deciduous and semi-deciduous forests, seasonal flooded grass Land*
16	Mui Ca Mau	Ca Mau	41,862	Mangrove forests, *
17	Nui Chua	Ninh Thuan	29,865	Dry forests
18	Phong Nha Ke Bang	Quang Binh	85,754	Limestone forests, *Excentrodendron tonkinense*, *Diospyros mun**
19	Phu Quoc	Kien Giang	31,422	Forests on the island, *Hopea siamensis*, *Nageia fleuryi*, *
20	Pu Mat	Nghe An	91,113	Evergreen forests, *Fokienia hodginsii, Cunninghamia lanceolata,*

	Name of protected area	Location (provinces)	Area (ha)	Objectives
I	*National Parks*			
21	Tam Dao	Vinh Phuc, Thai Nguyen, Tuyen Quang	34,995	Evergreen forests, *Fokienia hodginsii,* *
22	Tram Chim	Dong Thap	7,588	Mangrove forests, flooded ecosystem, flooded grass land, *
23	U Minh Thuong	Kien Giang	8,038	Mangrove forests, *
24	Vu Quang	Ha Tinh	55,029	Evergreen forests, *Fokienia hodginsii,* *
25	Xuan Son	Phu Tho	15,048	Limestone forests, *
26	Xuan Truong	Nam Dinh	7,100	Mangrove forests, *
27	Yok Don	Dak Lak	115,545	Dry Dipterocarp forests, *
II	*Nature conservation areas*		*1,283,209*	
1	Ba Na - Nui Chua	Da Nang City, Quang Nam	38,210	Evergreen forests, *
2	Peninsula Son Tra	Da Nang City	4,370	Forests on the peninsula, beautiful landscapes, *
3	Bac Me	Ha Giang	27,800	Limestone forests, *Markhamia stipulata, Garcinia fagraeoides, Excentrodendron tonkinense, Chukrasia tabularis,* *
4	Binh Chau Phuoc Buu	Ba Ria Vung Tau	11,392	Dry Dipterocarp forests, *
5	Bidoup-Nui Ba	Lam Dong	64,366	Evergreen forests, *Pinus krempfii*, *Fokienia hodginsii,* *
6	Cham Chu	Tuyen Quang	58,187	Limestone forests, *
7	Copia	Son La	19,353	
8	Cu Lao Cham	Quang Nam	1,535	
9	Du Gia	Ha Giang	24,293	Forests on limestone hills
10	Dakrong	Quang Tri	40,526	Evergreen forests, *
11	Easo	Dak Lak	22,000	Dipterocarp forests, natural grasses lands, *
12	Huu Lien	Lang Son	10,640	Limestone forests, *Cupressus torulosa, Excentrodendron tonkinense*, *
13	Ke Go	Ha Tinh	24,801	Evergreen forests, *
14	Khe Ro	Bac Giang	5,675	Evergreen forests, *Fokienia hodginsii*

	Name of protected area	Location (provinces)	Area (ha)	Objectives
II	*Nature conservation areas*			
15	Kim Hy	Bac Can	15,461	Limestone forests, *Markhamia stipulata*, *Excentrodendron tonkinense*, *
16	Kon Cha Rang	Gia Lai	15,900	Evergreen forests, *Dacrydium elatum*, *Craibiodendron selenranthum*, *
17	Krong Trai	Phu Yen	9,107	Dipterocarp forests, Semi-deciduous forests, *
18	Ky Thuong	Quang Ninh	17,640	Evergreen forests
19	Muong Nhe	Lai Chau	182,000	
20	Nam Ca	Dac Lak	24,555	Evergreen forests, *Afzelia xylocarpa, Dalbergia oliveri*, *
21	Nam Nung	Dac Lak	10,849	Evergreen forests, *Pinus kesiya, Hopea siamensis*, *
22	Ngoc Linh	Kon Tum	41,424	Evergreen forests, *Panax vietnamensis,* *
23	Nui Ong	Binh Thuan	25,468	Evergreen forests, *
24	Nui Dai Dinh	Lam Dong	5,000	
25	Nui Cam	An Giang	1,500	
26	Nui Pia Oac	Cao Bang	10,000	
27	Hang Kia – Pa Co	Hoa Binh	7,091	Limestone forests, *Pinus kwangtungensis*
28	Phong Quang	Ha Giang	18,840	Limestone forests, *Fagraea fragrans, Excentrodendron tonkinense*, *
29	Phong Dien	Thua Thien Hue	41,548	Evergreen forests, *
30	Phu Canh	Hoa Binh	5,647	
31	Phuoc Binh	Ninh Thuan	19,814	Evergreen forests, *Fokienia hodginsii,* *
32	Pu Hoat	Nghe An	67,934	Evergreen forests, *Fokienia hodginsii*, *Cunninghamia lanceolata*, *
33	Pu Hu	Thanh Hoa	27,503	Evergreen forests, Chukrasia tabularis, *Excentrodendron tonkinense, Podocarpus pilgeri.*
34	Pu Huong	Nghe An	50,075	Evergreen, *Fokienia hodginsii*, *Cunninghamia lanceolata*, *
35	Pu Luong	Thanh Hoa	17,662	Limestone forests, *
36	Song Thanh	Quang Nam	93,249	Evergreen forests, *
37	Sop Cop	Son La	27,886	
38	Ta Dung	Dac Lac	18,893	

	Name of protected area	Location (provinces)	Area (ha)	Objectives
II	*Nature conservation areas*			
39	Ta Kou	Binh Thuan	17,823	
40	Ta Sua	Son La	17,650	
41	Tay Con Linh	Ha Giang	28,261	Limestone bamboo forests, *Fokienia hodginsii*, *Excentrodendron tonkinense, Dacrydium elatum*, *Podocarpus pilgeri* ,*Nageia fleuryi*
42	Tay Yen Tu	Bac Giang	16,466	
43	Thach Phu	Ben Tre	4,510	*Melaleuca* forests, *
44	Than Sa-Phuong Hoang	Thai Nguyen	11,220	
45	Thuong Tien	Hoa Binh	7,308	Limestone forests
46	Trung Khanh	Cao Bang	3,000	
47	Xuan Lien	Thanh Hoa	27,668	Evergreen forests, *Fokienia hodginsii* ,*
48	Xuan Nha	Son La	38,069	Limestone forests, *
49	Yen Tu	Quang Ninh, Bac Giang	3,040	Limestone forests, *Podocarpus chinensis*
III	*Species/Habitat management protected area*		*85,849*	
1	Earal	Dak Lak	50	*Glyptostrobus pensilis*
2	Kien Luong	Kien Giang	14,605	Mangrove forests, seasonal flooded grass lands, *
3	Lung Ngoc Hoang	Can Tho	6,000	Mangrove forests, *
4	Mo Re-Bac Son	Lang Son	4,000	Limestone forests, *
5	Na Hang	Tuyen Quang	41,930	Limestone forests, *Cupressus torulosa* , *
6	San Chim Bac Lieu	Bac Lieu	127	*
7	Tam Quy	Thanh Hoa	500	Evergreen forests, *Madhuca pasquieri*
8	Tien Hai	Thai Binh	12,500	Mangrove forests, *
9	Trap Kso	Dak Lak	100	*Glyptostrobus pensilis*
10	Van Long	Ninh Binh	2,643	Limestone forests, *
11	Vo Doi	Ca Mau	3,394	Mangrove forests, *

	Name of protected area	Location (provinces)	Area (ha)	Objectives
IV	*Protected Landscapes or Seascape*		*215,287*	
1	An toan khu	Thai Nguyen	10,059	
2	Ai Chi Lang	Lang Son	1,000	
3	Ba To	Binh Dinh	6,770	
4	Bai Chay	Quang Ninh	562	
5	Bac Hai Van	Thua Thien Hue	14,547	Landscape of Hai Van Pass
6	Cao Muon	Quang Ngai	6,770	
7	Islands of Thac Ba	Yen Bai	5,000	
8	Islands of Halong Bay	Quang Ninh	1,000	
9	Chang Riec	Tay Ninh	11,488	
10	Chien Khu Boi Loi	Tay Ninh	2,000	
11	Con Son Kiep Bac	Hai Duong	1,477	Pine forests, Nguyen Trai Vestige
12	Duong Minh Chau	Tay Ninh	5,000	
13	Ba Trieu Temple	Thanh Hoa	300	
14	Hung Temple	Phu Tho	285	Vestige of Hung Kings
15	Islands of Songda Lake	Hoa Binh	3,000	
16	Ca-Hon Nua Pass	Phu Yen	8,876	Landscape of Ca Pass and coast line forests
17	Do Son	Hai Phong	267	
18	Ghenh Rang	Binh Dinh	2,616	Landscape and historical area
19	Cam Son Lake	Bac Giang	15,000	
20	Ho Lac	Dak Lak	12,744	Natural lake in the high lands
21	Hoa Lu	Ninh Binh	5,624	Limestone forests, Vestiges of Dinh King and Le King
22	Nui Coc	Thai Nguyen	6,000	
23	Hon Chong	Kien Giang	3,495	Limestone landscapes
24	Huong Son	Ha Tay	4,355	Limestone forests, Huong Tich Pagoda

	Name of protected area	Location (provinces)	Area (ha)	Objectives
IV	*Protected Landscapes or Seascape*			
25	Kim Binh	Tuyen Quang	1,937	Historical Heritage Site
26	Lam Son	Thanh Hoa	300	
27	North of Hai Van	Da Nang	10,850	Landscape of Hai Van Pass
28	Ngoc Trao	Thanh Hoa	300	
29	Ngu Hanh Son	Da Nang	400	
30	Ba Den Mountain	Tay Ninh	1,855	
31	Ba Ra Mountain	Binh Phuoc	940	
32	Sam Mountain	An Giang	177	
33	Thanh Mountain	Quang Nam	1,500	
34	Chung Mountain	Nghe An	600	Kim Lien Heritage Site
35	Pac Po	Cao Bang	32,051	Limestone forests, historical Heritage Site
36	Pine forests of Da Lat	Lam Dong	32,051	Pine forest on the High Lands
37	Tan Trao	Tuyen Quang	6,633	Evergreen forests, historical Heritage Site
38	Vuc Mau	Nghe An	24,842	
39	Yen The	Bac Giang	1,883	Historical Heritage Site

*: Several rare wildlife species

The establishment of 126 protected areas covering more than 2.5 million ha has required a substantial effort (SRVN 2003). However, this system still has several problems and needs to be improved in order to protect and conserve effectively forests, landscapes and biodiversity.

The protected area in Vietnam is not as large enough for an effective strategy of protection and conservation and several protected areas are too small for conservation purposes (FSTA 2001). The total protected area in Vietnam was around 8% of the country in 2003 (Forest Department 2004). This is low compared to neighboring countries such as Cambodia (18.05%), Lao (11,6%), Thailand (13.01%) and Indonesia (11.62%) (IUCN 1997). It is also below the minimum of 10% recommended by IUCN (1997). Recently, Vietnam has developed the watershed protection regime for several important basins, which may help protect forests and threatened tree species in those areas (Taylor & Wright 2001). However, in order to protect and effectively conserve threatened species and landscapes, the country still needs not only to increase the number of protected areas, but also to expand some small protected areas, and ensure that protected areas are indeed properly protected.

In most protected areas, basic research such as on taxonomy of the species, inventories of biodiversity or surveys of threatened species are still insufficient (FSTA 2001). Control of human activities in protected areas has proved difficult due to a large number of local people, who rely on the forests for a living (Quy 1985). They practice agriculture in the forests, also extract timber from the forests, collect fire wood, medicinal plants and other forest products, hunt and fish. In addition, a movement from the neighboring areas to protected areas has increased the population density, which makes protection and conservation more difficult. For instance, many people have moved to Ba Be National Park, Nam Cat Tien National Park and Yokdon National Park (Tai 1995).

To reduce the pressure of a high human population density on protected areas, local people from the cores (restricted zones) have been moved to the buffer zones, as implemented in Cuc Phuong National Park in 1987 (Thu 2002). Other national parks are also divided into two parts, in which the cores are strictly protected, but local people can live and practice agriculture in the buffer zones. However, this is not sufficient to provide a sustainable strategy of protection and conservation if the living standard of local people is not improved. Local people should be taught new methods of cultivation and production or should be provided with other ways to improve their living conditions.

Several other problems are also affecting protected areas. Investment from the Government for protection and conservation is limited. Lack of funds and useful equipment for implementing protection and conservation is common in protected areas (Tai 1995, FTSA 2001). Human resources are also limited: The capacity of staff to implement protected and conservation projects is limited both by insufficient number of people and by the lack of qualification, experience or skills of the staff (Tai 1995). To improve this situation, protected areas should seek additional funding from donors, particularly international donors. The staff should also be increased both in quantity and quality in order to implement sustainable protection and conservation activities.

In summary, Vietnam is characterized by a monsoonal climate and a complex terrain. Vietnam possesses a very diverse forest vegetation, ranging from mangrove, limestone, and tropical-rain forests to subtropical, bamboo and coniferous forests. Being a venue of plants emigrated from the three floras nearby, Vietnam also harbors a huge number of plant species. Nevertheless, due to many reasons, the forests of Vietnam have severely reduced for last decades, leading to a threat of extinction risks for many species. Recently, by a great effort, Vietnam has established a good system of protected areas, and increased the forest cover in the whole country. To effectively conserve threatened species, however, more attention is required, not only to protect and increase the forest cover, but also to study and improve the situations of these species.

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Note: * The initial titles in Vietnamese were translated into English.

Chapter 3

Conservation prospects for threatened Vietnamese tree species: results from a demographic study

With P.A. Zuidema & N.H. Nghia

Abstract

Effective conservation of threatened tree species requires information on the future prospects of populations that obtained from demographic studies. We investigated the demography of six threatened tree species in four protected areas in Vietnam: the broad-leaved *Annamocarya sinensis*, *Manglietia fordiana* and *Parashorea chinensis*, and the coniferous *Calocedrus macrolepis*, *Dacrydium elatum* and *Pinus kwangtungensis*. In a two-year field study, we quantified recruitment, growth and survival, and used these data to build matrix projection models. Recruitment of new seedlings was found for both study years and over all research plots, indicating that all six species were regenerating naturally. Furthermore, the continuous and inverse J-shaped population structures of all species also suggest abundant and continuous natural regeneration.

To evaluate whether natural recruitment is sufficient, we calculated three parameters. First, asymptotic growth rates (λ) obtained from matrix models were slightly below 1 (0.97-0.99) for all species, but a significant population decline was only found for two of the six species. Second, projected population growth rates for the next 50-100 y also suggested slight population decline (0-3%/y) for five of the six species. Third, we evaluated whether lifetime production of seedlings by an adult tree is sufficient to replace itself – a prerequisite for population maintenance. For three of the six species lifetime recruitment was sufficient, but the three other species required extremely long (480-1000 y) reproductive period to produce sufficient recruits to replace themselves. Combining the three parameters, we concluded that the future prospect for populations of *Dacrydium* and *Parashorea* is good, that for *Annamocarya*, *Manglietia* and *Pinus* is worrisome, while *Calocedrus* takes an intermediate position.

We suggest that conservation measures include strict protection of juvenile and adult trees, as these are most important for population maintenance (high elasticity values). Other effective conservations include: improving growth of seedlings and juvenile trees, enriching populations with planted seedlings obtained from controlled germination and – for *Calocedrus* and *Pinus* species with very low population sizes (<500) – restoring habitat to increase populations.

Finally, we argue that – as long-lived species are slow in responding to conservation measures – these measures should be taken before populations decline below critical levels.

Key words: Threatened tree species, protected area, matrix population models, elasticity analysis, conservation strategy, *Annamocarya*, *Calocedrus*, *Dacrydium*, *Manglietia*, *Parashorea*, *Pinus*.

Introduction

Tropical and subtropical forest area has declined at an alarming rate over the past decades (Achard et al. 2002), particularly in Southeast Asia (Whitmore 1997, Sodhi et al. 2004). As a consequence, many tree species have lost a substantial part of their habitat and have become rare, either due to their restricted distribution or their low abundance. This is illustrated by the large amount of critically endangered (477), endangered (333) and vulnerable (962) tree species in Southeast Asia (World Conservation Union 'IUCN' 2006). The survival of such endangered species is strongly depending on protected areas (Bawa & Ashton 1991). But, within protected areas, isolated populations of endangered species may also be vulnerable to local extinction due to demographic stochasticity or lack of genetic variation (Menges 1992, Lande 1993, Oostermeijer et al. 2003). It is therefore important to evaluate the viability of remaining populations of threatened tree species, by answering questions such as: Are they growing or declining? What factors determine their fate? What processes or stages in the life cycle are most important for the survival of the population? To answer these questions, studies on spatial distribution, densities, or genetic variation or cultivation of the species are not sufficient as they do not provide information on likely population changes in time (Schemske et al. 1994, Dowe et al. 1997, Keith 2000). Demographic (or population dynamics) studies - on the other hand – do provide such information, and have shown to be useful to evaluate viability of threatened populations, e.g., using matrix population models (Harvey 1985, Lande 1988, Silvertown et al. 1996, Menges 2000).

In this paper, we present a study on the demography of threatened tree species in Vietnam, a country where natural forest cover declined from 43% natural forest cover in 1943 to 30 % in 2003 (Hung 2004). We studied six threatened tree species in four protected areas. All species are included in Vietnam's Red List: four are endemic to Vietnam and Southern China, and two others are relict species that occur in only a fraction of their historical geographical range (Ministry of Science, Technology and Environment 'MSTE' 1996, Nghia 2000). To our knowledge, this is the first study that evaluates conservation prospects of Southeast Asian tree species using demographic analyses.

We addressed the following questions: (i) Are populations of our study species naturally regenerating? To answer this, we carried out a 2 year demographic field study, in which we examined recruitment and evaluated population structures. (ii) What is the future prospect for these species? To this end, we constructed population transition matrices for all six species, and calculated population growth rates, survival curves and ages. (iii) What are the most important processes or stages in the life cycle of the species that should be the focus for conservation measures? This question was answered by calculating elasticity values from matrix models (de Kroon et al. 2000), and comparing these among vital rates (survival, growth and fecundity) and species.

Our study delivers essential information for effective conservation of our study species, but also for similar tree species in the region.

Methods

Study species

The study focuses on six threatened Vietnamese tree species (Table 1), referred to by genus name.

Annamocarya sinensis, an endemic species of Vietnam and Southern China, is a large-size deciduous forest tree species. *Annamocarya* occurs in evergreen tropical forests at elevations of 100-600 m a.s.l (above sea level) (MSTE 1996). In Vietnam, *Annamocarya* is restricted to several protected areas such as Cuc Phuong (Ninh Binh), Tam Dao (Vinh Phuc) and Lang Chanh (Thanh Hoa) (Fig. 1). Even in such areas, its populations are limited in both the number of individuals and the range of distribution (MSTE 1996, Nghia 2000). *Annamocarya* fruits annually, producing heavy (50-60 grams) seeds (Thu & Can 1999).

Calocedrus macrolepis is a relict coniferous species that dominates the canopy of subtropical forests in high mountains. Despite its wide distribution (southwest China, Myanmar, Thailand, Laos and Vietnam), this species has become rare and is represented only in small populations (Hiep et al. 2004, Wang et al. 2004). In Vietnam, it occurs in small populations in the Central Highland and Ba Vi Mountains in the North (Fig. 1) (Hiep et al. 2004).

Dacrydium elatum is also a relict coniferous species, occurring in tropical and subtropical rain forests (500-1800 m a.s.l) in Southeast Asia and Hainan Island (China). In Vietnam, the distribution of *Dacrydium* has severely declined due to habitat loss (MSTE 1996), and is currently sparsely found in high mountains of some provinces (Fig. 1), particularly in Bach Ma National Park (Thua Thien Hue province) (Hiep et al. 2004). Regeneration of the species has been observed in open and moist forests close to parent trees (Keo 2003).

Manglietia fordiana is an endemic species of Vietnam and Southern China. In Vietnam, *Manglietia* is sparsely distributed in tropical rain forests at elevations from 100-1000 m a.s.l. (Fig. 1). Seedlings are shade-tolerant and adults reach the forest canopy. Currently, the species is restricted to small populations in protected areas, and it is an important focal species for conservation (MSTE 1996).

Parashorea chinensis is a large-size tree species that reaches the canopy of dense evergreen tropical forests in the North of Vietnam (Fig. 1). Both habitat extent and local abundance of *Parashorea* have severely declined strongly due to deforestation and overexploitation. Adult trees of the species are strongly restricted to protected areas, such as Cuc Phuong National Park (Nghia 2000). Seeds of the species are small, winged and wind-dispersed. Abundant natural regeneration is found along streams and in wet open areas (MSTE 1996).

Table 1. Characteristics of the study species and their categories in the IUCN Red List.

Species (family)	Max height (m)	Max DBH (cm)	Main uses	Main threats	IUCN Red List category
Annamocarya sinensis (Dode) Leroy (Juglandaceae)	35[a]	150[a]	Timber, seed consumption	Habitat loss and fragmentation, overexploitation, low natural regeneration	CR D[b]
Calocedrus macrolepis Kurz (Cupressaceae)	15-25[b]	>100[b]	Timber, incense extracted from wood, young tree for ornamental purpose	Habitat loss and fragmentation, overexploitation, restricted distribution	EN D[b]
Dacrydium elatum (Roxb) Wall ex Hook *(*Podocarpaceae)	20-25[b]	50-70[b]	Timber, incense, chemicals for pesticide	Habitat loss and fragmentation, overexploitation, restricted distribution	VU A cd[b]
Manglietia fordiana (Hemsl.) Oliv. (Magnoliaceae)	15-20[b]	50-60[b]	Timber	Habitat loss and fragmentation, overexploitation, restricted distribution	EN D[b]
Parashorea chinensis Wang Hsie (Diptero-carpaceae)	60[b]	>100[b]	Timber	Habitat loss and fragmentation, high demand for wood, overexploitation	VU A cd[b]
Pinus kwangtungensis Chun ex Tsiang (Pinaceae)	15-20[b]	50-70[b]	Timber, resin extraction	Habitat loss and fragmentation, overexploitation, restricted distribution, low natural regeneration	EN D[b]

[a] Modified from Thu and Can (1999).

[b] Mofified from Nghia (2000)

CR: Critically endangered (threatened level decreases from A to E)

EN: Endangered (threatened level decreases from A to E)

VU: Vulnerable (threatened level decreases from A to D)

cd: Conservation dependence.

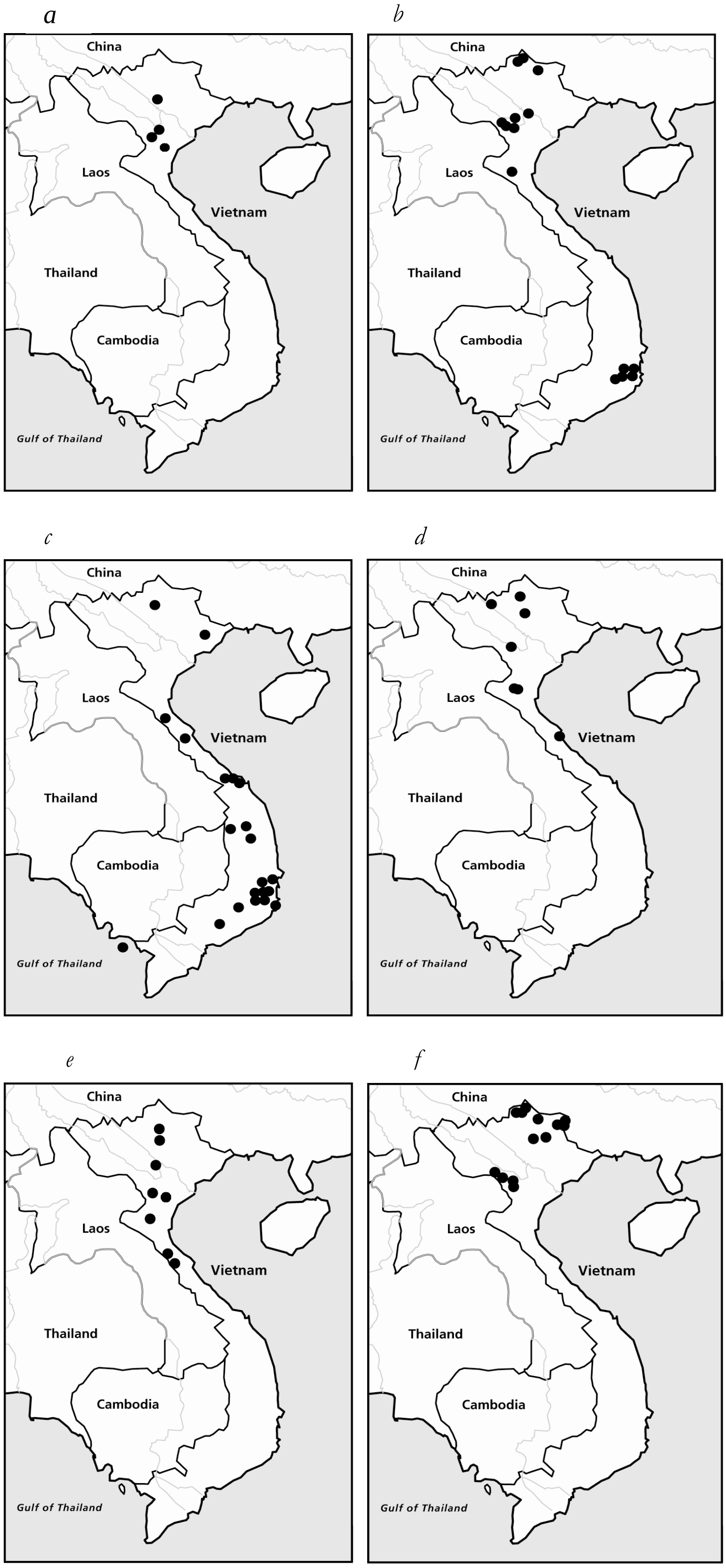

Figure 1. Distribution of six threatened tree species in Vietnam: *Annamocarya sinensis*: a, *Calocedrus macrolepis*: b, *Dacrydium elatum*: c, *Manglietia fordiana*: d, *Parashorea chinensis*: e, *Pinus kwangtungensis*: f (adapted from MSTE 1996, Hiep et al. 2004).

Pinus kwangtungensis is a big subtropical coniferous forest tree that is endemic to Vietnam and Southern China. In Vietnam, its distribution is restricted to limestone mountains at 1200-1400 m a.s.l (Fig. 1) (MSTE 1996). Is has been reported that only less than 100 adult trees of the species remain in the country, and seedlings are rarely found (Nghia 2000).

Study sites

Table 2. Characteristics of study sites for six threatened Vietnamese tree species.

Species	Study site (Coordinates)	[c]Altitude (m)	Mean annual rainfall (mm)	Mean annual temperature (ºC)	[c]Canopy height (m)
Annamocarya	[a]Cuc Phuong (20ºN, 105ºE)	250	2160	20.6	25-30
Calocedrus	[a]Ba Vi (21ºN, 105ºE)	1200	2590	23.4	15-20
Dacrydium	[a]Bach Ma (16ºN, 107ºE)	1200	3600	25	15-20
Manglietia	[a]Ba Vi (21ºN,105ºE)	900	2590	23.4	15-20
Parashorea	[a]Cuc Phuong (20ºN, 105º E)	300	2160	20.6	25-30
Pinus	[b]Hang Kia – Pa Co (20º , 104ºE)	1100	1925	20	15-20

[a]National Park
[b]Nature Reserve
[c]Value specific for study plots

The six threatened tree species were studied in 3 National Parks and one Nature Reserve (Table 2). Cuc Phuong National Park is located on two parallel limestone mountains, at about 300-400 m a.s.l. Study plots for *Annamocarya* were located in the central valley of the park on flat terrain and in highly diverse forests, those for *Parashorea* were located at similar forest structure and terrain conditions, but higher elevation. Ba Vi National Park includes three main mountain peaks (> 1000 m a.s.l), surrounded by plains. The study plots for *Calocedrus* were located on peaks, in rather open subtropical evergreen coniferous-broad-leaved forest, with abundance of bamboos. Plots for *Manglietia* were at lower elevation in denser tropical evergreen broad-leaved forest. Bach Ma National Park is located in Central Vietnam, and includes forests at different elevations (100-1200 m a.s.l). The study plots for *Dacrydium* were established at 1000-1200 m a.s.l in evergreen subtropical forest. Hang Kia - Pa Co Nature Reserve is located on the high limestone mountains of Hoa Binh province, and experiences a subtropical climate with hot and cold seasons. The study plots were covered by subtropical coniferous-broad-leaved forests, in which *Pinus* is one of the dominant canopy tree species.

Data collection

In the study sites, permanent plots were established in 2003: 3 plots (2.5 ha/plot) for *Annamocarya*, 2 plots (2.5 ha/plot) for *Calocedrus*, 3 plots (2 ha/plot) for *Dacrydium*, 2 plots (3 ha/plot) for *Manglietia*, 3 plots (4 ha/plot) for *Parashorea*, and 3 plots (2 ha/plot) for *Pinus*. At first measurement, all juvenile and adult trees (diameter at breast height, DBH > 5 cm) of the study species in the plots were searched, tagged and measured. Remeasurements were carried out in 2004 and 2005. At each measurement, DBH, total height, and height to the first branch of the trees were measured. Mortality and reproductive status of individuals were also recorded.

Within the plots, subplots (20x20 m) were randomly established to study seedlings and saplings (< 5 cm DBH). Per species a total 20-60 subplots were established, depending on seedling density. At first measurement in 2003, all seedlings and saplings of the study species in the subplots were searched, tagged and measured. Measured parameters were total height and diameter at ground level (or DBH if possible). Remeasurements were conducted in 2004 and 2005. Mortality and recruitment of seedlings and saplings were recorded during remeasurements.

Data analysis

As the demographic parameters were collected at different plots and years, survival and growth rates were tested for differences between plots and years, using analysis of variance (ANOVA), linear, non-linear or logistic regression models. In case of no significant difference, data were pooled for constructing transition matrices.

We related height growth of seedlings and seedling height, using the linear regressions, and used logistic regressions to relate seedling survival probability to height.

Growth of the tree diameter is typically non-linearly related to the initial diameter, with high growth rates for intermediate-sized trees. Therefore, diameter growth was related to DBH, using Hossfeld IV equation (Zeide 1993):

$$\Delta DBH = \frac{b*c*DBH^{(c-1)}}{[b + (DBH^{c/a})]^2} \quad (1)$$

where ΔDBH is DBH growth rate (cm y^{-1}), and a, b and c are fitted parameters. We used non-linear regression analysis with a least-square loss function to fit this function through observed data on DBH growth and DBH.

The relation between reproductive status and DBH was analysed using logistic regression.

Transition matrix construction and analysis

We used the Lefkovitch matrix model (Caswell 2001) to project population dynamics of our study species. These models use the equation: n(t+1) = **A**n(t), where n(t) and n(t+1) are population structures at time t and t+1, and **A** is a square matrix containing transition probabilities among categories during one time step. For our study, the time step was 1 year. When the multiplication of **A** and n(t) is repeated many times, the relative structure and growth rate of the population will become stable. When a stable size distribution is reached, the dominant eigenvalue (λ) and the right eigenvector of matrix **A** are equal to the growth rate and the stable stage distribution of the population, respectively.

The populations of the six study species were divided into 14 to 18 size categories, depending on the abundance and size structure of each population (Appendix 1). For all species, the four smallest categories were based on seedling height and the remaining on DBH. Elements (a_{ij}) of matrix **A** can be grouped into growth, stasis or fecundity. Growth elements (G, elements in the sub-diagonal of the matrix) that represent the probability of an individual to grow from one category to the next, were calculated as $G_i = \sigma_i \times \gamma_i$, where γ_i is the probability that a surviving individual in category i moves to i+1, σ_i is the survival probability in category i. The value of γ_i was calculated as g_i / c_i, in which g_i is the height or DBH growth rate for category i (in cm yr^{-1}) and c_i the category width (in cm height or DBH). Stasis elements (P, in the diagonal of the matrix) presenting the probability that an individual survives and stays at the same category, were calculated as $P_i = \sigma_i - G_i$. Fecundity elements (F, the upper row, except for the top-left element) represent the number of seedlings produced by an adult individual. We assumed that all reproductive individuals had the same reproductive output (number of seedlings). Therefore, F was calculated as $F_i = \sigma_i \times \mathit{Prob}\{f\}_i \times f_i$, where $\mathit{Prob}\{f\}_i$ is probability of being reproductive for individuals in category i, and f_i was calculated by dividing the abundance of new seedlings (per ha, per year), by that of reproductive trees.

We estimated the similarity between the stable stage structures resulting from the matrix models and the observed population structures using the similarity index PS (Horvitz & Schimske 1995). $PS = \sum(\min[ops_i, ssd_i] \times 100$, where ops_i, is vector of observed population structures, and ssd_i is the vector of stable size distribution. Both vectors were scaled to sum to one. High values of PS indicate high values of similarity.

Dominant eigenvalues (λ) were calculated for all six matrix models (Caswell 2001). If λ > 1, populations are project to grow, whilst they decrease for λ < 1. To examine whether λ is significantly different from unity, we calculated the 95% confident limits of λ with the series approximation approach (Caswell 2001), and using sensitivity and variance of vital rates (survival, growth and reproduction) respectively. As we lacked information on variation in reproductive output among individuals, this was not taken into account in the calculation, thus probably leading to a slight underestimation of the confidence interval. Transient dynamics of the populations were analysed by multiplying population structure with the transition matrices. This was done for 50 and 100 years, for all six species. Based on the relative increase in the population over these periods, we then calculated the annual growth rate and compared these values to the value of λ.

The elasticity of λ to vital rates (survival, growth and reproduction) is the proportional change in λ due to a proportional change in a vital rate (de Kroon et al. 2000), and that it indicates the importance of vital rates to λ. We calculated the elasticity of λ to vital rates using the approach of Caswell (2001) and Zuidema and Franco (2001). It should be noted that vital rate elasticities differ from those for matrix elements in that they may be negative (if an increase in a certain vital rate leads to a reduction in λ) and that they do not sum to one (Caswell 2001).

Lastly, using the transition matrices, we constructed survival curves for each of the six study species following the approach of Cochran and Ellner (1992). We also calculated the age at which reproductive size is reached by calculating the conditional age (τ in Cochran & Ellner 1992) of entering the first reproductive size category.

Results

Size distribution and natural regeneration

The six study species differed considerably in maximum DBH. The largest trees of *Dacrydium*, *Manglietia* and *Pinus* were just over 60 cm DBH, those of *Calocedrus* 85 cm DBH, while those of *Annamocary* and *Parashorea* reached more than 100 cm DBH. The variation in maximum size corresponds to differences in forest structure: *Annamocarya* and *Parashorea* occur in forests at low elevation with high canopy height (25-30 m), while the other study species are typically found in forests with lower canopy at higher elevations (Table 2).

Population structures of the six study species showed inverse J-shaped curves (Fig. 2), with most individuals present in the seedling and juvenile categories. Although the abundance differed strongly between species, all population structures showed a continuous abundance of individuals without any clear ‘bottleneck’ (Fig. 2). This result suggests that there is continuous regeneration for all study species.

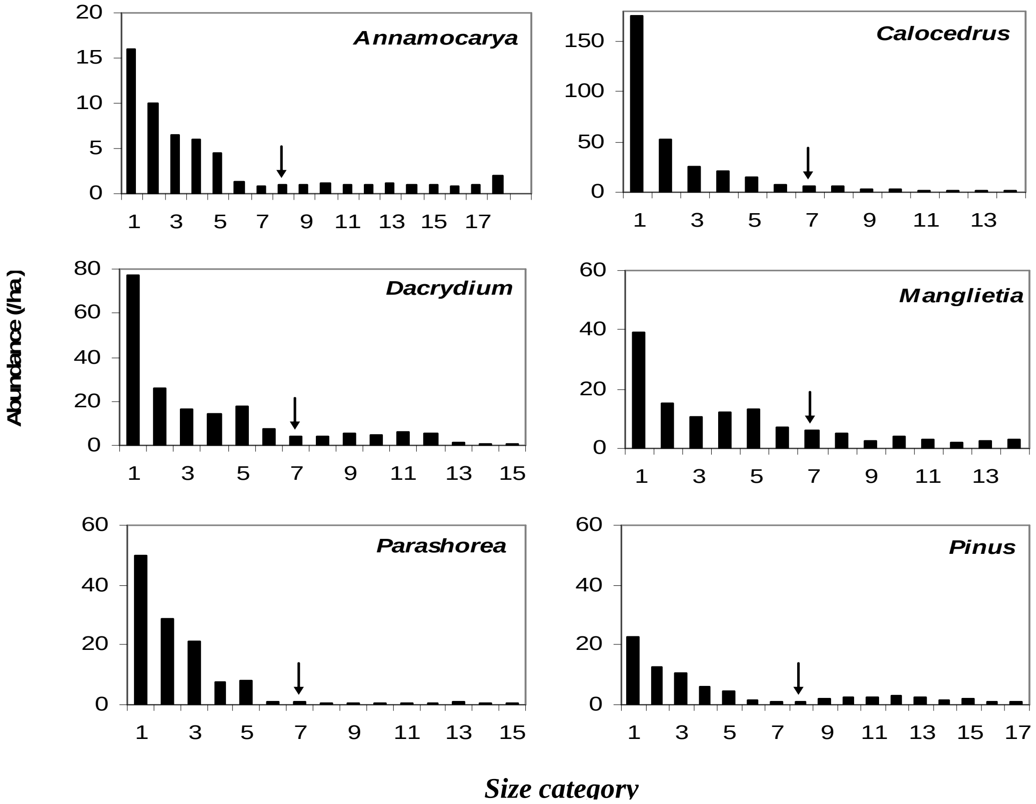

Figure 2. Population structures of six threatened Vietnamese tree species, as observed in four protected areas. The first four size categories are for seedling (< 1 cm DBH, diameter at breast height) and based on plant height, the remaining categories are based on DBH (see Appendix 1 for categorisation). Arrows show the category at which trees start reproducing.

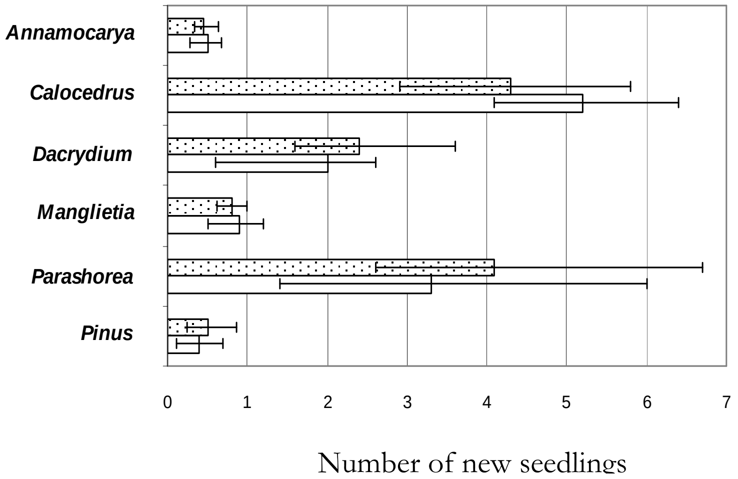

Figure 3. Recruitment of six threatened tree species in Vietnam, expressed as number of new seedlings appearing per year and per adult tree. Dotted bars are for 2003-4, open bars for 2004-05. Error bars indicate the maximum and minimum values of the study plots.

Natural regeneration was indeed observed in the populations of all study species: in both observation years new seedlings were found. For *Annamocarya*, *Calocedrus*, *Dacrydium*, *Manglietia*, *Parashorea* and *Pinus* we counted 5.2, 85, 47, 14.5, 16.3 and 7.3 seedlings per ha and per year, respectively (averaged over the two years). When expressed per reproductive tree, the number of seedlings produced by a reproductive tree ranged from 1-5 among species, without varying much between observation years (Fig. 3).

Vital rates

Survival probability of all study species increased from 65-85% for small seedlings (category 1) to 96-99% for adult trees, and was positively related to seedling height for all but one of the study species (*Annamocarya*, logistic regression, see Appendix 1). In contrast, large individuals (from category 5 and larger) maintained a relatively high and rather stable survival rate of 90-99%.

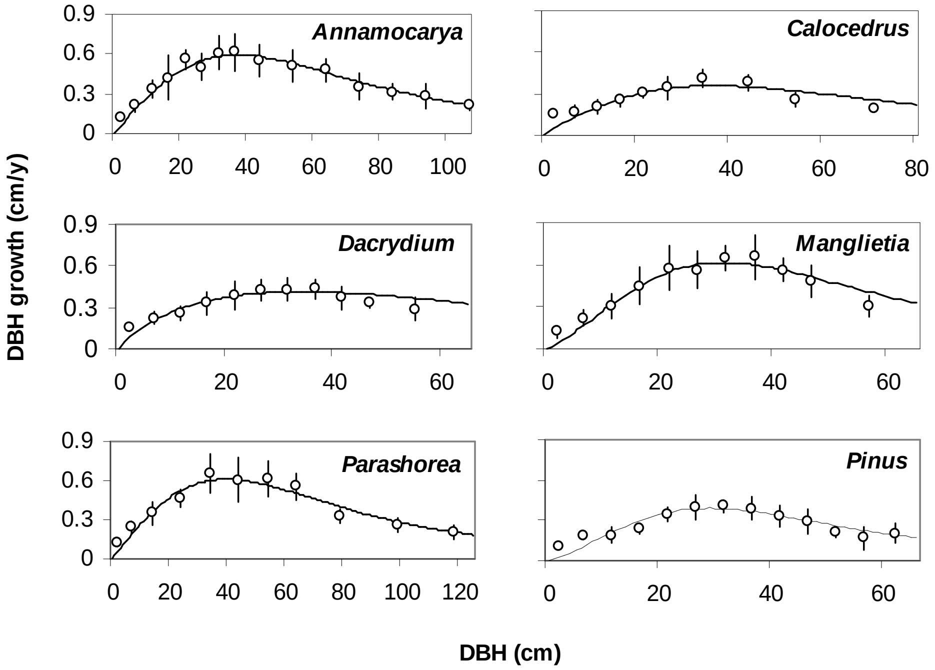

Figure 4. Size-dependent pattern in DBH growth of six threatened tree species in Vietnam. Shown are fitted Hossfeld IV curves (lines), and observed average (± 1SD) growth rates per category (dots). Fitted parameters a, b, c and R^2: *Annamocarya* 58.8, 68.4, 1.99 and 0.73, *Calocedrus* 38.4, 76.2, 1.89 and 0.59, *Dacrydium* 51.2, 29.4, 1.69 and 0.61, *Manglietia* 42.2, 141.3, 2.25 and 0.73, *Parashorea* 64.3, 70.4, 1.98 and 0.75, and *Pinus* 24.4, 228.5, 2.29 and 0.61, respectively.

The six study species differed in seedling height growth rate with *Maglietia* seedlings growing fastest (>11 cm/y for large seedlings) and *Dacrydium* seedlings growing slowest (<6 cm/y, Appendix 1). Seedling height growth was linearly related to initial height of seedlings for all species. DBH growth rate for all species increased from low values (0.1-0.2 cm y^{-1}) for small trees to high values (0.4-0.7 cm^{-1}) for mid-sized trees (20-50 cm DBH), and then gradually decreased to lower values again (Fig. 4). DBH growth of the broad-leaved species tended to be faster than that of the coniferous species. Also, the peaks in DBH growth curves of the broad-leaved species were higher and wider than those of the coniferous species (Fig. 4).

Reproductive status of the six species was strongly related to tree sizes (Fig. 5). Trees of all study species started reproducing at sizes of 10-20 cm DBH, although this tended to be smaller for coniferous species than for the broad-leaved species (Fig. 5). The DBH at which 90% of the individuals is reproductive ranged from 30-70 cm among species.

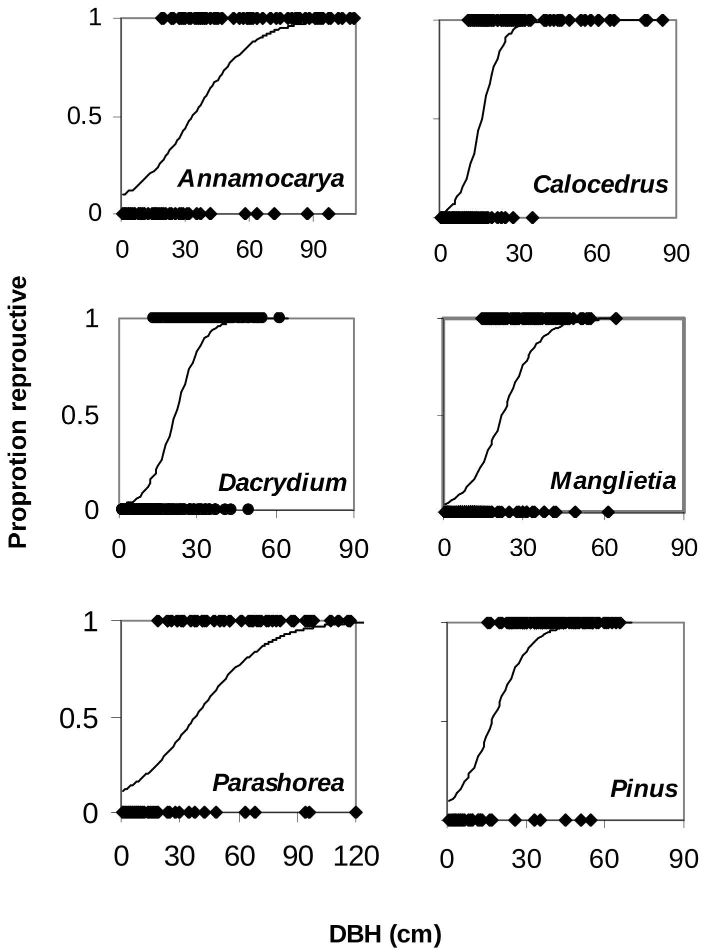

Figure 5. Relation between DBH and the proportion reproductive individuals of six threatened Vietnamese tree species. Dots are observed values for reproductive status, and lines are fitted logistic regression: Y = 1/(1+Exp(-(a+b*DBH))). Fitted parameters a, b and R^2: *Annamocarya* -2.32, 0.069 and 0.54, *Calocedrus* -3.838, 0.29 and 0.592, *Dacrydium* -4.027, 0.187 and 0.591, *Manglietia* -3.232, 0.146 and 0.559, *Parashorea* -2.114, 0.055 and 0.531, and *Pinus* -2.396, 0.139 and 0.483.

Matrix model output

The values for the similarity index PS were high (range: 85 for *Annamocarya* and *Pinus* to 95 for *Calocedrus*), indicating that our models provide realistical projection of the observed population structures.

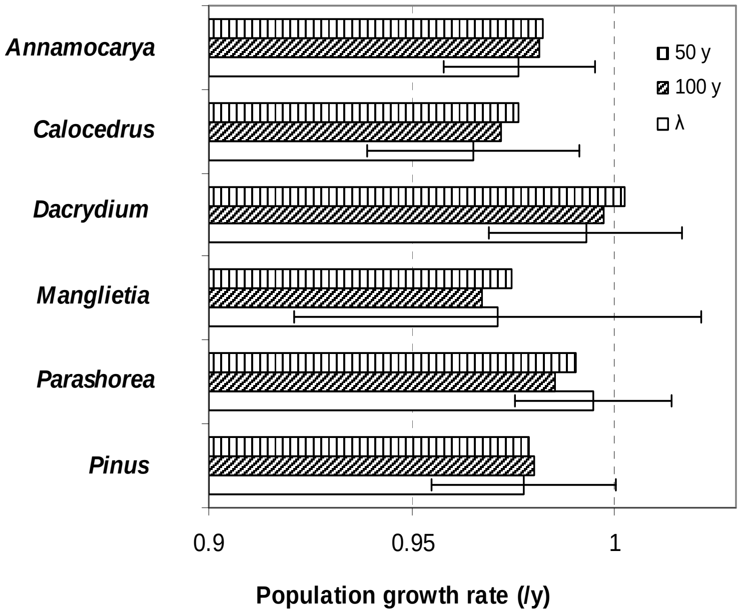

Figure 6. Three estimates of population growth rates for six threatened Vietnamese tree species obtained from matrix models. Shown are the projected population growth rates based on transient dynamics over 50 years and over 100 years, as well as the asymptotic population growth rate (λ, with 95% confidence interval).

The asymptotic population growth rates (λ) of the six study species were all slightly below 1 (Fig. 6). This suggests that populations are slightly declining. Nevertheless, the 95% confidence intervals of λ included the value 1 for four out of six species (*Dacrydium*, *Manglietia*, *Parashorea* and *Pinus*). For these species, there is no indication of a significant decline in size of the studied populations. For the two other species - *Annamocarya* and *Calocedrus*, - the 95% confidence limits did not include 1, suggesting that these populations were declining.

As λ is the asymptotic population growth rate when the population structure equals to stable stage structure, its value may differ from the population growth rate that obtained when projecting the present population structure for a limited period of time (based on the transient dynamics of the population). For the comparison, we therefore calculated the annual population growth rate based on matrix projection of 50 and 100 years. For all six species, the projected population growth rates based ontransient dynamics were close to asymptotic growth rates (λ, Fig. 6). The projected growth rates based on 50-y projections were lower than unity for five of the six species, while for those based on 100-y projections this was the case for all species. The projections suggest that population sizes will decline in time by <1-3 % per year. But, these results have to be interpreted with caution, as natural variability in vital rates and estimation errors may lead to strong variation in the projected population growth. This variability is probably of the same magnitude as that of λ..

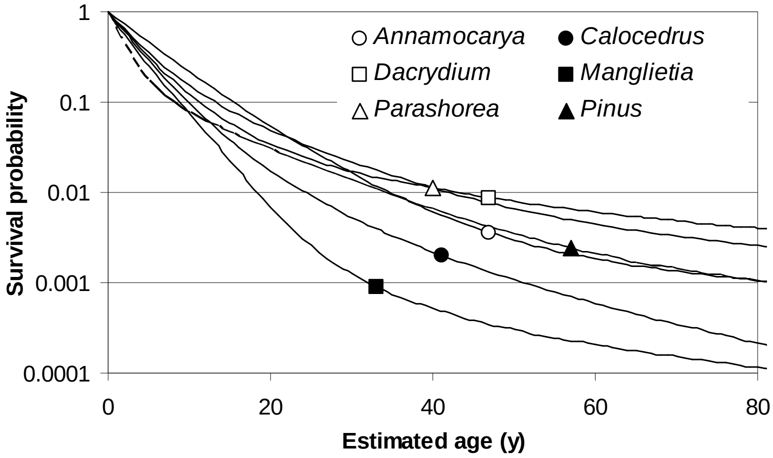

Figure 7. Survivorship curves for six threatened tree species in Vietnam, based on matrix models. Symbols show the age at which trees reach the first reproductive category (conditional age τ, Cochran & Ellner 1992), and the corresponding survival probability to that age. Note that the Y axis has a logarithmic scale.

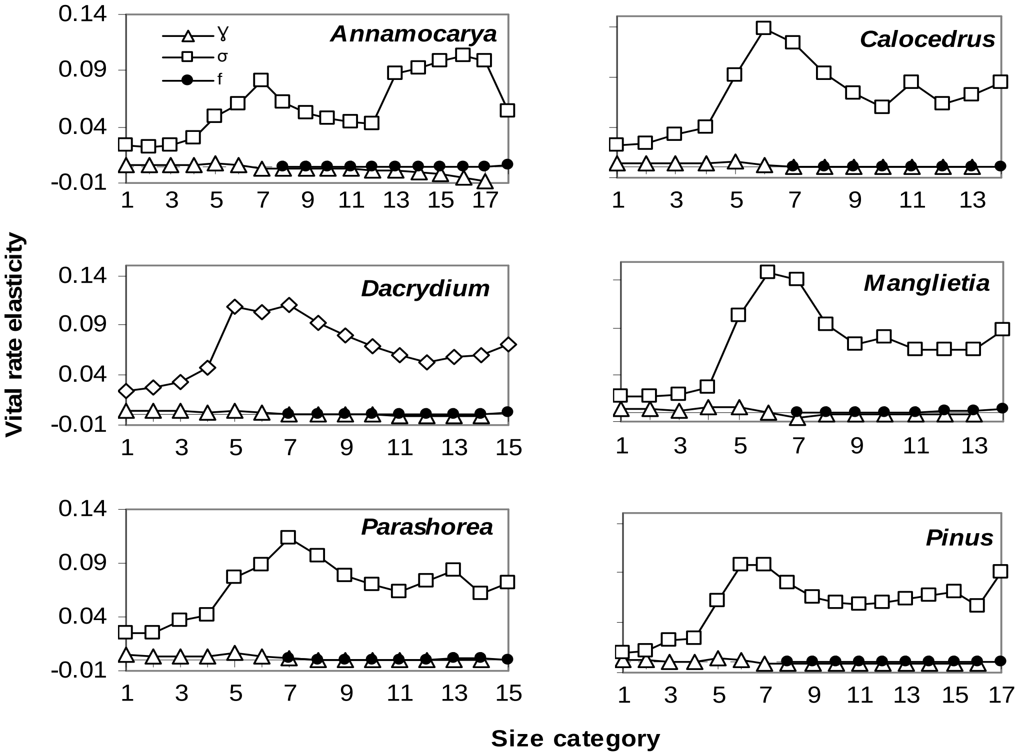

Figure 8. Vital rate elasticity for six threatened Vietnamese tree species. Shown is elasticity for growth (γ), survival (σ) and fecundity (f), denoting the proportional change in λ due to a proportional change in that vital rate.

The estimated age at first reproduction varied among species, from 35 years for the relatively fast growing *Manglietia* to 60 years for the slow-growing *Pinus*. We obtained these age values with survival curves to estimate the average fraction of newborns that becomes reproductive. The results (Fig. 7) show that only a very small fraction (0.1-1%) of the seedlings recruited in the population survives to reproductive size. This value varied strongly among species, being one order to magnitude larger for *Dacrydium* and *Parashorea* compared to *Manglietia*.

Elasticity analysis showed that survival was the most important vital rate for population growth, in all species, followed by growth and fecundity (Fig. 8). In particular, survival of juvenile and small reproductive trees (category 5-8) was most important for population growth. The negative elasticity values for tree growth in *Annamocarya* (Fig. 8) show that that increased diameter of large trees (category 10 and larger) reduces the population growth.

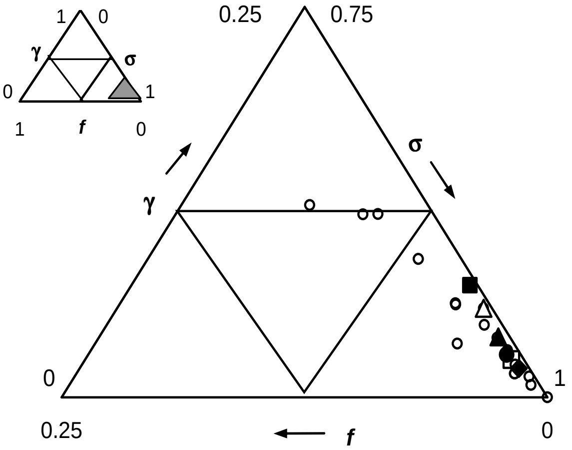

Figure 9. Position of six threatened Vietnamese tree species in relation to that of 22 other tree species (open dots) in a triangular ordination of vital rate elasticity values (survival, σ, growth, γ, fecundity, f). Data for the 22 tree species are from published demographic studies (reviewed by Franco & Silvertown 2004). The six study species are indicated by open triangle (*Annamocarya*), open square (*Calocedrus*), open diamond (*Dacrydyum*), filled triangle (*Manglietia*), filled dot (*Parashorea*) and filled square (*Pinus*). Absolute values of elasticity were used, these were summed over categories per vital rate and scaled to sum to 1.

To compare elasticities of vital rates between our study species and other tree species for which matrix models are available, we constructed a triangle ordination using elasticities of vital rates, following Franco and Silvertown (2004, Fig. 9). We found that the elasticity distribution over vital rates of our study species is consistent with that for other tree species, represented by points close to the survival vertex of the triangle, indicating strong importance of survival for population maintenance. Nevertheless, our study species had relatively high elasticity for survival and low for fecundity.

Discussion

Differences between species

Although our study species are all non-pioneer trees that reach the forest canopy as adult, they show differences in performance and population dynamics. These differences are probably partly caused by variation among habitats. The relatively slow DBH growth of *Calocedrus*, *Dacrydium* and *Pinus* is probably related to the typical mountain microclimate of these species with shallow soils and periodical low temperature. These coniferous species also demonstrate rather constant growth rates over their size range, compared to the peaked growth-diameter relation of the broad-leaved species (Fig. 4). High juvenile growth is probably possible due to typically open structure of high elevation forests.

Natural regeneration and future prospects of populations

Ultimately the prospect of population survival depends on whether populations are regenerating naturally, and whether this is sufficient to maintain populations. We found that all six species were regenerating naturally in all sites and in both observation years. Our results are consistent with those of previous studies on recruitment for some of the study species (Thu & Can 1999, Nghia 2000, Keo 2003). Another indication of natural regeneration was observed in population structures: all species showed continuous and inverse J-shaped size distributions, without signs of regeneration bottlenecks (e.g., Peres et al. 2003). Such size distributions are typically found for forest tree species with good recruitment (Poorter et al.1996, Newbery & Gartlan 1996, Zuidema & Boot 2002). Clearly, unfavourable recruitment conditions outside protected areas due to harvest pressure or anthropogenic disturbances, may lead to population structures that differ from the ones we observed inside parks.

To find out whether natural regeneration is sufficient for population maintenance we calculated three measures. First, we used the common asymptotic growth rate of population, λ. The value of λ was below 1 for all species, but only significantly for two species. For these two species, the real confidence interval is likely larger as variability in vital rates has been underestimated due to lacking information on variation in seed production. Thus, there is a possibility that population growth rates for these species are not different from unity. The confidence intervals we calculated may be relatively high as the sampled populations are rather small (less than 450 individuals), which is unavoidable in studies on threatened tree species (Bierzychudek 1999, Coulson et al. 2001). In addition, the accuracy of λ and its confidence interval is likely limited by the short study period that did not capture the range of temporal variability that determines long-term dynamics of tree populations (Menges 1990, Enright & Watson 1991, Bierzychudek 1999, Van Mantgem & Stephenson 2005).

Second, we estimated population growth based on transient dynamics (Fox & Gurevitch 2000, Van Mantgem & Stephenson 2005). These population growth rates are close to the values of λ. This comparison is useful as it shows the extent to which the differences between observed and stable population structures determine population growth rates. If differences are large, transient dynamics are characterized by strong fluctuations, and resulting population growth rates differ much form λ. In our analyses the differences were small (high values for similar index PS), and these differences did not lead to strong deviation between the two estimates for population growth rate. Population growth rates based on transient dynamics consistently suggested population declines for all six species, except for *Dacrydium* (Fig. 6). However, as these measures lack confidence intervals, growth rates could also have been higher due to variation among individuals and uncertainty in parameter estimation.

Finally, the third measure of future population growth that we applied did not use the population growth rate, but combined information on recruitment and ages to check whether an adult tree produces sufficient seedlings to replace itself. For example, in *Manglietia*, survival to adult size amounts to 0.1% (Fig. 7), implying that an adult tree should produce 1000 seedlings in its entire reproductive life to replace itself. At the rate of less than one seedling per year that we observed (Fig. 3), this takes over 1000 years. In a similar way, we calculated the required reproductive life span for the other species: this was 480 y for *Annamocarya*, 70 for *Calocedrus*, 52 for *Dacrydium*, 25 for *Parashorea* and 580 for *Pinus*. For *Annamocarya*, *Manglietia* and *Pinus*, these reproductive periods are far longer than maximum ages estimated from matrix models (ranging from 150 to 250 y, P.D.C., unpublished data). Clearly, these calculations are based on the recruitment rates estimated over the two-year study period and assume that there are no strong fluctuations in recruitment over time. For instance, years with exceptional seed production could strongly reduce the required reproductive period. To our knowledge, most of our study species are fruiting annually, and we are not aware of strongly inter-annual variation in recruitment for any of the species (Nghia 2000).

We combined the results obtained from the three measures (Table 3) to draw conclusions on future prospects for populations of our study species. It appeared that there was little consistency among the measures. This discrepancy underscores the limitation of drawing conclusions about the fate of populations on the basis of just one parameter, as is often done (Floyd & Ranker 1998, Bierzychudek 1999).

Table 3. Comparing three measures to estimate future prospects for populations of six threatened Vietnamese tree species.

Species	Future prospects of populations based on:		
	[a]λ	[b]Transient dynamics	[c]Reproductive output
Annamocarya	-	-	-
Calocedrus	-	-	+
Dacrydium	+	+	+
Manglietia	+	-	-
Parashorea	+	-	+
Pinus	+	-	-

[a] + indicates asymptotic population growth rate (λ) above 1 or not sign different from 1, – indicates asymptotic population growth rate < 1.

[b] + indicates expected population increase over 50-100 y, – indicates expected population decline over 50-100 y.

[c] + indicates that an adult tree produces sufficient offspring to replace itself, – indicates the reverse.

The future prospects for *Dacrydium* and *Parashorea* are good, as their populations are not declining and recruitment is sufficient to replace adult trees. On the other hand, the future prospects for *Annamocarya*, *Manglietia* and *Pinus* are worrisome: although there is no evidence for a population decline based on the variance of the asymptotic population growth rate for two of these species, the amount of recruits produced per year is clearly insufficient to guarantee replacement of the adult tree. For *Calocedrus*, the future prospects are not just good as populations are projected to decline, but recruitment appears to be sufficient for adult replacement.

Finally, all three measures presented here were based on a short-term demographic study and do therefore not take into account sporadic events leading to peaks in recruitment or mortality. To the extent that such events drive the long-term population dynamics of our study species, the conclusions on population prospects presented here may be changed (Keith 2000, Van Mantgem & Stephenson 2005).

Implications for conservation

Our results suggest that successful protection of the six study species requires various conservation measures. First, strict protection of juvenile and adult trees is crucial as these are the stages that are most important for population maintenance (cf. Zuidema

& Boot 2002, Franco & Silvertown 2004, Kwit et al. 2004). Preventing damage and logging within and outside protected areas therefore is of high priority. Second, growth of seedlings and juvenile trees may be improved (e.g., by controlled liberation) in order to increase population growth. Although elasticity analyses suggest that the effect of such measures is limited in comparison to maximizing tree survival, seedling and tree growth can probably be altered more than tree survival, and with less difficulty (Batista et al. 1998, Zuidema & Boot 2002, Kwit et al. 2004). A third conservation measure is enrichment of populations with seedlings grown under controlled conditions. If germination success under controlled conditions is higher than that under natural conditions, seeds can be collected from the same natural populations which are enriched with seedlings. This measure is particularly important for species with an apparent insufficient recruitment (*Annamocarya*, *Manglietia* and *Pinus*). Finally, for species with small remaining populations such as *Calocedrus* and *Pinus* (populations of <500 trees, MSTE 1996, P.D.C., personal observation), the expansion of habitat area through nature restoration would be an effective measure.

Declines in population sizes of tree species are slow, as they are long-lived. As a consequence, there is more time for taking conservation measures, but slow dynamics also imply that it takes long before such measures result in population increase. Taking action before populations have declined to critical levels is therefore important, as well as close monitoring of population size and recruitment.

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Note: * Initial titles in Vietnamese were translated into English.

Appendix 1. Classification criteria and vital rate values used for construction of transition matrices for the six study species. Categories 1-4 are based on seedling height, 5-18 on DBH. Shown are estimates for vital rates based on regression analyses: growth rate (g, in height for seedlings, and in DBH for trees), percentage of reproductive individuals (Rep), survival probability (σ) and sample size (n). Seedling height growth as related to height as $Y = ax + b$, with a, b and R^2 are 0.0243, 3.483 and 0.74 for *Annamocarya*, 0.0195, 3.2451 and 0.73 for *Calocedrus*, 0.0167, 2.9977 and 0.64 for *Dacrydium*, 0.0533, 4.3551 and 0.52 for *Manglietia*, 0.0358, 32838 and 0.75 for *Parashorea*, and 0.0287, 4.1816 and 0.47 for *Pinus*. DBH growth was fitted by Hossfeld IV curve (see Fig. 3). Seedling survival rate was calculated using the logistic equation $Y = 1/(1 + \mathrm{EXP}(-(c + d*\mathrm{height})))$, where fitted parameters c and d and R^2 (Nagelkerke) for *Annamocarya* ns, *Calocedrus* 0.313, 0.006 and 0.039, *Dacrydium* 0.304, 0.011 and 0.123, *Manglietia* 0.095, 0.008 and 0.109, *Parashorea* 0.427, 0.01 and 0.084, and *Pinus* -0.814, 0.032 and 0.329, respectively. Survival percentage of juvenile and adult trees was not significantly influenced by tree DBH, and was calculated as average over various categories.

	Annamocarya					*Calocedrus*				
Cat	Height or DBH [cm]	g [cm/y]	Rep [%]	σ	n	Height or DBH [cm]	g [cm/y]	Rep [%]	σ	n
1	*0-30*	3.8		0.85	31	*0-30*	3.5		0.77	140
2	*30-60*	4.5		0.86	21	*30-60*	4.1		0.80	42
3	*60-100*	5.4		0.87	18	*30-120*	5.0		0.84	21
4	*100-175*	6.8		0.88	17	*120-195*	6.3		0.91	17
5	1-5	0.09	0	0.90	15	1-5	0.07	0	0.93	12
6	5-10	0.21	0	0.94	8	5-10	0.15	0	0.96	35
7	10-15	0.33	0	0.98	6	10-15	0.22	30	0.96	30
8	15-20	0.43	25	0.98	8	15-20	0.27	59	0.96	27
9	20-25	0.51	32	0.98	8	20-25	0.32	83	0.96	16
10	25-30	0.56	43	0.98	9	25-30	0.34	94	0.96	17
11	30-35	0.59	57	0.98	7	30-40	0.36	99	0.96	10
12	35-40	0.57	69	0.98	8	40-50	0.35	100	0.96	10
13	40-50	0.52	81	0.98	9	50-60	0.32	100	0.96	6
14	50-60	0.45	90	0.98	8	>60		100	0.96	5
15	60-70	0.38	95	0.98	7					
16	70-80	0.32	96	0.98	6					
17	80-90	0.23	97	0.95	7					
18	>90		99	0.95	15					
	∑				208					388

		Dacrydium					*Manglietia*			
1	*0-30*	3.2		0.78	93	*0-30*	5.4		0.74	57
2	*30-60*	3.7		0.83	31	*30-60*	7.0		0.78	34
3	*60-100*	4.3		0.88	20	*60-100*	8.9		0.82	24
4	*100-160*	5.1		0.92	17	*100-165*	11.5		0.87	27
5	1-5	0.12	0	0.96	25	1-5	0.07	0	0.96	30
6	5-10	0.22	0	0.97	46	5-10	0.19	0	0.98	42
7	10-15	0.29	16	0.99	26	10-15	0.34	0	0.98	38
8	15-20	0.35	32	0.99	26	15-20	0.47	34	0.98	31
9	20-25	0.39	55	0.99	33	20-25	0.56	51	0.98	16
10	25-30	0.41	75	0.99	28	25-30	0.61	67	0.98	25
11	30-35	0.42	88	0.99	35	30-35	0.60	82	0.98	18
12	35-40	0.41	95	0.99	31	35-40	0.57	90	0.98	12
13	40-45	0.40	99	0.99	10	40-45	0.51	95	0.98	15
14	45-50	0.36	99	0.99	6	>45		98	0.98	17
15	>50		97	0.99	2					
	∑				432					386
		Parashorea					*Pinus*			
1	*0-30*	3.8		0.80	80	*0-30*	3.4		0.65	54
2	*30-60*	4.9		0.84	46	*30-60*	4.9		0.81	27
3	*60-120*	6.5		0.89	34	*60-100*	8.0		0.92	30
4	*120-190*	8.8		0.93	12	*100-154*	10.4		0.98	12
5	1-5	0.08	0	0.92	13	1-5	0.04	0	0.95	11
6	5-10	0.20	0	0.96	13	5-10	0.13	0	0.96	9
7	10-20	0.38	22	0.98	12	10-15	0.23	0	0.99	6
8	20-30	0.54	32	0.98	9	15-20	0.31	51	0.99	5
9	30-40	0.60	45	0.98	9	20-25	0.37	68	0.99	11
10	40-50	0.60	59	0.98	7	25-30	0.39	81	0.99	15
11	50-60	0.56	71	0.98	6	30-35	0.38	94	0.99	15
12	60-70	0.49	81	0.98	7	35-40	0.36	97	0.99	18
13	70-90	0.39	91	0.98	10	40-45	0.33	99	0.99	16
14	90-110	0.28	97	0.98	9	45-50	0.29	99	0.99	9
15	>110		99	0.98	8	50-55	0.25	99	0.99	13
16						55-60	0.22	100	0.98	7
17						>60		100	0.98	5
	∑				275					263

Chapter 4

Population viability analysis of threatened tree species in Vietnam

With P.A. Zuidema

Abstract

Population viability analysis is a good tool to estimate the impact of stochastic factors on the persistence of threatened tree species. We used population viability analysis to investigate the impact of demographic and environmental stochasticity on population development and extinction risk for six threatened tree species in Vietnam (*Annamocarya sinensis*, *Calocedrus macrolepis*, *Dacrydium elatum*, *Manglietia fordiana*, *Parashorea chinensis*, and *Pinus kwangtungensis*). We carried out a two-year field study, in which we quantified the vital rates (survival, growth, reproduction and recruitment) and their variation, and used those to construct stochastic matrix models. We also included in the models the variation in DBH growth rate, which was estimated from ring indices of trees. To consider how sensitive the extinction risk is to changes in mean and variation of vital rates, and initial population size, we changed the inputs of the stochastic models by 1%, and compared the results.

Stochastic variation in vital rates due to environmental stochasticity decreased population sizes, leading to increasing extinction risk. Of the two components of environmental stochasticity, temporal variation has less impact on extinction risk than small-scale variation. Demographic stochasticity decreased the time to extinction, but by chance it could slightly reduce full extinction risk from around 7% for *Pinus* to 49% for *Manglietia* at 300 y. Extinction risk was more sensitive to changes in the means of vital rates and initial population size than to changes in variation of vital rates. Among the vital rates, survival was the most important to estimate extinction risk. This implies that reliable estimates of mean vital rates are crucial for obtaining reliable extinction rates.

The future prospects of *Dacrydium* and *Parashorea* are good, as their populations are expected not to face extinction in 300 y. That of the other species, however, is worse as they are predicted to face extinction in around 100 y. We suggest that effective conservation should be implemented for these species before population sizes drop below critical levels.

Key words: Threatened tree species, demographic stochasticity, environmental stochasticity, stochastic matrix models, extinction risk.

Introduction

Conservation of threatened tree species is a focal concern for conservationists and managers. As these species often have small and/or isolated populations, they are likely to face extinction due to unpredictable elements such as demographic and environmental stochasticity (Menges 1998, Menges & Quintana-Ascencio 2003, Munzbergova 2006). Demographic stochasticity is the variation in population dynamics that is generated by independent stochastic contribution from each individual of the population to the next generation (Engen et al. 1998, Menges 2000). Demographic stochasticity does not strongly impact on population development of abundant species, but it can severely increase the extinction risk for rare species (Menges 1998). Environmental stochasticity, on the other hand, is related to variation in demographic parameters (e.g. survival, growth and reproduction) due to environmental variation. Natural catastrophes can be considered as especially extreme, episodic or discrete types of environmental stochasticity (Menges 2000). Environmental stochasticity can strongly increase the extinction risk for both abundant and rare species (Menges 1998). In order to protect and effectively conserve threatened tree species, it is therefore important to estimate the effect of demographic and environmental stochasticity on the extinction risks for these species.

Population viability analysis (PVA) is a useful tool for estimating extinction risks, and for prioritizing conservation needs for threatened species (Shaffer 1990, Clark et al. 1991, Boyce 1992, Possingham et al. 1993, Carroll et al. 1996, Menges 1998, 2000, Brook et al. 2000b, Chapman et al. 2001, Beissinger & McCullough 2002, Morris & Doak 2002, Garcia 2003, Kaye & Pyke 2003, Reed et al. 2003, Boyce et al. 2006). By taking into account the combined impacts of unpredictable factors (e.g. demographic, environmental and genetic stochasticity) and deterministic elements (e.g. habitat loss, overexploitation, fragmentation), PVA provides a stochastic projection of population size over time (Miller & Lacy 1999, Chapman et al. 2001, Beissinger & McCullough 2002). Most commonly PVAs are conducted using simulation models that incorporate deterministic matrices with demographic and environmental stochasticity (Burgman et al. 1993, Akçakaya et al. 1997, Menges 2000). Currently, several software packages [e.g. VORTEX (Lacy 1993), RAMAS/Stage (Ferson 1994), ALEX (Possingham & Davies 1995), RAMAS/Metapop (Akçakaya 1997), MATLAB (Math Works 1999)] have been developed and applied, leading to an increase in using PVAs in conservation science (Fieberg & Ellner 2001).

As most PVAs for tree species are based on studies on a few populations and short periods (e.g. several years), the data collected are not likely to be sufficient, particularly for threatened tree species (Groom & Pascual 1998, Menges 2000). Poor data can cause difficulties in parameter estimation, which in turn leads to unreliable estimates of extinction risk (Beissinger & Westphal 1998). In order to improve the accuracy of prediction, high quality of data is required. However, this can not always be achieved as field study for PVAs is often time consuming and expensive (Menges 2000). Alternatively, we could focus efforts on the most important factors for precise predictions. It is therefore important to evaluate the role of parameters in the estimate of extinction risk.

In this study, we present PVAs for six threatened tree species in protected areas in Vietnam. All six species have severely declined in both distribution and population sizes due to overexploitation and habitat loss. Population sizes of these species in protected areas range from 300 to 2500 individuals (> 5 cm DBH- diameter at breast height). All six species are considered as threatened species in the Red List of Vietnam (Ministry of Science, Technology and Environment 'MSTE' 1996, Nghia 2000).

Our main goal was to estimate population development and the time to extinction for the six threatened tree species under the influence of demographic and environmental stochasticity. We also considered the effects of parameter and variation estimation on the estimates of extinction risk. Specifically, we addressed the following questions: (a) How do demographic and environmental stochasticity affect population development of the study species? To answer this question, we used transition matrices incorporating demographic and environmental stochasticity to estimate population sizes over time for these species. (b) What are the future prospects for the study species? From the results generated from the stochastic matrix models above, we estimated the extinction probability over 300 y. (c) How sensitive are fluctuations in the mean and the variation of vital rates? To this end, we changed the inputs of the PVAs, and compared the outcomes of the models. Our results contribute information on the relationship of means and variances of vital rates with population development, and with the extinction risk for the threatened tree species.

Methods

Species and sites

We studied six threatened Vietnamese tree species: three are broad-leaved (*Annamocarya sinensis*, *Manglietia fordiana* and *Parashorea chinensis*) and three others are coniferous (*Calodecrus macrolepis*, *Dacrydium elatum* and *Pinus kwangtungensis*). From now onwards, the species will be indicated by their genus names only. All species are long-lived tree species and reach the canopy as adult. The broad-leaved species are distributed in tropical forests at low altitudes, whereas the conifers occur in subtropical forests at higher elevation (for details see Chapter 3). The populations of the six species have been reduced in both density and distribution range due to overexploitation and habitat loss (Ministry of Science, Technology and Environment 'MSTE' 1996), and all are included in the Vietnam Red List as threatened species (Nghia 2000).

The study was carried out in four protected areas in Vietnam. Study plots for *Annamocarya* and *Parashorea* were located in tropical rain forests of Cuc Phuong National Park. In Ba Vi National Park, plots for *Calocedrus* were constructed on peak areas, in rather open subtropical forest, whereas those for *Manglietia* were located at lower elevation in dense tropical forest. Plots for *Dacrydium* were established at 1000-1200 m a.s.l. in evergreen subtropical forest of Bach Ma National Park, and those for *Pinus* were constructed at the same elevation in subtropical forest of Hang Kia – Pa Co Nature Reserve (for details see Chapter 3).

Data collection

To quantify the vital rates (annual rates of survival, seedling height growth, tree diameter growth and fecundity) of the six study species, we established 2-3 permanent plots (2-4 ha/plot) for each species in the protected areas in 2003, and performed measurements in 2003, 2004 and 2005. We measured DBH (diameter at breast height) of all juvenile and adult trees (DBH $\geq$ 1 cm), total height of seedlings (DBH $\leq$ 1 cm), and recorded mortality and reproductive status of individuals and seedling recruitment in the study plots (for details see Chapter 3).

We obtained data on the population sizes of the six study species in the four protected areas using information from previous studies (Huy & Cu 1990, Huyen 1997, Thu & Can 1999, Nghia 2000, Keo 2003, Can 2005) and our field trips to check the distribution areas and densities of these species. Our estimates for the number of mature individuals (>5 cm DBH) of these species in protected areas were: *Annamocarya*: 850, *Calocedrus*: 450, *Dacrydium*: 2500, *Manglietia*: 700, *Parashorea*: 300, and *Pinus* 400. We then converted these estimates to values of the entire populations, using the observed structures in the study plots.

We also obtained diameter growth rates from wood cores taken from 30-40 trees (DBH > 30 cm) per species for four species (*Annamocarya*, *Calocedrus*, *Dacrydium* and *Pinus*) (for details see Chapter 5). Ring width data were used to quantify temporal variation in diameter growth.

Matrix model construction

We used Lefkovitch matrix models (Caswell 2001) as the basis for our Population Viability Analysis. The models use the equation: $n(t+1) = \mathbf{A}n(t)$, where $n(t)$ and $n(t+1)$ are population structures at time t and t+1, and **A** is a square matrix containing transition probabilities among categories during one time step.

We divided populations of the six study species into 14-18 categories. For all species, the four smallest categories were based on seedling height, and the remaining on DBH. Elements (a_{ij}) of matrix **A** can be grouped into growth (G, elements in the sub-diagonal of the matrix), stasis (P, elements in the diagonal of the matrix), and fecundity (F, the upper row, except for the top-left element) (for details see Chapter 3). Using the values obtained from the vital rates, transition matrices were constructed. One transition matrix was constructed per species, as differences between years and between plots were not significantly different (see Chapter 3). We used these mean matrices as a basis for the PVA analysis: the matrices are included in Chapter 3.

Stochastic matrix model construction and analysis

We used the information on temporal variation in diameter growth and seedling recruitment, and variation among individuals (partly small-scale spatial variation) in growth, survival and reproduction to construct stochastic matrix models (Table 1).

Table 1. Overview of types of variation included in simulation with environmental stochasticity.

Vital rate	Environmental stochasticity		
	Temporal variation (temp)	Variation among individuals (ind)	Both (t+i)
Survival		- In survival of seedlings and trees	- In survival of seedlings and trees
Growth	- In diameter growth from index of ring series [1]	- In seedling height growth and DBH growth	- In diameter growth from index of ring series[1], and in seedling height growth and DBH growth
Productivity of reproduction		- In the probability of reproduction of large trees	- In the probability of reproduction of large trees
Recruitment	- In number of new seedlings produced per adult tree, among plots and years		- In number of new seedlings produced per adult tree, among plots and years

[1]: Only for *Annamocarya*, *Calocedrus*, *Dacrydium* and *Pinus*.

The temporal variation that we quantified included changes in DBH growth and seedling recruitment over time. For DBH growth, we obtained information on variation from ring data: For each cored tree, we calculated the 5-year moving average for the entire ring series to filter the long-term temporal processes and ontogenetic changes in growth rate. We then calculated the residuals around this curve. These values are indicative for the growth variation caused by year-to-year temporal (climatic) variation. We calculated the standard deviation (SD) of the residuals for individuals per size category. We did such measurements for *Annamocarya*, *Calocedrus*, *Dacrydium* and *Pinus*, but not for *Manglietia* and *Parashorea* as these species do not produce clearly visible rings. For these two species, we considered the temporal variation for growth to be zero. For recruitment variation, we calculated the standard deviation of the number of new seedlings produced per adult tree over plots and years; this variation includes both spatial and temporal variation.

The variation in vital rates among individuals may reflect small-scale spatial variation (e.g. in light and soil conditions), size differences and uncertainty/error in parameter estimation. We were unable to separate these sources of variation. For probability of plant survival and reproduction, we estimated variation in each category, using the equation: SD = sqrt(p*(1-p)/n), where p is the proportion of plants surviving or reproducing, and n is the number of individuals in the category. For the variation of growth rates, we calculated the standard deviation of seedling height growth for categories 1-4, but for larger categories, we calculated standard deviation of DBH growth (Appendix 1).

We developed stochastic matrix models running in MATLAB (Math Works 1999) to project the population sizes over time and the extinction risk. We started constructing models with the population structure as observed in Zuidema & Franco (2001). Every simulation model was run in three steps. First, random values for the vital rates (survival, growth and fecundity) were drawn from normal distributions with mean and standard deviation as measured in the field (Appendix 1). The model only accepted values that were biologically realistic (e.g. survival probability of an individual must be equal or less than 1), and were within 95% confidence intervals. Second, a transition matrix was constructed, using these random values. Third, the population vector was premultiplied with the random transition matrix.

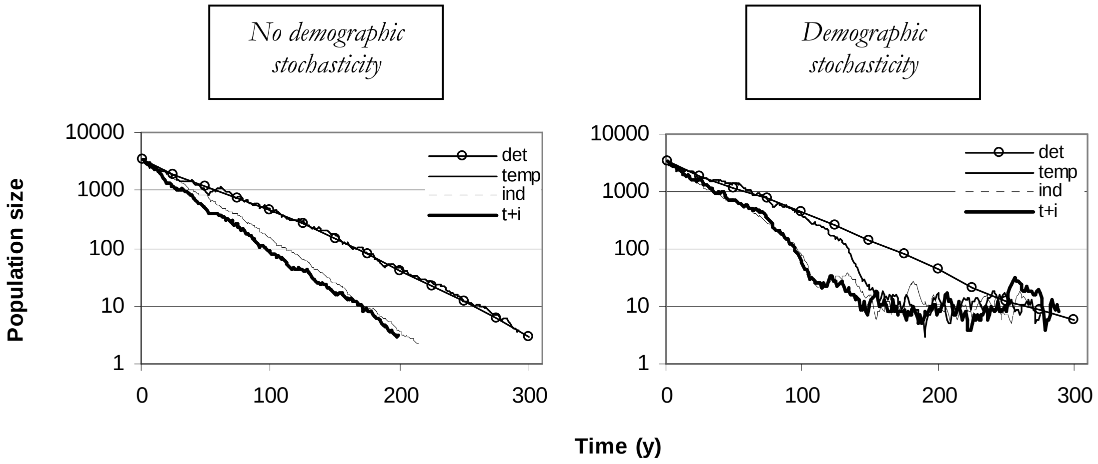
We carried out six types of simulations (temp, ind and t+1, with and without demographic stochasticity). First, we randomly drew values of vital rates using only temporal variation in tree growth and recruitment. For the vital rates that were varied, new random values were drawn for each time step, for the other vital rates mean values were used. Second, we constructed transition matrices, using variation among individuals (survival, growth and probability of reproduction), and did the same above procedure. Third, we used both temporal variation and variation among individuals to construct transition matrices. The fourth, the fifth and the sixth were similar to the first, second and third but now demographic stochasticity was included in the simulations. The demographic stochasticity was implemented following Akçakaya et al. (1997).

For the sensitivity analysis of extinction risk, we ran the stochastic matrix models using temporal variation, variation among individuals and demographic stochasticity. Before running the model, we changed the inputs by increasing or decreasing one by one the mean or the standard deviation of vital rates, or the initial population sizes, by 1%. For each input constructed, we ran the stochastic matrix models with 100 simulations over 200 y, and calculated the extinction risk as the % of simulation, which ended with a population size of 0 or 1. This whole procedure was repeated 10 times for each set of input values.

Results

Effect of stochasticity on population dynamics

Our simulations showed decreasing populations for all species and all types of stochasticity, although the pattern of decrease depended somewhat on the types of stochasticity, which were in effects (Fig. 1, Fig. 2). The variation in population sizes at each time step for these species was not large, particularly for those that were not affected by demographic stochasticity (Fig. 2).



No demographic stochasticity

Demographic stochasticity

Figure 1. Examples of simulated population trajectories of *Annamocarya sinensis*. Shown are projected population sizes of one simulation under the influence of temporal variation (temp), variation among individuals (ind), both temporal variation and variation among individuals (t+i), population sizes obtained from deterministic matrix models (det), and with or without demographic stochasticity.

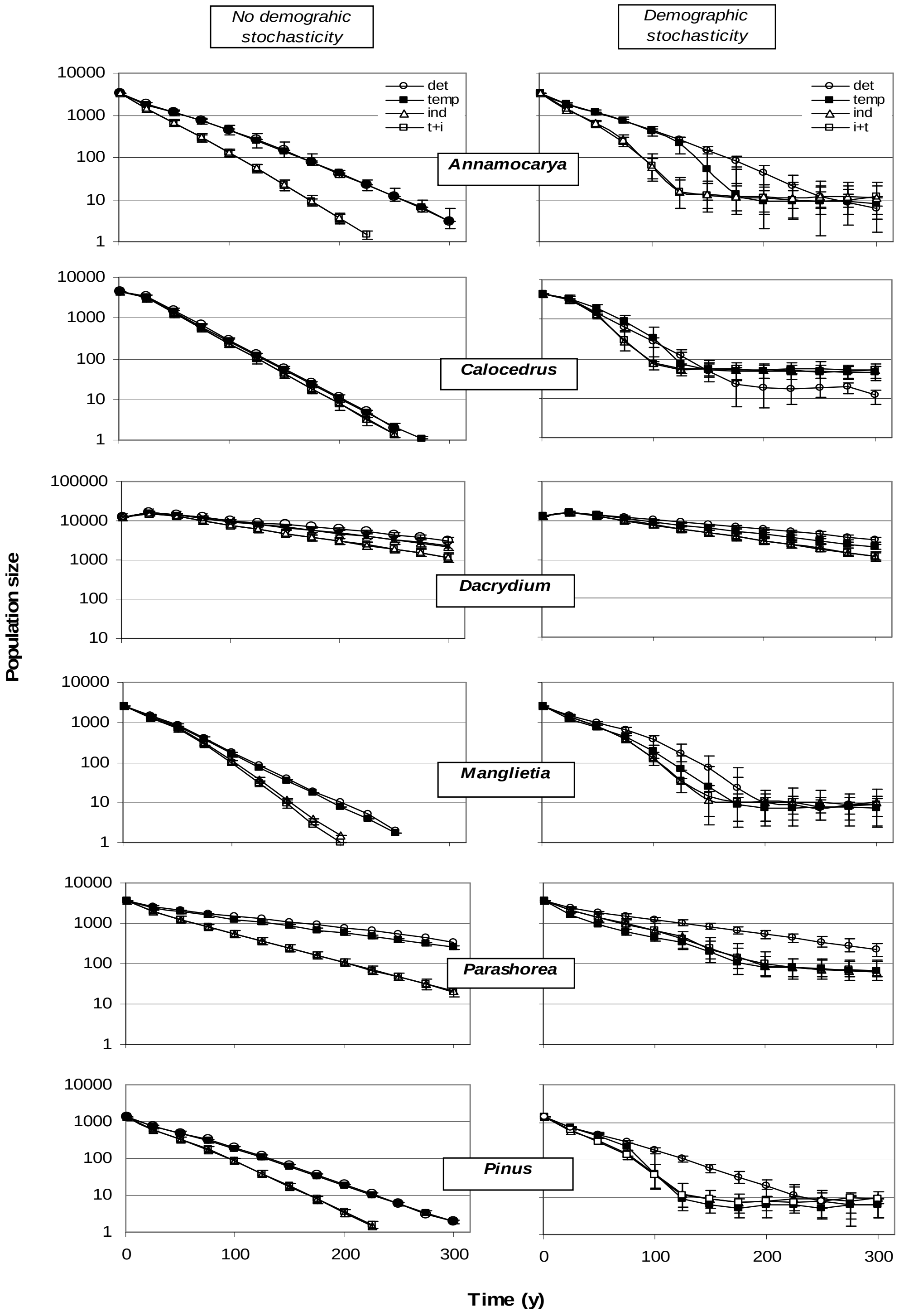


Figure 2. Simulated population trajectories for six threatened tree species under the influence of different kinds of stochasticity. Shown are projected population sizes (median population size of 100 simulations and 95% confidence interval) affected by temporal variation (temp), variation among individuals (ind), both temporal variation and variation among individuals (t+i), and no environmental variation (det), with and without demographic stochasticity. Note that only populations with > 1 individual were included.

Without demographic stochasticity, population trajectories affected by temporal variation and variation among individuals differed greatly (Fig. 2). The trajectories describing the impact of temporal variation were similar to those obtained from deterministic matrix models (Fig. 2). This indicates that temporal variation did not much affect the population growth rate. The influence of variation among individuals, however, was much stronger than that caused by temporal variation (Fig. 2). Accordingly, after 200 y, population sizes under the influence of both types of variation were similar to those affected by variation among individuals only, but significantly smaller than those affected by temporal variation (Table 2). This suggests that the variation among individuals of the six study species had the largest impact on population dynamics.

Table 2. Projected population sizes of six Vietnamese threatened tree species under the influence of temporal variation (temp), variation among individuals (ind), both temporal variation and variation among individuals (t+i), and no environmental variation (det). Shown are medians of population size of 100 simulations at 200 y (only populations with > 1 individual were included). Different letters indicate significant difference (Dunn Test). Det (with no demographic stochasticity) was not included in the tests because it was obtained from deterministic matrix models (no variation). For initial population sizes see Appendix 1.

Species	Population size after 200 y							
	No demographic stochasticity				With demographic stochasticity			
	det	temp	ind	t+i	det	temp	ind	t+i
Annamocarya***	41	42^{a}	4^{c}	4^{c}	43^{a}	9^{b}	11^{b}	9^{b}
Calocedrus***	11	10^{b}	8^{c}	8^{c}	12^{b}	47^{a}	50^{a}	49^{a}
Dacrydium***	4860	4416^{b}	3027^{c}	2995^{c}	5021^{a}	4048^{b}	3038^{c}	3007^{c}
Manglietia***	10	9^{b}	2^{c}	2^{c}	10^{b}	12^{a}	11^{a}	10^{b}
Parashorea***	781	577^{a}	105^{b}	104^{b}	542^{a}	97^{c}	88^{c}	84^{c}
Pinus***	19	18^{a}	3^{c}	3^{c}	20^{a}	9^{b}	9^{b}	8^{b}

***: P<0.000 (Kruskal-Wallis Test).

During the first 50-80 years in the simulations, while population sizes were still large, population trajectories under the influence of demographic stochasticity were not much different from those unaffected by demographic stochasticity (Fig. 2). When population sizes were smaller, the decrease in population trajectories affected by demographic stochasticity was much stronger than that of populations unaffected by demographic stochasticity (Fig. 2). In addition, the variation in population sizes was also greater if populations were affected by demographic stochasticity (Fig. 2). However, when populations were very small (less than 100 individuals), population trajectories affected by demographic stochasticity remained rather stable (around 10-80 individuals/population), whereas population trajectories unaffected by demographic stochasticity continued to decline to one individual (Fig. 2). Clearly, demographic stochasticity did not affect much large populations, but had a great impact on small populations.

Risk of extinction

Table 3. Mean time and accumulative risk of extinction for five threatened tree species.

Species	Pseudo extinction risk				Full extinction risk			
	Without demo stochasticity		With demo stochasticity		Without demo stochasticity		With demo stochasticity	
	Mean time (y)	*Accu risk at 150 y (%)	Mean time (y)	*Accu risk at 150 y (%)	Mean time (y)	*Accu risk at 300 y (%)	Mean time (y)	*Accu risk at 300 y (%)
Annamocarya	110	100	85	100	250	100	175	65
Calocedrus	125	100	85	100	275	100	-	11
Manglietia	120	100	100	100	275	100	200	51
Parashorea	205	0	190	5	-	0	-	0
Pinus	100	100	75	100	250	100	150	93

Note: * Accumulative

The population development and the extinction risk of all six species were influenced by the combined effect of demographic and environmental stochasticity. In our study, the environmental stochasticity included temporal variation and variation among individuals. We therefore used the stochastic simulation models affected by temporal variation, variation among individuals and demographic stochasticity to measure the probability of extinction for the study species. We applied two measures of extinction: (1) 'full extinction' if a population declines to ≤ 1 individual, or (2) 'pseudo-extinction' for a population that drops below 100 individuals, which is considered to be much lower than the minimum viable population (MVP) size for long-lived plant species (Geburek 1992).

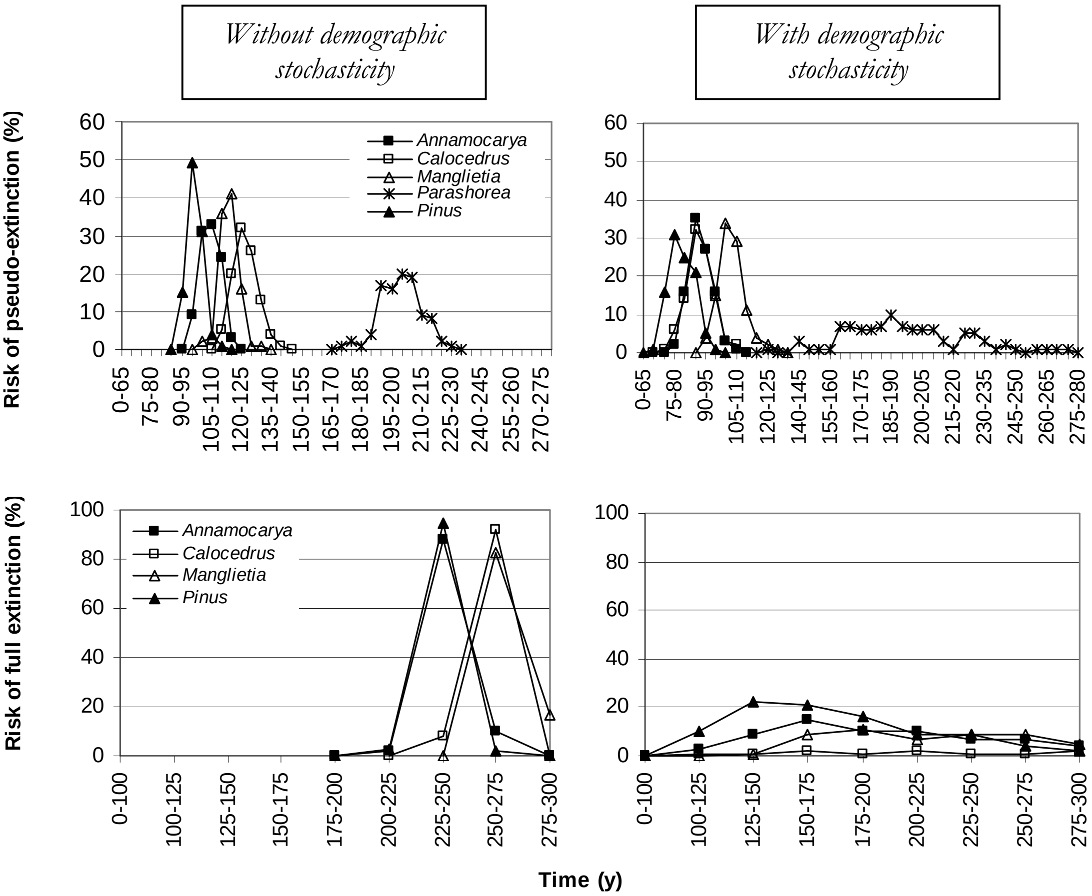


Figure 3. Projected extinction risk for threatened tree species. Shown are probabilities of arriving at pseudo-extinction (top panels) or full extinction (bottom panels) during the interval indicated on the X-axis of the populations under the combined influence of temporal variation and variation among individuals, and without (left panels) or with (right panels) demographic stochasticity.

Among the six study species, *Dacrydium* was not expected to go extinct or drop below 100 individuals within the time span studied, as the projected population size remained above 1000 individuals after 300 y (Fig. 2). Similarly, *Parashorea* did not face full extinction, but did have 100% of pseudo-extinction after 300 y (Table 3, Fig. 3). For the other species, extinction was common. After 150 y, all populations of these species were projected to be smaller than 100 individuals (Table 3, Fig. 3). The mean time for pseudo-extinction was also short, from 70-115 y (Table 3). Moreover, the probability of full extinction of these populations after 300 y was high: 65% for *Annamocarya*, 11% for *Calocedrus*, 51% for *Manglietia*, and 93% for *Pinus* (Table 3). The mean time for full extinction was 150-225 y for *Annamocarya*, 175-200 y for *Manglietia*, and 125-200 y for *Pinus* (Table 3).

Demographic stochasticity decreased the time to extinction for all five study species (Fig 3). For *Annamocarya*, *Calocedrus*, *Manglietia* and *Pinus*, populations under the impact of demographic stochasticity were predicted to face pseudo-extinction after 70-90 y, compared with 90-100 y without the impact of demographic stochasticity (Fig. 3). These four species also faced full extinction after around 100 y if affected by demographic stochasticity, whereas this time was 200 y with no effect of demographic stochasticity (Fig. 3). Similarly, *Parashorea* was expected to have a pseudo-extinction risk after 120 y if affected by demographic stochasticity, and after 170 y with no impact by deterministic stochasticity (Fig. 3). However, the extinction risk was highly concentrated for populations unaffected by demographic stochasticity (Fig. 3), indicating a small variation in population sizes of these populations.

Sensitivity analysis of extinction risk

To analyse how sensitive the extinction risk is to changes in the mean and variation of vital rates, and the initial population size, we carried out simple sensitivity analyses for the four species facing extinction risk.

The sensitivity analyses showed that changes in the mean of vital rates has greater impact on the extinction risk than changes in variation of vital rates, and the survival rate was the most important for extinction risk (Fig. 4). For instance, for *Annamocarya*, when we decreased survival, growth, productivity or recruitment with 1%, the respective changes in extinction risk were 11%, 3.5%, 1.5% and 2.5% (Fig. 4). However, when we decreased the variation of survival, growth, probability of reproduction or recruitment with 1%, the respective changes in extinction risk were 2.5%, 1.5%, 0%, and 1.5% (Fig. 4). The change in population size was also more important for the estimate of extinction risk than the change in variation of vital rates (Fig. 4). For example, the change in extinction risk of *Calocedrus* was 1-1.5% if we decreased the initial population size by 1%, but this was 0-0.5% if we changed the variation of vital rates with 1% (Fig. 4). It is clear that the simulated extinction risk for our study species is thus much more sensitive to the mean value and the initial population size than to the variation in vital rates.

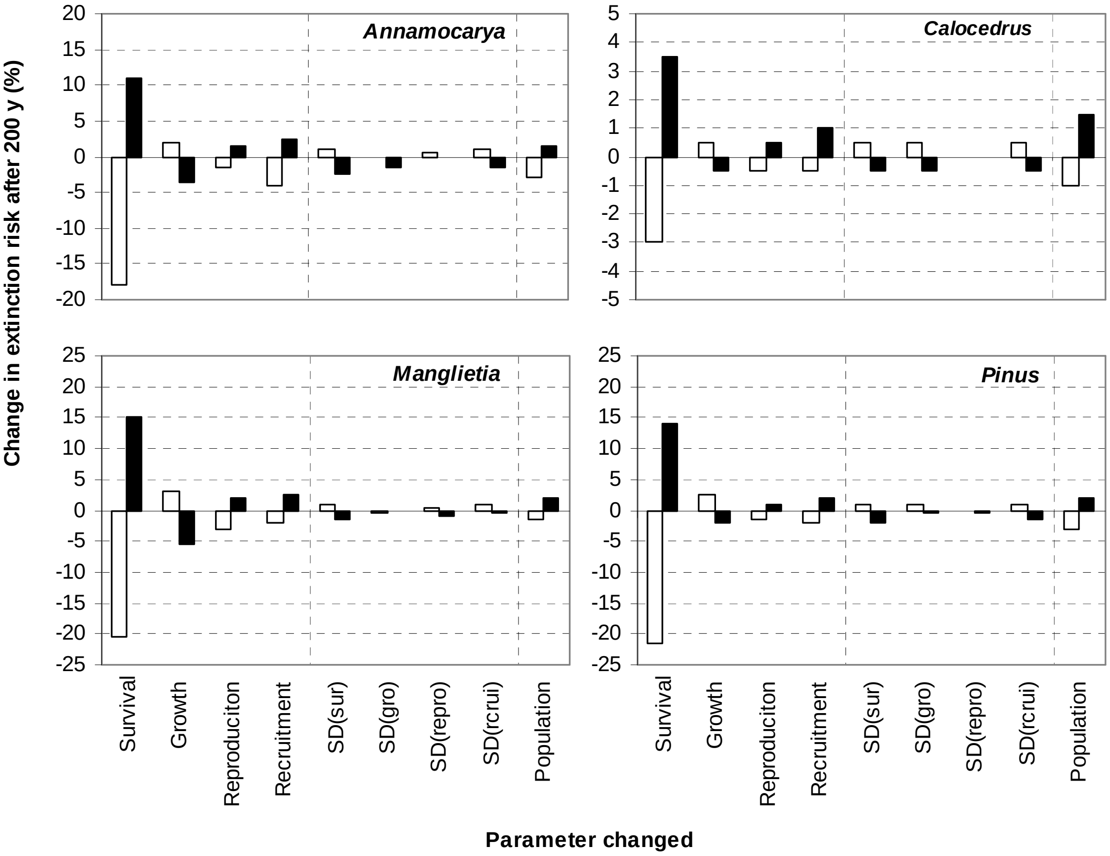


Figure 4. The sensitivity analysis of extinction risk for threatened tree species. We ran the stochastic matrix models (under the combined impact of temporal variation, variation among individuals and demographic stochasticity) 100 simulations at 200 y, and with 10 replicates. Shown are changes in extinction risk (%) of populations when we increased the means, standard deviation (SD) of vital rates or initial population sizes with 1% (open bars), and when decreased those values with 1% (filled bars).

Discussion

Extinction risk in relation to stochasticity

In general, we found all population trajectories were going down over time (Fig. 2), indicating that all six species could probably face extinction in the future. Yet, the time to extinction of populations depended on types of stochasticity and the studied species and size of initial populations.

We found that including variation in vital rates (both temporal variation and variation among individuals) due to environmental variation strongly decreased simulated population size, leading to increased extinction risk and earlier extinction

(Table 2, Fig. 2). Our results resemble those of previous studies, which showed that environmental stochasticity decreases population growth rate and increases extinction risk (Menges 1998, Lande et al. 2003, Tuljapurkar et al. 2004, Doak et al. 2005, Engen et al. 2005). We distinguished two types of environmental stochasticity: temporal variation and variation among individuals (often related to small-scale spatial variation). Comparing these two types of stochasticity, we found that temporal variation had much smaller effects on population sizes for all species (Fig. 2). Furthermore, the population trajectories affected by temporal variation was some how similar to those obtained from deterministic matrix models (Fig 1, Fig. 2). This indicates that the effect of temporal variation on the development of the study populations was small. This corresponds to a report of Colling & Matthies (2006), showing that the effect of temporal variability on populations of *Scorzonera humilis* (an endangered, long-lived perennial herb) is small, leading to a small decrease in population growth rate. However, the effect of temporal variation on population can also be very large, leading to strong decreases in population size and increased extinction risk (Pfister 1998, Picó & Riba 2002).

For our study species, the temporal variation is probably underestimated due to a lack of data. First, we did not find much variation in recruitment for the two years of study, but this is likely to fluctuate more over longer time spans. Moreover, our data did not experience extreme years, which may have a strong impact on vital rates, and also on extinction risk. Finally, we did not include temporal autocorrelation, which may strongly impact population dynamics (Pfister & Stevens 2003).

We found that demographic stochasticity did not affect much large populations, but decreased population sizes of small populations, leading to an early threat of extinction (Fig. 2, Fig. 3). Our results are consistent with those of previous studies on the impact of demographic stochasticity on population growth rate and extinction time for plant species (Dinnétz & Nilsson 2002, Morris & Doak 2002, Engen et al. 2005, Boyce at al. 2006). We also found that the variation in population trajectories without the influence of demographic stochasticity was much smaller than that affected by demographic stochasticity (Fig. 2). This accounts for a decrease in population size to extinction without much fluctuation of populations unaffected by demographic stochasticity (Fig. 2, Fig. 3). For very small populations (less than 100 individuals) that affected by demographic stochasticity, however, several populations by chance could increase the time to extinction due to a great variation in population sizes (Fig. 2).

The relative importance of parameters for extinction risk

We found that the extinction risk was more sensitive to changes in the mean of every vital rate than to changes in their variation (Fig. 4), suggesting that the mean is more important for extinction than the variation. It also is clear that the mean of the survival rate had the largest influence on extinction risks (Fig. 4). This confirms the results of elasticity analysis arguing that the survival rate is crucial for the population growth rate and the extinction risk of long-lived plant species (Caswell 2001, Zuidema & Boot 2002, Franco & Silvertown 2004, Kwit et al. 2004, Chapter 3). If the mean of survival rate is not estimated with precision, the PVA will give bad results. The extinction risk was also sensitive to changes in initial population size (Fig. 4), indicating that the initial population size is also important for extinction risk. This result resembles those other studies revealing that population viability is expected to increase with population size, and that a large population size is likely to decrease the risks of extinction (Pimm et al.1988, Barrett & Kohn 1991, Ellstand & Elam 1993, Young et al. 1996, Munzbergova 2006). Population size, however, may not be a good indicator of population viability for long-lived plant species, due to the time delay between the deterioration of conditions and the reduction in size of local populations (Colling & Matthies 2006). To allow better comparison across species with different life spans, we should perhaps express time to extinction in number of generations rather than years.

Future prospects of the study species

Among the six study species, the future prospects of *Dacrydium* and *Parashorea* is alright, as they are expected not to face full extinction in 300 y (Fig. 2), even though *Parashorea* may face pseudo-extinction in 150 y (Fig. 3). The future of *Calocedrus* is not really good, because the species is likely to face pseudo-extinction in 90 y (Fig. 3), although its risk of full extinction is low (11% in 300 y, Fig. 3). The futures of *Annamocarya* and *Manglietia* are worse, because they are predicted to face pseudo-extinction in 80 y, and full extinction in around 125 y. The future of *Pinus* is worst, as the species is projected to face pseudo-extinction in 70 y. Moreover, *Pinus* is projected to face full extinction in 120 y, and the species is predicted to be extinct in around 300 y (93% accumulative of chance to go extinct, Table 3).

Our results, however, should be interpreted with caution, because the estimate of the mean of vital rates, particularly survival, is crucial for the precise projection for the study species. In order to make a more precise prediction that leads to an effective conservation strategy, great care should be paid to the estimate of the mean of vital rates and the initial population size. As regards conservation, it is therefore not necessary to take any special conservation measure for *Dacrydium* and *Parashorea*, but to protect their natural habitats from human disturbances (see Chapter 3). For the other species, however, more attention should be paid, not only to protect their habitats, but also to improve their population growth rates (see Chapter 3) before the populations decline below critical levels.

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Appendix 1. Mean and standard variation of vital rates, and initial population sizes of the threatened tree species used in stochastic matrix models. Cat: category, **σ**: survival rate, g: growth rate, Pr: probability of reproduction of large trees, f: seedling recruitment, Cat wid: category width, ini Po: initial population size, SD: standard deviation, SD(g,t): standard deviation of DBH growth obtained from ring index series.

Species	Cat	σ	SD(σ)	g	SD(g)	SD(g,t)	Pr	SD(Pr)	f	SD(f)	Cat wid	Ini Po
	1	0.854	0.064	3.848	1.005	0	0	0	0	0	30	960
Annamocrya	2	0.860	0.076	4.577	1.269	0	0	0	0	0	30	600
	3	0.868	0.08	5.427	1.639	0	0	0	0	0	40	392
	4	0.880	0.079	6.812	1.385	0	0	0	0	0	75	352
	5	0.894	0.079	0.086	0.021	0.053	0	0	0	0	4	152
	6	0.935	0.06	0.21	0.043	0.07	0	0	0	0	5	80
	7	0.982	0.062	0.332	0.068	0.078	0	0	0	0	5	48
	8	0.982	0.054	0.433	0.164	0.086	0.247	0.176	0.48	0.215	5	64
	9	0.982	0.054	0.509	0.072	0.103	0.317	0.165	0.48	0.215	5	64
	10	0.982	0.051	0.559	0.104	0.093	0.396	0.173	0.48	0.215	5	72
	11	0.982	0.058	0.586	0.132	0.105	0.481	0.167	0.48	0.215	5	56
	12	0.982	0.054	0.592	0.139	0.104	0.566	0.187	0.48	0.215	5	64
	13	0.982	0.051	0.575	0.125	0.113	0.687	0.164	0.48	0.215	10	72
	14	0.982	0.054	0.52	0.119	0.076	0.814	0.13	0.48	0.215	10	64
	15	0.982	0.058	0.45	0.085	0.069	0.897	0.107	0.48	0.215	10	56
	16	0.982	0.062	0.381	0.097	0.069	0.946	0.086	0.48	0.215	10	48
	17	0.982	0.058	0.319	0.087	0.069	0.972	0.067	0.48	0.215	10	56
	18	0.950	0.044	0	0	0	0.986	0.045	0.48	0.215	0	120
	1	0.774	0.065	3.538	0.529	0	0	0	0	0	30	2275
Calocedrus	2	0.801	0.062	4.123	0.752	0	0	0	0	0	30	780
	3	0.837	0.081	5	1.048	0	0	0	0	0	60	390
	4	0.882	0.078	6.307	1.229	0	0	0	0	0	75	315
	5	0.913	0.081	0.066	0.015	0.028	0	0	0	0	4	225
	6	0.958	0.017	0.145	0.046	0.04	0	0	0	0	5	105
	7	0.958	0.017	0.217	0.051	0.046	0.302	0.084	4.7	2.25	5	90
	8	0.958	0.017	0.274	0.05	0.049	0.59	0.095	4.7	2.25	5	81
	9	0.958	0.017	0.315	0.071	0.056	0.827	0.095	4.7	2.25	5	48
	10	0.958	0.017	0.341	0.082	0.069	0.941	0.057	4.7	2.25	5	51
	11	0.958	0.017	0.357	0.066	0.062	0.99	0.031	4.7	2.25	10	30
	12	0.958	0.017	0.347	0.063	0.056	0.99	0.031	4.7	2.25	10	30
	13	0.953	0.064	0.317	0.051	0.051	0.99	0.044	4.7	2.25	10	15
	14	0.953	0.064	0	0	0	0.99	0.04	4.7	2.25	0	18

Species	Cat	σ	SD(σ)	g	SD(g)	SD(g,t)	Pr	SD (Pr)	f	SD f)	Cat wid	Ini Po
Dacrydium	1	0.784	0.043	3.248	0.95	0	0	0	0	0	30	5115
	2	0.831	0.067	3.749	1.26	0	0	0	0	0	30	1705
	3	0.875	0.074	4.334	1.64	0	0	0	0	0	40	1100
	4	0.922	0.065	5.169	1.36	0	0	0	0	0	60	935
	5	0.959	0.04	0.122	0.028	0.03	0	0	0	0	4	1188
	6	0.967	0.012	0.222	0.045	0.039	0	0	0	0	5	506
	7	0.987	0.007	0.299	0.053	0.043	0.156	0.071	1.84	0.6	5	286
	8	0.987	0.007	0.352	0.081	0.049	0.32	0.091	1.84	0.6	5	286
	9	0.987	0.007	0.387	0.104	0.05	0.545	0.087	1.84	0.6	5	363
	10	0.987	0.007	0.406	0.079	0.049	0.753	0.081	1.84	0.6	5	308
	11	0.987	0.007	0.414	0.081	0.059	0.886	0.054	1.84	0.6	5	385
	12	0.987	0.007	0.412	0.07	0.055	0.952	0.038	1.84	0.6	5	341
	13	0.987	0.007	0.404	0.087	0.044	0.981	0.044	1.84	0.6	5	110
	14	0.987	0.007	0.362	0.03	0.042	0.992	0.036	1.84	0.6	5	66
	15	0.97	0.076	0	0	0	0.992	0.039	1.84	0.6	0	55
Manglietia	1	0.74	0.058	5.455	1.59	0	0	0	0	0	30	780
	2	0.78	0.071	7.054	1.66	0	0	0	0	0	30	304
	3	0.84	0.075	8.919	2.60	0	0	0	0	0	40	214
	4	0.90	0.058	11.58	3.30	0	0	0	0	0	60	242
	5	0.91	0.052	0.063	0.04	0	0	0	0	0	4	260
	6	0.95	0.034	0.193	0.06	0	0	0	0	0	5	140
	7	0.98	0.011	0.342	0.08	0	0.197	0.064	0.83	0.36	5	127
	8	0.98	0.011	0.47	0.13	0	0.337	0.085	0.83	0.36	5	103
	9	0.98	0.011	0.559	0.16	0	0.513	0.125	0.83	0.36	5	53
	10	0.98	0.011	0.605	0.13	0	0.686	0.093	0.83	0.36	5	83
	11	0.98	0.011	0.613	0.09	0	0.820	0.091	0.83	0.36	5	60
	12	0.98	0.011	0.591	0.16	0	0.904	0.085	0.83	0.36	5	40
	13	0.98	0.011	0.515	0.09	0	0.951	0.056	0.83	0.36	5	50
	14	0.94	0.041	0	0	0	0.976	0.037	0.83	0.36	0	57

Species	Cat	σ	SD(σ)	g	SD(g)	SD(g,t)	Pr	SD (Pr)	f	SD(f)	Cat wid	Ini Po
	1	0.80	0.04	3.78	1.10	0	0	0	0	0	30	1500
Parashorea	2	0.84	0.05	4.86	1.26	0	0	0	0	0	30	863
	3	0.89	0.05	6.48	1.55	0	0	0	0	0	60	638
	4	0.94	0.07	8.82	1.31	0	0	0	0	0	70	225
	5	0.92	0.08	0.08	0.03	0	0	0	0	0	4	244
	6	0.96	0.05	0.20	0.05	0	0	0	0	0	5	33
	7	0.98	0.04	0.38	0.09	0	0.22	0.12	3.68	1.36	10	30
	8	0.98	0.04	0.54	0.07	0	0.32	0.16	3.68	1.36	10	23
	9	0.98	0.04	0.60	0.15	0	0.45	0.17	3.68	1.36	10	23
	10	0.98	0.05	0.60	0.17	0	0.59	0.19	3.68	1.36	10	18
	11	0.98	0.05	0.56	0.14	0	0.71	0.18	3.68	1.36	10	15
	12	0.98	0.05	0.49	0.10	0	0.81	0.15	3.68	1.36	10	18
	13	0.98	0.04	0.39	0.05	0	0.91	0.09	3.68	1.36	20	25
	14	0.98	0.04	0.28	0.06	0	0.97	0.06	3.68	1.36	20	23
	15	0.98	0.05	0	0	0	0.99	0.04	3.68	1.36	0	20
	1	0.646	0.065	4.912	1.622	0	0	0	0	0	30	405
Pinus	2	0.807	0.076	6.373	2.068	0	0	0	0	0	30	225
	3	0.91	0.052	8.078	2.225	0	0	0	0	0	60	186
	4	0.92	0.078	10.36	2.671	0	0	0	0	0	80	105
	5	0.92	0.082	0.041	0.011	0.039	0	0	0	0	4	78
	6	0.96	0.065	0.129	0.031	0.05	0	0	0	0	5	27
	7	0.98	0.057	0.23	0.056	0.061	0	0	0	0	5	18
	8	0.987	0.05	0.314	0.039	0.07	0.509	0.224	0.42	0.19	5	15
	9	0.987	0.034	0.368	0.052	0.069	0.675	0.141	0.42	0.19	5	33
	10	0.987	0.029	0.39	0.098	0.081	0.806	0.102	0.42	0.19	5	45
	11	0.987	0.029	0.385	0.049	0.066	0.893	0.08	0.42	0.19	5	45
	12	0.987	0.026	0.361	0.088	0.062	0.944	0.054	0.42	0.19	5	54
	13	0.987	0.028	0.328	0.079	0.075	0.971	0.042	0.42	0.19	5	48
	14	0.987	0.037	0.291	0.092	0.055	0.985	0.04	0.42	0.19	5	27
	15	0.987	0.031	0.254	0.038	0.069	0.993	0.024	0.42	0.19	5	39
	16	0.98	0.053	0.219	0.082	0.053	0.996	0.023	0.42	0.19	5	21
	17	0.96	0.063	0	0	0	0.998	0.019	0.42	0.19	0	15

Chapter 5

What dimension to use for matrix models of trees? Recommendations based on a validation of age estimate by tree ring analysis

With P. A. Zuidema

Abstract

The choice of the number of categories in constructing matrix models is an important one, as it has consequences for model output (population growth rate (λ), elasticity of λ and ages of trees). We validated the output of matrix models of four Vietnamese tree species by comparing age estimates obtained from matrix models with varying amount of categories with ring counts. Our study species were *Annamocarya sinensis*, *Calocedrus macrolepis*, *Dacrydium elatum* and *Pinus kwangtungensis*. We carried out a two-year field study, in which we quantified the probability of survival, growth and reproduction, and used those to construct matrix models with different sizes. We then estimated λ, elasticity of λ and ages of trees for each matrix model. We also carried out a dendrochronological study, in which ring data were collected for estimating tree ages.

Age estimates strongly increased when the number of categories was increased. The population growth rate slight decreased (by 0.1-1.2%) with increased matrix size, from a small matrix with broad categories (10 cm DBH) to a very large matrix with narrow categories (1.25 cm DBH). The elasticity of λ to stasis and fecundity (matrix elements) decreased with increasing matrix sizes, while the elasticity value for progression (matrix element) increased. However, the elasticity of λ to vital rates (growth, survival and reproduction) was much less sensitive to changes in matrix sizes compared to matrix elements.

Our results showed that the width of categories for which matrix age estimates best correspond to observed (ring) ages equals 2.5 cm DBH for *Annamocarya sinensis*, 1.5 cm for *Calocedrus macrolepis*, 1.5 cm for *Dacrydium elatum* and 3 cm for *Pinus kwangtungensis*.

We argue that narrow categories (1.5-3 cm DBH) are used in matrix models of trees to obtain best estimates of tree age, population growth rate and elasticity.

Key words: Matrix dimension, population growth rate, elasticity, tree ages.

Introduction

Matrix population models are widely used in demographic analyses as they are easily constructed and provide clearly interpretable output (Caswell 2001). To date, matrix models have been constructed for a large number of species, including birds (Saether & Bakke 2000), mammals (Heppell et al. 2000) and plants (Franco & Silvertown 2004). To construct a matrix population model, individuals are classified into discrete classes according to their age (often applied to animals) or size (often applied to plants) (Caswell 2001). The main outputs of matrix models are the asymptotic population growth rate (λ) and the elasticity of λ to different life history transitions (Caswell 2001). These two parameters are used to evaluate the population performance and the most important life stages for the population growth rate, and to suggest effective conservation actions (Ratsirarson et al. 1996, Benton & Grant 1999, Contreras & Valverde 2002, Zuidema & Boot 2002, Kwit et al. 2004). In addition, size-classified matrix models can be used to estimate ages of trees using algorithms developed by Cochran & Ellner (1992) (Zagt 1997, Zuidema 2000, Caswell 2001, Barot et al. 2002). For tree species, this method allows to estimate ages without using annual rings or other dating techniques (Martinez-Ramos & Alvarez-Buylla 1998).

An important choice in the construction of size-structured matrix models is the dimension (or size) of the transition matrix, i.e. the number of size categories in which the population is divided. For transition matrices in which the values of the elements are observed transitions from one to another category, or based on the average of growth and survival in a category, choosing wide or narrow categories has implications for the errors of distribution and sampling (Vandermeer 1978, Moloney 1986). If a transition matrix has few and wide categories, the error of distribution may be large, as individuals within a category behave very differently (Vandermeer 1978, Moloney 1986). In a transition matrix with many narrow categories the error of sampling is large as the number of individuals used to calculate transition is low (Vandermeer 1978, Moloney 1986). If transitions are calculated using overall relations of growth and survival vs. size, instead of observed transitions or averages of growth and survival, these errors are not applicable, but also in these models, the number of categories influences model output. In large transition matrices, population growth rate and the elasticities of λ to stasis and fecundity are generally smaller, while elasticity for progression increases (Zagt 1997, Zuidema 2000, Yearsley & Fletcher 2002, Ramula & Lehtilä 2005).

Different criteria have been proposed to determine matrix dimension. Vandermeer (1978) and Moloney (1986) developed a mathematical method to classify individuals into stage classes by minimizing both errors of distribution and sampling. Other studies suggested that the stage classification should be based upon biological criteria that maximize differences in vital rates among categories (Caswell 2001, Zuidema & Boot 2002). Recently, Ramula & Lehtilä (2005), argued that constructing small matrices is more suitable, particularly for woody species, as this saves time and money required for obtaining demographic data.

In spite of the ample debate on choosing matrix model size, so far no validation has been carried out to determine what is the optimal matrix dimension. One way to determine the most suitable number of categories is to correlate age estimates from matrix models to those from annual rings, which are obtained from a dendrochronological study or other ageing methods.

In this paper, we validate tree ages obtained from matrix models of different dimension for four Vietnamese tree species. Specially, we address the following questions: (1) What is the effect of matrix dimension on tree age estimates? (2) What matrix dimension best corresponds with independently obtained tree ages? (3) What is the effect of matrix dimension on population growth rate and elasticity? To answer these, we carried out a 2-year demographic study and constructed stage-based transition matrices with different dimensions for four study species. From these matrices, we calculated tree ages, population growth rates and elasticities. We also carried out a dendrochronological study to determine actual ages of the individual trees. Based on the comparison between the matrix outputs and the results obtained from ring counts, recommendations for applying matrix dimension are proposed.

Methods

Study species

We studied four Vietnamese tree species: *Annamocarya sinensis*, *Calocedrus macrolepis*, *Dacrydium elatum*, and *Pinus kwangtungensis* (hereafter referred to their genus names). All four species are long-lived, and reach the forest canopy when being mature. Three species (*Calocedrus*, *Dacrydium* and *Pinus*) are conifers while *Annamocarya* is a broad-leaved deciduous species. The coniferous species grow in subtropical forests in high mountains, whilst the broad-leaved species occurs in lowland tropical forests. Several characteristics of the four species and their field sites are described in Table 1 (more details in Chapter 3).

Study sites

The study was carried out in four protected areas in Vietnam (Table 1). The structure of the coniferous forests (e.g., canopy layers, species diversity) is simpler than that of the lowland forests, where *Annamocarya* occurs. The canopy the coniferous forest is also lower and more open than the canopy of *Annamocarya* forest.

The precipitation is high in the four study areas: around 2000 mm y^{-1} in Ba Vi, Cuc Phuong and Hang kia – Pa Co, and more than 3000 mm y^{-1} in Bach Ma. In all four areas, rainfall is not evenly distributed over the year. The dry season is rather pronounced in all areas with 5 dry months (< 100 mm mo^{-1}) in Ba Vi, 6 in Cuc Phuong and Hang Kia –Pa Co, and 3 in Bach Ma.

Table 1. Characteristics of the study species and study areas

Species (family)	Max height (m)	Max DBH (cm)	Location (Coordinates)	Altitude (m) (*)	Canopy height (m) (*)
Annamocarya sinensis (Dode) Leroy (Juglandaceae)	35[1]	150[1]	Cuc Phuong (20° N, 105° E)	250	25-30
Calocedrus macrolepis Kurz (Cupressaceae)	15-25[2]	>100[2]	Ba Vi (21° N, 105° E)	1200	15-20
Dacrydium elatum (Roxb) Wall ex Hook *(*Podocarpaceae)	20-25[2]	50-70[2]	Bach Ma (16° N, 107° E)	1200	15-20
Pinus kwangtungensis Chun ex Tsiang (Pinaceae)	15-20[2]	50-70[2]	Hang Kia – Pa Co (20° N, 104° E)	1100	15-20

Note: [1]: from Thu and Can (1999), [2]: from Nghia 2000, *: at the study site

Data collection

For the demographic study, permanent plots were established in the study sites in 2003. Measurements of individuals (parameters: DBH, total height, fruit status, recruitment and mortality) were carried out in 2003, 2004 and 2005 (more details see Chapter 3). For the dendrochronological study, in 2004 and 2005 we took wood samples from selected trees using a hand drill. We selected adult trees (> 30 cm DBH) that had round boles, occurring both inside and outside the plots. On each tree, we extracted 1-2 wood cores from the stem at approximately 1.3 m above the ground.

All cores were sanded until we could easily see the rings. Ring boundaries could be identified visually by a magnifier. Ring-widths were measured to the nearest 0.1 mm. When the cores did not include the tree pith, we estimated the distance to the pith and used the average number of rings of the other samples of the same species to obtain an estimate of the number of missing rings. However, we often eliminated cores taken from hollow trees or cores that deviated far from the pith. For the trees having two cores, the average values of these cores were taken to describe average diameter increment. The numbers of *Annamocarya*, *Calocedrus*, *Dacrydium* and *Pinus* trees from which the cores were used were 30, 32, 34 and 31, respectively.

In order to examine the relationship between rainfall of the study sites and tree growth for the four species, we collected annual rainfall data (1970-2004) from the nearest meteorological stations: Nho Quan for *Annamocarya*, Son Tay for *Calocedrus*, Nam Dong for *Dacrydium*, and Mai Chau for *Pinus*.

Dendrochronological data analysis

The annual ring data of the four species were first tested for accuracy using correlation analysis (COFECHA Program, Gissino-Mayer 2001) to detect measurement errors such as wedging or missing rings. Tree ring series that had high correlation to the rest of the collective were chosen for establishing a tree ring chronology for each species using program ARSTAN (Cook & Holmes 1985). For this purpose, the raw ring series were standardized using the cubic spline with the same stiffness as used in COFECHA. The standardized series were then averaged into one size-dependent growth pattern per species. These values were used to compare with tree ages obtained from matrix models. To study the relationship between precipitation and tree growth, we related the size-dependent growth pattern of each species with annual rainfall of the study sites using Pearson correlations.

Data analysis and matrix model construction

As stem growth is non-linearly related to the diameter, we used a Hossfeld IV equation (Zeide 1993) to describe this pattern:

$$g\,(d) \quad = \quad \frac{b * c * d^{(c-1)}}{[b + (d^{c/a})]^2}$$

where g(d) is the expected DBH growth rate (cm y^{-1}), d is DBH, and a, b and c are fitted parameters.

Reproductive probability of a tree relates positively to its stem size. To describe this pattern, we used the logistic regression function:

$$\mathrm{Prof}\{f\} = 1/(1 + \mathrm{Exp}(-(m + n * d)))$$

where Prof{f}is the probability that the tree is reproductive, d is DBH, and m and n are fitted parameters.

The populations of the four species were divided into 14 to 18 size categories, depending on the abundance and size structure of each population (Appendix 1 – Chapter 3). For all species, the first four categories were based on seedling height and the remaining on DBH (for more details see Chapter 3).

We applied a Lefkovitch matrix model (Caswell 2001), using the equation: n(t+1) = ***A***n(t), where n is a vector containing the population structure at time t (or t+1), and **A** is a square matrix containing demographic information of the population during one time step (1 year for our study). The population structure at time t+1 is obtained by multiplying the population structure at time t with matrix ***A***. When the multiplication of **A** and n(t) is repeated many times, the relative structure and growth rate of the population will become stable. At that time, the dominant eigenvalue (λ) and the right eigenvector of matrix **A** are equal to the growth rate and the stable stage distribution of the population, respectively (Caswell 2001).

Elements (a_{ij}) of matrix **A** can be grouped according to their position in the matrix: growth elements (G), stasis elements (P) or fecundity elements (F). Growth elements (in the sub-diagonal of the matrix) were calculated as $G_i = \sigma_i * g_i * c_i^{-1}$, where G_i is the probability for trees in category i of growing to category i+1, σ_i the survival probability of trees in category i, g_i the growth rate (cm yr^{-1}) and c_i the category width (cm, for height or diameter). Stasis elements (in the diagonal of the matrix) were calculated as $P_i = \sigma_i - G_i$. Fecundity elements (in the top-right row) were calculated as $F_i = \sigma_i * Prob\{f\}_i * f_i$, where $Prob\{f\}_i$ is probability of being reproductive for individuals in category i, and f_i was calculated by dividing the abundance of new seedlings (per ha, per year), by that of reproductive trees per ha. The vital rates (survival, growth and probability of reproduction) we used here were obtained from regression data, but not from the observed class average.

Matrix dimension and age estimation

We applied two ways of changing the matrix size (we used matrices in Appendix 1 – Chapter 3). First, we changed the category width of matrices. For all reconstructed matrices, we kept the first four categories (based on seedling height) the same. The other categories (category 5 and larger) of each matrix were constructed using one category width (cm DBH); matrices with different sizes were created by using different category widths. We reconstructed 6 types of matrix models with category width of 1.25, 1.5, 2.5, 3, 5 and 10 cm. Second, we varied the size of matrices by changing γ, the probability that a surviving individual in category i moves to category i+1. γ was varied from 0.03-0.28 and the category width was calculated as $c_i = g_i/\gamma_i$. Low value of γ would lead to small matrices and large value of γ to large matrices.

We estimated tree ages for categories of matrices using algorithms for determining ages in stage-based matrix models (Cochran & Ellner 1992, Barot et al. 2002):

$$E(\tau_{1,\,s}) = 1 + \sum_{i=1}^{s-1} \frac{1}{1-p_i}$$

Where $E(\tau_{1,\,s})$ is the time for individuals to first reach the stage s from the first stage (1 cm DBH in our study), p_i is the stasis element in stage i.

We then compared tree ages estimated from different matrices with those obtained from annual ring data.

Estimation of λ and elasticity

Asymptotic growth rates (λ) of all matrix models were calculated using the method of Caswell (2001). The elasticity of λ to changes in vital rates, or in matrix elements is the proportional change in λ due to a proportional change in vital rates or matrix elements (de Kroon et al. 2000, Caswell 2001). We calculated the elasticity of λ to vital rates and matrix elements using the approach of Caswell (2001), and Zuidema & Franco (2001)

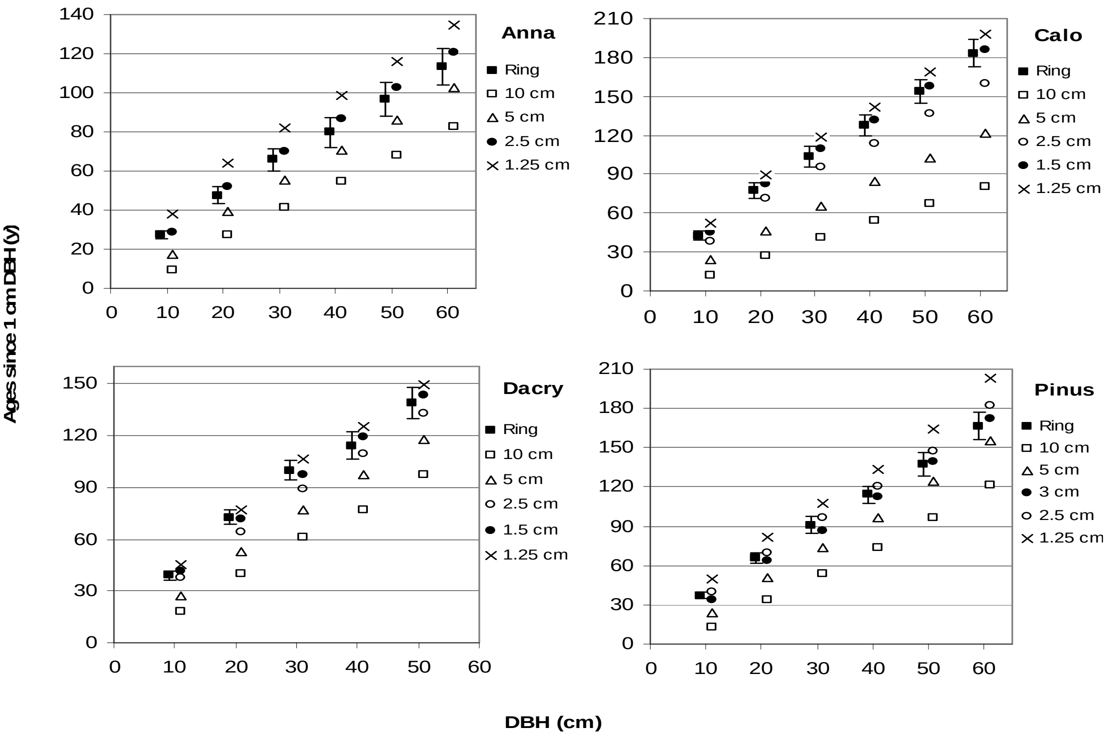

Figure 1. Tree ages obtained from annual rings and from matrix models in relation to DBH. Shown are tree ages obtained from annual rings (ring, mean ± 1.96 SE) and ages obtained from matrices constructed using different category widths: from 1.25 – 10 cm DBH. All symbols (but not filled dots) denote significant difference between ages obtained from matrices and from annual rings (t test).

Results

Results of tree ring analysis

Rings of the four study species were found to be sufficiently clear for marking and counting. Ring width of all species significantly correlated with total annual rainfall in the year during which that ring was formed (Pearson, $n = 34$, $p<0.01$ for *Annamocarya* and *Pinus*; $n = 34$, $p<0.05$ for *Calocedrus*; $n = 28$, $p<0.05$ for *Dacrydium*). Clarity of rings produced and the strong correlation of ring width with annual rainfall indicated that the rings formed by the four species indeed were annual rings.

Tree ages obtained from annual rings greatly differed within and between the species. The mean ages (± standard error) at 50 cm DBH (estimated from 1 cm DBH) of *Annamocarya*, *Calocedrus*, *Dacrydium* and *Pinus* were 96.8 (± 4.4), 153 (± 5.3), 139.4 (± 4.9) and 137 (± 4.7) y, respectively (Fig. 1).

Matrix dimension and age estimates

Matrix based age estimates strongly increased with increased matrix size. When we increased matrix size by decreasing category width from 10 to 1.25 cm/category, age estimates significantly increased (Fig. 1 & Fig. 2). For instance, we found only 83 y for *Annamocarya* at 60 cm DBH when we applied a small matrix 10-cm categories, 15 categories, while this increased to 135 y for a large matrix 1.25-cm categories, 90 categories. Similarly, age estimates also strongly increased if we increased matrix size by changing γ (Fig. 2). For instance, when we increased matrix size of *Annamocarya* by increasing γ from 0.05 (corresponding to 22 categories) to 0.10 (corresponding to 38 categories), age estimates at 60 cm DBH were 101 and 128 y, respectively (Fig. 2). As all values of vital rates used in the matrices were based on regression data, the increase in age estimates therefore is not the result of sample size problems (cf. Vandermeer 1978, Moloney 1986).

The ages of trees obtained from ring series were similar to those estimated from large matrix size. For *Annamocarya*, ring age was not significantly different from that estimated from 2.5-cm category matrix (corresponding with 48 categories) (Fig. 1 & Fig. 2). Similarly, for *Calocedrus*, *Dacrydium* and *Pinus*, matrices constructed from 1.5, 1.5 and 3 cm category widths, respectively, were best for estimating tree ages, as they were not significantly different from those estimated from ring series (Fig. 1 & Fig. 2).

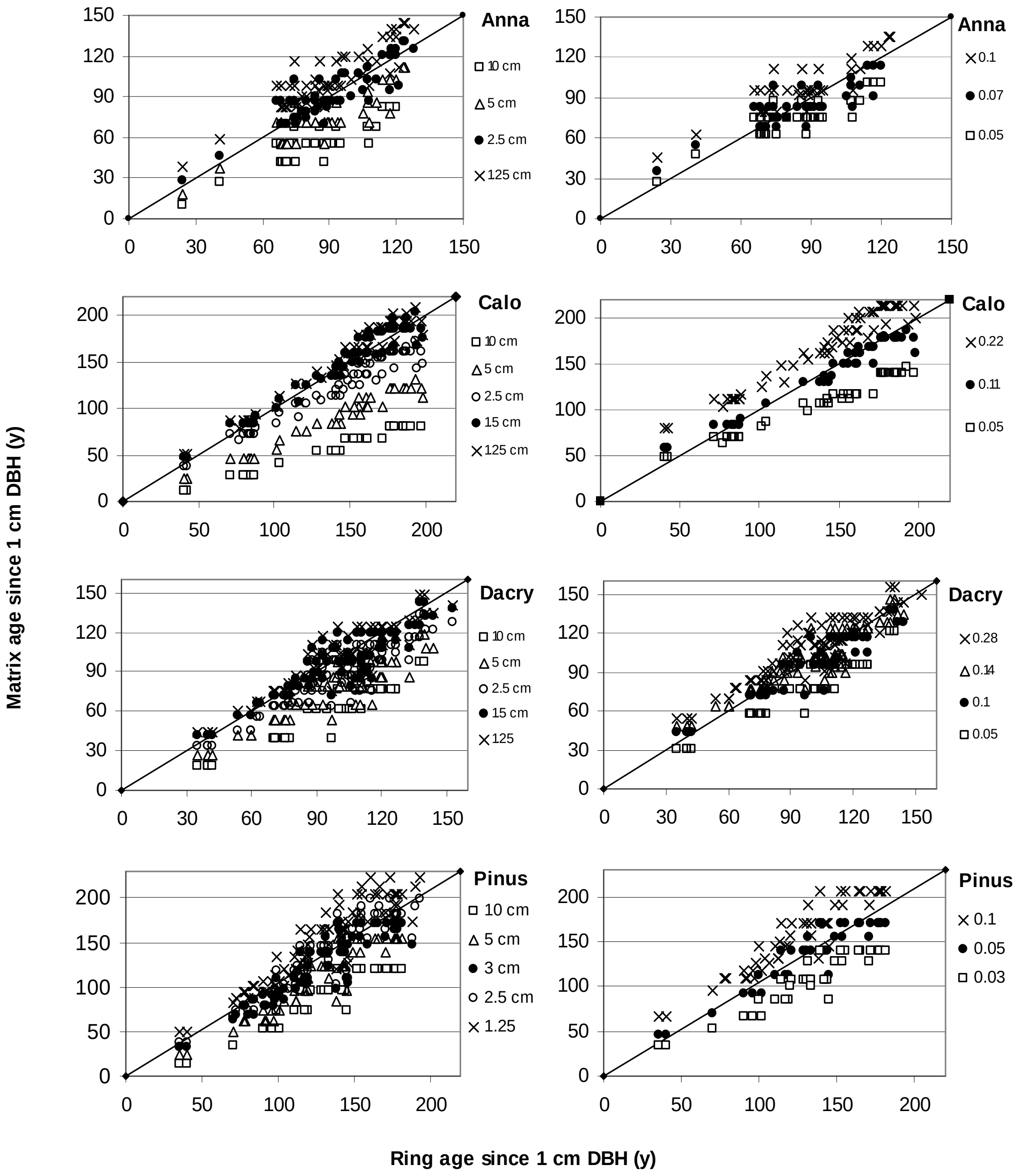

Figure 2. Tree ages estimated from different matrix dimension in relation to ages obtained from annual rings. The left panels present tree ages estimated from matrices of varying category widths: 1.25-10 cm DBH. The right panels present tree ages estimated from matrices constructed by varying the growth probability (γ) between 0.03 and 0.28. All symbols (but not filled dots) denote significant difference between ages obtained from matrices and from annual rings (paired t test).

Table 2. An example of age estimates obtained from different matrix sizes (using basis matrices constructed for *Annamocarya*). We estimated ages since 1 cm DBH of 60 cm DBH trees. We assumed that the survival rate was unchanged (0.982), and the growth rate was constant (0.5 cm/y) for all categories in the matrices.

	Category width (cm)									
	0.5	0.7	1	2	3	4	5	10	20	30
Number of Categories	120	86	60	30	20	15	12	6	3	2
Estimated age of trees of 60 cm DBH (y)	121	120	118	115	111	107	104	90	72	59

In order to check whether the effect of matrix size on age estimate is sensitive, we reconstructed matrices for an imaginary tree species, and applied these to estimate the ages of 60 cm DBH tree (Table 2). We started to calculate ages for trees larger than 1 cm DBH. To keep things simple, we assumed that the survival rates were equal ($\sigma = 0.982$) for all categories, and the growth rate was also constant ($g = 0.5$ cm/y). We constructed a range of matrices: from the smallest matrix (with only two categories above 1 cm DBH) to the largest matrix (120 categories - category width of 0.5 cm) (Table 2). Using the approach of Cochran & Ellner (1992) and Barot et al. (2002) to estimate tree ages, we found that the age estimates increased from 59 y for the smallest matrix to 121 y for the largest matrix (Table 2). Clearly, age estimates strongly increased with the expansion of matrices, and this increase in this simplified model could not be attributed to size-dependent patterns of growth and survival.

Variation in lambda (λ) and elasticity

Table 3. Comparison of population growth rates (λ) obtained for matrix models for different size for four tree species. Shown are differences in λ estimated from different matrix dimensions: 10 cm category width matrices, 5 cm category width matrices, 2.5 cm category width matrices, and 1.25 cm category width matrices.

	Matrices with category width		
	10 cm	5 cm	2.5 cm
5 cm	0.004 ns		
2.5 cm	0.007 *	0.003 ns	
1.25 cm	0.009 *	0.005 *	0.002 ns

Note: * p<0.05, ns: p>0.05 (ANOVA)

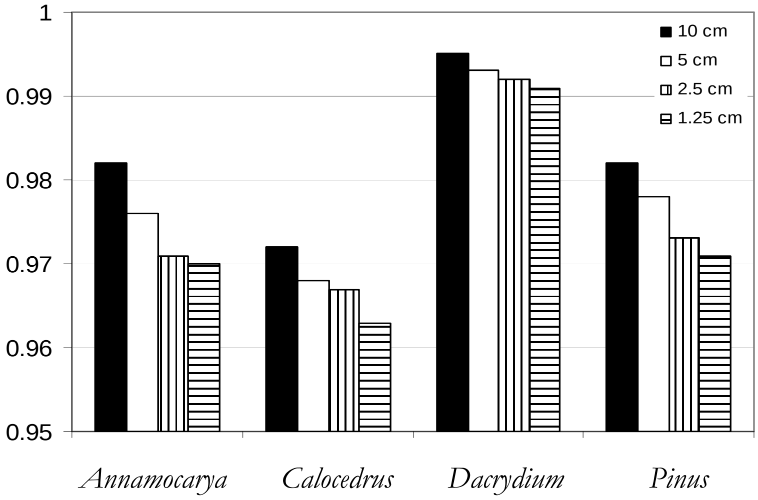

Figure 3. Population growth rate (λ) of four species estimated from different matrix dimensions: 10 cm category width matrix, 5 cm category width matrix, 2.5 cm category width matrix, and 1.25 cm category width matrix.

Table 4. Comparison of elasticities of λ to matrix elements estimated from different matrix dimension for four study species. Shown are comparison among elasticities of λ estimated from 10 cm category width matrices, 5 cm category width matrices, 2.5 cm category width matrices, and 1.25 cm category width matrices.

		Matrices with category width		
		10 cm	5 cm	2.5 cm
Progression elasticity				
	5 cm	-0.0182 ns		
	2.5 cm	-0.0627 *	-0.0445 ns	
	1.25 cm	-0.1463 *	-0.1281 *	-0.0835 *
Stasis elasticity				
	5 cm	0.0165 ns		
	2.5 cm	0.0604 *	0.0438 ns	
	1.25 cm	0.1429 *	0.1264 *	0.0826 *
Fecundity elasticity				
	5 cm	0.0015 ns		
	2.5 cm	0.0023 *	0.0007 ns	
	1.25 cm	0.0032 *	0.0017 *	0.0009 ns

Note: * p<0.05, ns p>0.05 (ANOVA)

The population growth rate (λ) gradually decreased with increased matrix size (Fig. 3). The change in λ was large if we substantially changed the matrix size (Table 3). For instance, the growth rates obtained from the smallest matrix (constructed by largest category width – 10 cm/category), were 0.982, 0.972, 0.995 and 0.982 for *Annamocarya*, *Calocedrus*, *Dacrydium* and *Pinus*, respectively. These numbers, however, decreased to 0.970, 0.963, 0.991 and 0.971, if we applied the largest matrices (constructed by smallest category width – 1.25 cm/category).

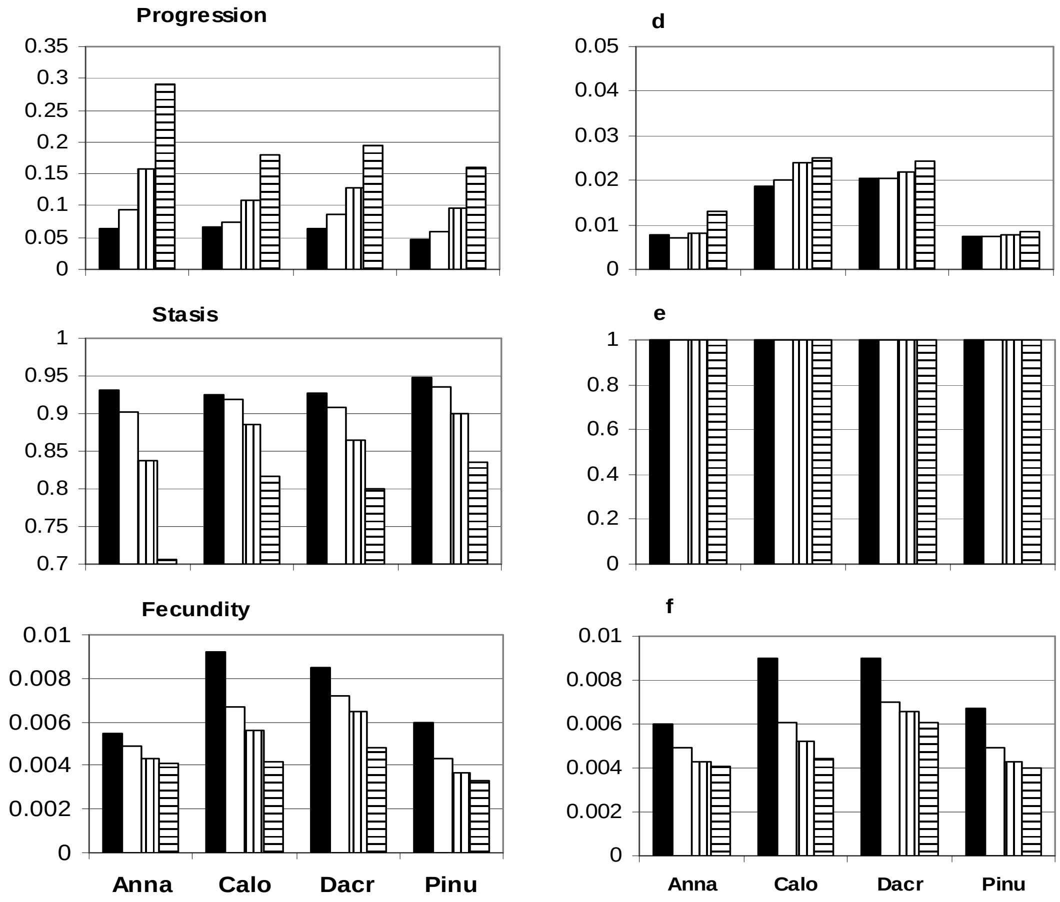

Figure 4. Elasticities of λ to changes in matrix elements (left panels) and to vital rates (right panels) calculated for matrices of different sizes. Shown are elasticities estimated from matrices constructed with 10 cm DBH (filled bars), 5 cm DBH (open bars), 2.5 cm DBH (vertical line bars), and 1.25 cm DBH (horizon line bars).

Matrix size also affected the elasticities of λ. When we expanded matrices, the elasticity of λ to progression significantly increased (Table 4, Fig. 4). With a small matrix (10 cm/category), the elasticities of λ to progression were 0.06, 0.07, 0.06 and 0.05 for *Annamocarya*, *Calocedrus*, *Dacrydium* and *Pinus*, respectively. When we expanded matrices by reducing the category width to 1.25 cm/category, the elasticities of λ to progression strongly increased to 0.29, 0.18, 0.19 and 0.16 for *Annamocarya*, *Calocedrus*, *Dacrydium* and *Pinus*, respectively (Fig. 4). In contrast, as the elasticities of λ to matrix elements are scaled to sum to 1, the elasticities of λ to stasis were strongly decreased with expanded matrices (Table 4, Fig. 4). The elasticities of λ to stasis of *Annamocarya*, *Calocedrus*, *Dacrydium* and *Pinus* were 0.93, 0.92, 0.92 and 0.95, when we applied small matrix (10 cm/category), but these numbers were 0.71, 0.82, 0.80 and 0.84 if we applied larger matrix (1.25 cm/category). The elasticities of fecundity also decreased with increasing matrix dimension, but these absolute changes were very small in comparison with those of stasis and progression (Fig. 4).

Matrix size did not affect much the elasticity of λ to vital rates. When we expanded matrix size, the elasticities of λ to growth (vital rate) increased whereas the elasticity of λ to reproduction decreased. However, we did not find substantial change in elasticity of λ to growth with expanded matrices (Fig. 4). We also found that these changes were very small in comparison with those obtained from matrix elements (progression and stasis) (Fig. 4). We found some changes in elasticity of λ to reproduction due to a change in matrix dimension (Fig. 4), but these absolute changes were even smaller than those of growth rate (Fig. 4). On the other hand, we found that the elasticity values for survival always equaled 1 despite changes in matrix size (Fig. 4). This is because λ is a homogeneous function of degree 1 of survival (σ) (Franco & Silvertown 2004). The results reveal that matrix dimension was important for the estimates of elasticities of λ to changes in matrix elements, but not in vital rates.

Discussion

Causes of variation in age estimates

We found that age estimates were strongly increased when expanding the number of categories in transition matrices. This was consistently found for all four species (Fig. 1 & Fig. 2). Similar results on estimating ages of *Bertholletia excelsa* and *Chlorocardium rodiei* by matrix models can be found in Zuidema (2000). The impact of matrix size on age estimates can be explained by several reasons. Firstly, low age estimates for small matrices with wide categories can probably be explained as ages are strongly determined by individuals that by chance pass rapidly through the whole life cycle. For instance, if categories have a width of 10 cm DBH, an individual in the category 1-10 cm DBH, could by chance reach the category 60-70 cm DBH within 5 years. With wide categories, many trees will stay long in a size class, but these individuals will experience a higher accumulative probability of death before reaching 60 cm DBH. With narrow categories, more slow growing individuals pass from one category to the next, which may help to increase the average age in each category, leading to an increase in the total life span. Secondly, the increase in age estimates due to narrow categories may partly be affected by the divergence of tree ages at a certain size class, caused by stochastic effects. In the actual population, there is a similar potential of divergence in age, produced by differences among individuals in annual growth rates and the autocorrelation in growth. With the small effect of stochasticity on narrow categories, the variation on growth rate will therefore decrease, leading to an increase in age estimates.

Consequences of matrix dimension for λ and elasticity

Although the population growth rates (λ) tended to decrease with the expansion of matrices (Fig. 3), the changes were not substantial with small to medium changes in matrix dimension, even when we doubled the matrix sizes (Table 3). Our results are consistent with findings of some previous studies. Zuidema (2000) found that λ for *Bertholletia excelsa* and *Chlorocardium rodiei* was not strongly affected by changing matrix size. Ramula & Lehtilä (2005) also indicated that λ for woody species did not change much with a doubling of the matrix size, from 3x3 to 6x6.

However, we also found that the change in λ was large when we substantially changed the matrix size (Table 3). For instance, if we increased matrix sizes by four times (by decreasing the initial category width by four times – from 10 to 2.5 cm), λ was substantially changed (Table 3). According to Ramula & Lehtilä (2005), if the observed stage frequencies of populations are very close to the stable stage distribution (the right eigenvector of the matrix, W), λ does not strongly change due to the changing in matrix size. In our case, however, the observed population structures of the study species were a bit far from the stable stage structures (PS index from 85-95, Chapter 3), which may lead to a change in λ due to a change in matrix size. In addition, the changing in matrix size may also cause a change in vital rates, leading to a difference in λ (Ramula & Lehtilä 2005). This is particularly sensitive for fast growing tree species with high value of reproduction because in large-stage matrices, they tend to reproduce sooner with highly reproductive values compared with that from the narrow-stage matrices.

When matrix size increased, the elasticity of λ to stasis and fecundity decreased, whereas the elasticity of λ to progression increased (Table 4, Fig. 4). Similar results can be found in a series of studies on the impact of matrix size on elasticities of λ (Enright et al. 1995, Ramula & Lehtilä 2005). The change in elasticity corresponding with the change in matrix dimension can be explained by the fact that during the same period of time, more individuals from one category moving to the next in large matrices than in small matrices. This may lead to an increase in elasticity of λ to progression in large matrices. At the same time stasis values in large matrices are small and thus their elasticities decrease.

In contrast to elasticities of elements, those for vital rates (growth and survival) did not greatly depend on matrix dimension (Fig. 4). On the other hand, the elasticity of λ to reproduction decreased with increased matrix dimension (Fig. 4). Nevertheless, these changes were very small, so that they did not substantially contribute to the value of elasticity. Our results confirm the findings of Zuidema (2000) indicating that the elasticity of λ to vital rates is not greatly affected by matrix dimension.

Recommendations for choosing matrix dimension

We found that age estimates were sensitive to matrix sizes, and large matrices yielded high ages, whereas small ages were obtained from small matrices. We also found that very large or very small matrices were not suitable for estimating tree ages as the estimated ages significantly differed from those obtained from ring series (Fig 1, Fig. 2). From our results, matrices with category width of 1.5-4 cm DBH yielded best age estimates (Fig 1, Fig. 2). Because we did not use standard errors for ages estimated from matrices when comparing those with ring ages, the suitable category width therefore could probably be larger a bit than those we found. In short, we suggest that very large or very small matrices should not be used for estimating tree ages.

The population growth rate did not change much if we doubled matrix size. We also found that the matrix size (category width equals 5-8 times of juvenile growth rates) were suitable for age estimates, therefore we could then double the size of these matrices without substantial changes in λ. These matrices therefore are suggested to be applied for estimating λ. For the estimate of elasticity, on the other hand, we argue that we should use vital rates instead of matrix elements, as these are less affected by matrix dimension.

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Chapter 6

General discussion and summary

Forests and threatened tree species in Vietnam

Affected by a tropical climate and a complex terrain, forest types of Vietnam are very diverse, ranging from tropical rainforest, mangrove forest and limestone forest to conifer and subtropical forests (Chapter 2). Vietnam is also a venue of plant species that migrated from three different floras nearby, which makes the flora of Vietnam very diverse in species (including more than 12000 plant species) (Thin 1997, Trung 1998).

The forests of Vietnam have severely declined in both quantity and quality over the last decades for many reasons, such as long wars, shifting cultivation, transformation of forests and forest land to agricultural fields, and overexploitation (Chapter 2). The cover of natural forests for the whole country was estimated at 43% in 1945, but it was reduced to around 27% in 1980 (Hung 2004). Recently, after a great effort from the Government, the forest cover increased to 36 % in 2003, including around 30% of natural forests and 6% of plantations (Forest Department 2004). However, the quality of the natural forests is generally low, as a result of a long period of degradation. The quality of plantation forests is also poor, and it needs to be improved both in species and silvicultural measures (Chapter 2). Clearly, great effort is required in order to improve both the quantity and quality of forests.

South-East Asia is facing the highest rate of deforestation, which, if not stopped or slowed down, would lead to the loss of three quarters of forest cover in 100 y, and up to 42% of its biodiversity (Sodhi et al. 2004). Being a country in the region, Vietnam also has a large number of species suffering extinction risk due to a severe loss of forests over last decades. According to the World Conservation Union 'IUCN' (2006), Vietnam currently has 261 endangered tree species, of which 148 are critically endangered and vulnerable. Populations of threatened tree species have severely declined in both densities and habitats, and many of them mainly depend on protected areas (Bawa & Ashton 1991). Furthermore, populations of these species are often small and/or isolated, and are likely to be vulnerable to local extinction due to demographic and environmental stochasticity or lack of genetic variation (Menges 1992, Lande 1993, Oostermeijer et al. 2003).

Table 1. Characteristics of the study species and study areas

Species (family)	Location (Coordinates)	Canopy height (m)	Max height (m)	Max DBH (cm)	DBH growth (cm/y)	Total remaining population	Age at reprodu-ction (y)	Age at 60 cm DBH (y)	Extinction risk in 300 y (%)
Annamocarya sinensis (Dode) Leroy (Juglandaceae)	Cuc Phuong (21° N-105° E)	25-30	35[1]	150[1]	0.46	3300	46	126	65
Calocedrus macrolepis Kurz (Cupressaceae)	Ba Vi (21° N-105° E)	15-20	15-25[2]	>100[2]	0.29	4450	41	202	11
Dacrydium elatum (Roxb) Wall ex Hook (Podocarpaceae)	Bach Ma (16° N-107° E)	15-20	20-25[2]	50-70[2]	0.36	12750	45	186	0
Manglietia fordiana (Hemsl.) Oliv. (Magnoliaceae)	Ba Vi (21° N-105° E)	15-20	15-20[2]	50-60[2]	0.53	2500	32	118	51
Parashorea chinensis Wang Hsie (Dipterocarpaceae)	Cuc Phuong (21° N-105° E)	25-30	60[2]	>100[2]	0.47	3700	38	122	0
Pinus kwangtungensis Chun ex Tsiang (Pinaceae)	Hang Kia – Pa Co (20° N-104° E)	15-20	15-20[2]	50-70[2]	0.31	1400	56	182	93

Note: [1]: from Thu and Can (1999), [2]: from Nghia 2000.

Regarding the importance of forests and biodiversity for the human beings, Vietnam has early developed a system of protected areas throughout the country. Currently, Vietnam has 126 protected areas, covering around 8% of the area of the country (Forest Department 2004). In addition, forests covering important watersheds are also under the protection regime. This increases the chance to reserve threatened tree species, as well as the vegetation cover in these areas.

However, in order to protect and effectively conserve threatened species, the protected areas of Vietnam still need to be improved both in quantity and quality. The proportion of protected areas in the country area is still lower than the minimum rate recommended by IUCN (1997). Furthermore, the area of several protected areas is small (Chapter 2), which is not effective for conservation of threatened species. It is therefore important for Vietnam not only to increase the number of protected areas, but also to expand their sizes.

In addition, in most protected areas, basic studies on taxonomy, biodiversity and demography of endangered species are still few. Clearly, great effort should be paid to gather information that assists in effectively protecting and conserving threatened species. This dissertation was therefore carried out with the goal of contributing to the information basis for conservation of threatened tree species.

Demography of six threatened tree species

In order to conserve threatened tree species, we need to understand the natural dynamics of their populations. Is there natural recruitment in populations? If yes, whether that recruitment is sufficient for replacing adult trees? Are populations growing or declining? What is the most important life stage for the persistence of populations?

To answer these questions, we carried out a two-year field study to collect demographic data for six threatened tree species in four protected areas (Table 1). We quantified the vital rates (survival, growth and fecundity) for the six species, and used these to estimate matrix elements (stasis, growth and fecundity), which were used to construct (deterministic) matrix models (Chapter 3). We used the output of the matrix models that indicates the population growth rate (λ) to project the future prospects of the species. When λ is more than 1, the population is growing, but if λ is less than 1, it is declining. On the other hand, the model output also indicates the importance of life stages to the population growth rate (elasticity analysis), which is used to suggest effective strategies for conservation (Benton & Grant 1999, Contreras & Valverde 2002, Zuidema & Boot 2002, Kwit et al. 2003).

We used two ways to project the future prospects for our species (Chapter 3). First, we used the asymptotic population growth rate (λ). For four species: *Dacrydium*, *Manglietia*, *Parashorea* and *Pinus*, we found no evidence of increasing or declining population. The populations of these species are therefore expected to be stable overtime. Nevertheless, our models projected the populations of *Annamocarya* and *Calocedrus* were declining over time. Second, we combined information on recruitment and ages to check whether the species can produce sufficient seedlings in order to replace adult trees. For example for *Manglietia*, we found that only 0.1% of new seedlings would survive to reproductive size. That means an adult tree should produce 1000 seedlings in its entire reproductive life to replace itself. If an adult tree produces less than one seedling per year, as we observed, it takes over 1000 y. This reproductive time is much more than the maximum age estimated for the species. In a similar way, we calculated the ability to produce sufficient seedlings for other species. We found that only *Calocedrus*, *Dacrydium* and *Parashorea* could sufficiently produce seedlings. In contrast, the other species (*Annamocarya*, *Manglietia* and *Pinus*) did not produce effective recruitment for the replacement of adult trees.

The output of the matrix models also indicated that among vital rates, survival of individuals, particularly for juvenile and adult trees, was most important for the population growth rate. Growth and fecundity, on the other hand, were less important for the persistence of the species (Chapter 3).

In short, by applying population matrix models in our demographic study, we projected that the populations of *Annamocarya* and *Calocedrus* were declining, but not for the other species. We also found that *Annamocarya*, *Manglietia* and *Pinus* could not produce enough seedlings to replace adult trees. In addition, the survival was found to be most important for the persistence of populations. These results importantly contribute to the basis information for making an effective conservation strategy for the threatened tree species.

Using stochastic matrix models to analyse the demography of threatened tree species

Population growth rates obtained from standard matrix models are interpreted with the assumption that vital rates do not change over time. Clearly, this is not realistic as populations are affected with time by unpredictable factors such as demographic and environmental stochasticity (Menges & Quintana-Ascencio 2003, Munzbergova 2006). Demographic stochasticity is the variation in population dynamics caused by independent stochastic contribution from each individual of the population to the next generation (Engen et al. 1998, Menges 2000). Environmental stochasticity, on the other hand, is related to variation in demographic parameters (e.g. survival, growth and reproduction) due to variation in the environment (Menges 2000). Demographic and environmental stochasticity can severely change the population growth rate, leading to changes in the extinction risk of populations, particularly in the case of threatened species (Menges 1998). Furthermore, stochastic phenomena such as drought, flood, hurricane or wildfire could destroy populations, even of redundant species (Menges 2000). It is therefore not possible to reliably project the long future prospects for populations and the time for which they go extinct, if using only matrix models. However, we can deal with this problem by using stochastic matrix models as those allow to project population growth rates under the influence of stochasticity.

We applied stochastic matrix models to investigate the impact of stochastic factors on population development and extinction risk for the six threatened tree species. We included both environmental and demographic stochasticity in the stochastic matrix models. For the variation affected by the environment, we estimated variation in vital rates (survival, growth, reproduction, and fecundity), which we obtained and quantified from the two-year field study. This variation may reflect small-scale spatial variation (e.g. in light and soil conditions), size differences and uncertainty in parameter estimation (Chapter 4). We also included temporal variation in growth based on ring indices of trees (Chapter 5).

Our models showed that the environmental stochasticity decreases population sizes and increases extinction risks for all study species. Compared with the temporal variation, the variation among individuals (or spatial variation) was more important for the population development, and for the risk of extinction. On the other hand, demographic stochasticity, in general, decreased the time to extinction for the species, but by chance might also decrease the extinction risk for some populations (Chapter 4). In addition, we also found that the risk of extinction was more sensitive to changes in the mean of vital rates, particularly the survival, than to changes in their variation (Chapter 4). This suggests that more attention should be paid to the estimate of this vital rate in order to get more reliable results from population viability analysis.

From the results obtained from the stochastic matrix models, we projected that *Dacrydium* and *Parashoea* did not face extinction within 300 y, even though the population of *Parashorea* might drop below 100 individuals after 150 y. However, the populations of the other species (*Annamocarya*, *Calocedrus*, *Manglietia* and *Pinus*) were projected to drop below 100 individuals after 80-90 y. Moreover, the extinction risk for *Annamocarya*, *Calocedrus*, *Manglietia* and *Pinus* was projected to be 65%, 11%, 51% and 93%, respectively, within 300 y (Table1, Chapter 4).

Population viability analysis (PVA) is widely used to estimate population dynamics and the extinction risk for threatened species, and also suggest effective conservation actions (Boyce 1992, Kaye & Pyke 2003, Boyce et al. 2006). By taking into account the combined impacts of unpredictable factors such as demographic, environmental and genetic stochasticity and deterministic elements such as habitat loss, overexploitation and fragmentation, PVA provides a stochastic projection of population dynamics over time (Chapman et al. 2001, Beissinger & McCullough 2002). In our study, the results obtained from the stochastic models are also more reliable than those obtained from the deterministic models. That is because the population is analyzed under the influence of environmental and demographic stochasticity. The population growth rate is therefore not stable, but fluctuates following the magnitude of variation. As a result, from stochastic matrix models, but not from deterministic matrix models, we can reliably predict population size and extinction risk for the study species over a long period of time (e.g. over 300 y).

However, using stochastic matrix models also means that we need more data from demographic and environmental stochasticity, which is often time consuming and expensive. Furthermore, parameterization is more complex than that in deterministic models, and constructing stochastic matrix models also is more complicated than doing so with deterministic matrix models. Therefore, based on the purposes of the study, one could choose the most suitable approach to get effective results.

Future prospects and conservation measures for threatened tree species

Combining the results obtained from Chapter 3 & 4, we can distinguish three groups of species with different future prospects. First, the future prospects of *Dacrydium* and *Parashorea* look good. The population growth rate suggests stable population size over time (Chapter 3). In addition, the recruitment of the two species was sufficient for the replacement of large trees (Chapter 3). Furthermore, remaining populations of these two species are not expected go extinct within a long period of time (in 300 y, Chapter 4). Second, for *Manglietia* and *Pinus*, our models did not find significant declines in their population sizes over time, but seedling recruitment appears to be insufficient to replace adult trees (Chapter 3). The future prospects of these species therefore may not be good due to lacking recruitment. This is consistent with the output of the population viability analysis (PVA, Chapter 4) that populations of these two species have a high chance (51-93%) to disappear within 300 y. Third, the future prospects of *Calocedrus* and *Annamocarya* are worrisome as the projected population growth rates indicates the population declines (Chapter 3). In addition, we found that the population sizes of the two species could drop below 100 individuals in just 80-110 y, and the species could face extinction within 125 y (Chapter 4). In short, by combining the results obtained from deterministic and stochastic matrix models, we project that future prospects of *Dacrydium* and *Parashorea* are good, while that for the other species are not.

Our results suggest that successful protection and conservation of the six threatened tree species require various conservation measures. First, for all species, strict protection of populations, particularly for juvenile and adult trees should be implemented, as these stages are most important for the maintenance of their populations (Chapter 3). Any human disturbance and logging within and if possible near the protected areas should be forbidden. On the other hand, great effort should be paid to reverse population decline into population increment for the four species, which are projected to face extinction (*Annamocarya*, *Calocedrus*, *Manglietia* and *Pinus*, Chapter 4). We argue that growth of seedlings and juveniles may be improved using silvicultural measures such as controlled liberation, which in turn can probably increase the growth rate of the populations. Though results from elasticity analyses suggest that the effect of such measures is limited in comparison to maximizing tree survival, growth of seedlings and trees can probably be altered more than tree survival, and with less difficulty (Batista et al. 1998, Zuidema & Boot 2002, Kwit et al. 2004, Chapter 3). Another important conservation measure is enrichment of populations with seedlings produced under controlled conditions. If germination success under controlled conditions is higher than that under natural conditions, seeds can be collected from the same natural populations which are then enriched with seedlings. This enrichment is particularly important for the species (*Annamocarya*, *Manglietia* and *Pinus*), which were found to produce insufficient numbers of seedlings for the maintenance of their populations (Chapter 3). Compared to survival rate, recruitment contributes less to the population growth rate (elasticity analysis, Chapter 3), but improved recruitment can probably be implemented with much less difficulty. Finally, for species with small populations such as *Calocedrus* and *Pinus* (Chapter 3 & 4), the expansion of their habitat area through nature restoration would be an effective conservation measure.

To what extent are the results of the study for the six species relevant to the hundreds of other threatened tree species in Vietnam? With some caution, our results can be applied to other threatened tree species with similar life history and similar status of the remaining populations. As population dynamics of long-lived tree species are to large extent governed in a similar way (see comparison of elasticity patterns in Chapter 3), some general guidelines for conservation threatened tree species can be formulated. First, because small and fragmented habitats increase extinction risks for plant species, it is necessary to increase the size of protected areas, and to stop activities causing fragmentation within these areas. Second, strict protection, particularly for juvenile and adult trees, should be implemented in protected areas, meaning that any human disturbance and logging should be strictly forbidden. Third, the improvement of seedling and juvenile growth (e.g. by controlled libration) can also help to improve population growth rates. Fourth, enrichment is also a good conservation measure in case germination of seeds under controlled conditions is better than under natural conditions. Fifth, for the threatened tree species that presently remain in small and/or isolated populations, expansion of their habitat area through natural restoration would be a crucial conservation measure.

Declines in population sizes of threatened tree species may be slow as they are long-lived. Consequently, there appears to be more time for taking conservation measures for these species, but slow dynamics also imply that it takes long before such measures result in population increase. We therefore argue that taking action before populations have declined to critical levels is important, as well as close monitoring of population size and seedling recruitment.

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Note: * Initial titles in Vietnamese were translated into English.

Samenvatting

Bossen en bedreigde boomsoorten in Vietnam

Er zijn veel verschillende bostypen in Vietnam, omdat het land een tropisch klimaat heeft en topografisch zeer gevariëerd is. Er zijn tropische regenbossen, mangrovebossen, bossen op kalksteen, naaldbossen en subtropische bossen (Hoofdstuk 2). Vietnam ligt ook op een kruispunt van migratiewegen van drie verschillende flora's en dat draagt er toe bij dat de flora van Vietnam heel rijk is (meer dan 12000 soorten).

De afgelopen decennia zijn de bossen in Vietnam door allerlei oorzaken sterk in omvang en kwaliteit verminderd (Hoofdstuk 2). In 1945 werd geschat dat 45 % van het land met natuurlijke bossen bedekt was, maar in 1980 was dat nog maar 27 %. Sindsdien heeft de regering veel in herbebossingsactiviteiten geïnvesteerd en in 2003 was de bosbedekking weer tot 36 % toegenomen, waarvan 6 % plantagebossen. De kwaliteit van al deze bossen is echter nogal laag en behoeft verbetering in termen van soortensamenstelling en bosbeheer (Hoofdstuk 2).

De snelheid van ontbossing is wereldwijd het hoogst in Zuid-Oost Azië: het huidige tempo zou er toe leiden dat over 100 jaar driekwart van het bosareaal is verdwenen tezamen met 42 % van de huidige biodiversiteit (Sodhi et al. 2004). In Vietnam lopen ook veel boomsoorten het risico uit te sterven als gevolg van de bosvernietiging. Volgens de lijst van de International Union for the Conservation of Nature (2006) telt Vietnam op het ogenblik 261 bedreigde boomsoorten, waarvan er 148 sterk bedreigd zijn. De populaties van deze soorten zijn sterk achteruit gegaan, geschikte groeiplaatsen voor veel soorten zijn vrijwel alleen nog in beschermde gebieden te vinden en, omdat de populaties klein en geïsoleerd zijn kunnen ze lokaal, als gevolg van demografische toevalsprocesses of milieu-fluctuaties, of door gebrek aan genetische variatie, gemakkelijk uitsterven.

Vietnam heeft een netwerk van 126 beschermde gebieden, verspreid over het hele land. Tezamen beslaan ze 8 % van het land, maar dat is volgens IUCN-normen te weinig. Daarenboven zijn bossen in belangrijke afwateringsgebieden ook beschermd. Maar de oppervlakte van veel beschermde gebieden is klein, zodat het belangrijk is om in Vietnam niet alleen het beschermde areaal uit te breiden, maar ook de gebieden zelf groter te maken. Er is nog weinig onderzoek gedaan naar de biodiversiteit in beschermde gebieden en naar de demografie van bedreigde soorten. Deze informatie is echter nodig om een effectieve bescherming mogelijk te maken. Het onderzoek dat in deze dissertatie beschreven wordt, wil een dergelijke bijdrage leveren.

Demografie van zes bedreigde boomsoorten

Om bedreigde boomsoorten te kunnen beschermen moeten we allereerst verschillende aspecten van de popultiedynamica van die soorten kennen, bijvoorbeeld of er natuurlijke verjonging optreedt en of die voldoende is om de volwassen bomen te vervangen, of de populaties groeien of afnemen, en wat de meest kritische levensstadia in de levenscyclus zijn.

Om dit soort vragen te beantwoorden heb ik gedurende twee jaren van veldwerk demografische data van zes bedreigde boomsoorten in vier beschermde gebieden verzameld. Ik heb de ‘vital rates’ (overleving, groei en vruchtbaarheid) voor de populaties van de zes soorten berekend en die gebruikt om de elementen (stasis, groei en vruchtbaarheid) van de matrixmodellen te kwantificeren (Hoofdstuk 3). De matrixmodellen leverden me de geschatte groeisnelheden (λ) van de populaties en die heb ik gebruikt om de toekomstige ontwikkelingen van de populaties te taxeren. Als λ groter is dan 1 groeit de populatie, maar als λ kleiner is dan 1 neemt de populatie af. Uit de modelberekeningen blijkt ook in welke mate de verschillende levensstadia de groeisnelheid van de populatie beïnvloeden (‘elasticiteitsanalyse’). Op grond daarvan is het mogelijk om effectieve strategieën voor de bescherming van de soorten te formuleren.

Ik heb twee methodes gebruikt om de toekomstige ontwikkeling van de zes soorten in te schatten (Hoofdstuk 3). Eerst heb ik groeisnelheid van de populatie berekend voor de populaties van alle zes soorten. Bij vier soorten, *Dacrydium*, *Manglietia*, *Parashorea* en *Pinus*, vond ik geen aanwijzingen voor een af- of toenemende populatiegrootte. De populaties van deze soorten lijken dus stabiel. Maar de populatiegrootte van *Annamocarya* en *Calocedrus* lijken af te nemen. Vervolgens gebruikte ik de gegevens over verjonging en leeftijden om na te gaan of de soorten voldoende jonge planten produceren om de oude te vervangen. Bij *Manglietia* vond ik bijvoorbeeld, dat de kans dat een kiemplant overleeft tot reproducerende boom slechts 0,1 % bedraagt. Dat betekent dat een volwassen boom tijdens zijn gehele reproductieve levensstadium dus 1000 kiemplanten zou moet produceren om zichzelf te vervangen. Maar als zo’n boom, zoals ik waarnam, nog minder dan 1 kiemplant per jaar levert, dan heeft hij gemiddeld dus 1000 jaar nodig om zichzelf te vervangen. Dit is veel langer dan de maximum leeftijd van zo’n boom. Ik vond dat alleen *Calocedrus, Dacrydium* en *Parashorea* voldoende kiemplanten produceerden. De andere drie soorten produceerden er niet genoeg om de volwassen bomen te vervangen.

Op grond van de matrixmodellen kon ik ook concluderen dat de groei van populaties het sterkst wordt bepaald door de overleving van jonge en volwassen bomen. Andere 'vital rates' (boomgroei en vruchtbaarheid) waren minder kritiek voor het voortbestaan van populaties van deze soorten (Hoofdstuk 3).

Dus uit de matrixmodellen bleek dat de populaties van *Annamocarya* en *Calocedrus* afnamen, en dat *Annamocarya*, *Manglietia* en *Pinus* niet genoeg kiemplanten produceerden om de oude bomen te vervangen. Een adequate beschermingsstrategie voor de soorten moet met deze kennis rekening houden.

Het gebruik van stochastische matrixmodellen voor de analyse van de demografie van bedreigde boomsoorten

De groeisnelheden van populaties zijn over lange tijdsintervallen niet noodzakelijk constant. Op onvoorspelbare wijze kunnen ze door demografische of milieugebeurtenissen stochastisch beïnvloed worden. Demografische stochasticiteit betreft de variatie in populatiedynamiek, die door de onafhankelijke bijdrage van elk individu in de populatie veroorzaakt wordt. Milieu-stochasticiteit betreft onvoorspelbare variatie in de populatiedynamica als gevolg van fluctuaties in het milieu, bijvoorbeeld door stormen, brand of droge jaren. Deze twee stochastische invloeden kunnen in belangrijke mate de groeisnelheden van populaties beïnvloeden en bij bedreigde soorten het risico van uitsterven veranderen. Daarom kan men op grond van deterministische matrixmodelberekeningen (die geen rekening houden met stochasticiteit) de lange termijn toekomst van een soort eigenlijk niet op een betrouwbare manier taxeren. Maar het gebruik van stochastische matrixmodellen biedt hier uitkomst.

Ik gebruikte deze methode om het risico van uitsterven voor de zes onderzochte soorten te berekenen, waarbij ik zowel demografische als milieu-stochasticiteit in aanmerking nam. Als een maat voor de variatie in het milieu gebruikte ik de variatie in de ‘vital rates’ (overleving, groei, reproductie en vruchtbaarheid) die ik op grond van de gegevens van twee jaar veldwerk had verkregen. Deze variatie tussen bomen weerspiegelt de klienschalige ruimtelijke variatie in milieu-omstandigheden, grootteverschillen, en schattingsonnauwkeurigheden Hoofdstuk 4). Ik heb ook nog de boomgroeivariatie in de tijd meegenomen, zoals die blijkt uit jaarringonderzoek.

Mijn modelberekeningen lieten zien dat milieustochasticiteit leidt tot een afname van berekende populatiegrootte en een hogere uitsterfrisico. Dit was het geval voor alle soorten. Individuele variatie (ofwel ruimtelijke variatie) was in grotere mate verantwoordelijk voor dit effect dan variatie in de tijd.

Demografische stochasticiteit verkortte de gemiddelde tijd totdat populaties uitstierven, maar leidde aan de andere kant ook tot een verlaagde kans op uitsterven (Hoofdstuk 4). Ik vond ook dat het uitsterfrisico gevoeliger was voor veranderingen in de gemiddelde waarden van de ‘vital rates’ dan voor veranderingen in de variatie van die 'vital rates'. Dit was vooral het geval voor de factor overleving. Hieruit blijkt dat men die factor zo nauwkeurig mogelijk moet bepalen om betrouwbare schattingen van de levensvatbaarheid van populaties te verkrijgen.

Mijn resultaten uit de stochastische modellen lieten zien, dat *Dacrydium* en *Parashorea* niet binnen 300 jaar zouden uitsterven, zelfs al zou de populatiegrootte van *Parashorea* binnen 150 jaar tot minder 100 individuen afnemen. Naar verwachting zullen de populaties van de andere soorten echter in 80-90 jaar tot minder dan 100 individuen teruglopen. De uitsterfrisico’s van *Annamocarya*, *Calocedrus*, *Manglietia* en *Pinus* zijn respectievelijk 65, 11, 51 en 93 % (Hoofdstuk 4).

Stochastische modelberekeningen, die overigens algemeen gebruikt worden in zogenaamde ‘population viability analyses’, geven ook in mijn geval veel betrouwbaarder resulaten dan deterministische modelberekeningen, juist omdat de verschillende vormen van stochasticiteit in de berekeningen meegenomen worden. Maar gebruik van deze methode betekent ook dat men meer gegevens over demografische en milieu-stochasticiteit moet verzamelen en dat is tijdrovend en duur. Ook zijn deze modellen complexer dan deterministische modellen.

Vooruitzichten en beschermingsmaatregelen voor de bedreigde soorten

Op grond van de resultaten in de Hoofdstukken 3 en 4 kunnen we 3 soortengroepen onderscheiden wat betreft hun vooruitzichten. De vooruitzichten voor *Dacrydium* en *Parashorea* zijn goed. De groeisnelheden van hun populaties zijn stabiel en de verjonging is voldoende om oude bomen te vervangen. Ook zullen naar verwachting de bestaande populaties van deze twee soorten binnen de komende 300 jaar niet uitsterven. Voor *Manglietia* en *Pinus* heb ik geen afnemende populatiegroeisnelheden gevonden, maar hun verjonging lijkt onvoldoende. Door gebrek aan verjonging lijkt de toekomst van de populaties van deze twee soorten niet goed. en de populaties hebben 51 – 93 % kans om binnen de komende 300 jaar uit te sterven. De toekomst van *Calocedrus* en *Annamocarya* is ronduit zorgelijk, want hun populatiegroeisnelheden nemen af, hun populaties kunnen binnen 80 – 110 jaar tot minder dan 100 individuen gekrompen zijn en ze kunnen naar verwachting beide binnen 125 jaar uitgestorven zijn. De gecombineerde resultaten van de deterministische en de stochastische modelberekeningen voorspellen dus geen goeds voor deze twee soorten.

Mijn resultaten suggereren dat er verschillende beschermingsmaatregelen nodig zijn voor deze zes soorten. Op de eerste plaats moeten populaties strikt beschermd worden, met name de jonge en volwassen bomen (zie Hoofdstuk 3). Verstoring door menselijk gebruik en houtkap in, en indien mogelijk, ook nabij deze populaties moet worden verboden. Ook moet men bij de vier soorten die met uitsterven bedreigd worden proberen de afname van de populatiegrootten om te zetten in een toename. Ik denk dat de groei van kiemplanten en jonge boompjes door silviculturele maatregelen, zoals ‘vrijstelling’, bevorderd kan worden en daardoor kan de groeisnelheid van de populatie toenemen. Hoewel mijn elasticiteitsanalysen suggereren dat het effect van zulke maatregelen beperkter is dan dat van het maximaliseren van de overleving van bomen, komt het mij voor dat men de groei van kiemplanten en bomen gemakkelijker kan doen toenemen dan de overleving van bomen.

Nog een belangrijke beschermingsmaatregel is het verrijken van de bestaande populaties met kiemplanten die onder gecontroleerde omstandigheden zijn geproduceerd. Als men betere kieming krijgt onder gecontroleerde dan onder natuurlijke omstandigheden moet men in de natuurlijke populaties zaden verzamelen, kiemplanten produceren en die in de populaties inbrengen. Dit is vooral belangrijk voor *Annamocarya*, *Manglietia* en *Pinus*, die immers te weinig kiemplanten blijken te produceren (Hoofdstuk 3). Hoewel verjonging minder aan de groeisnelheid van de populatie bleek bij te dragen dan een hogere overlevingskans, is het waarschijnlijk veel gemakkelijker om de verjonging te laten toenemen. Tenslotte zouden het groei-areaal van de kleine populaties van *Calocedrus* en *Pinus* vergroot moeten worden door natuurherstel.

In hoeverre zijn de resultaten voor deze zes soorten van belang voor de honderden andere bedreigde boomsoorten van Vietnam? Met de nodige voorzichtigheid kunnen mijn resultaten voor andere soorten met een overeenkomstige levenswijze en overeenkomstige populatiedynamica gebruikt worden. Omdat de populatiedynamica van lang-levende boomsoorten toch grotendeels door dezelfde factoren wordt aangestuurd, kan ik een aantal algemene richtlijnen formuleren. Ten eerste, omdat kleine en gefragmenteerde standplaatsen het risico op uitsterven doen toenemen, is het nodig dat de oppervlakte van beschermde gebieden wordt vergroot en dat activiteiten die fragmentatie veroorzaken worden tegengegaan. Ten tweede, in beschermde gebieden zullen populaties van bedreigde soorten strikt moeten worden beschermd, met name de jonge en volwassen bomen. Dit houdt in dat verstoring door houtkap en andere menselijke activiteiten strikt moet worden tegengegaan. Ten derde, door 'vrijstelling' van kiemplanten en jonge boompjes kan hun groei worden verhoogd, hetgeen bijdraagt aan een hogere groeisnelheid van populaties. Ten vierde, ‘verrijking’ is een goede beschermingsmaatregel als kieming onder gecontroleerde omstandigheden succesrijker is dan onder natuurlijke omstandigheden. Ten vijfde, de habitats van de bedreigde soorten met kleine en geïsoleerde populaties moeten door natuurbouw groter gemaakt worden.

De afname van populatiegrootten van bedreigde boomsoorten is, omdat bomen doorgaans nogal lang leven, een langzaam proces. Daarom lijkt het alsof er genoeg tijd is om beschermende maatregelen te nemen. Maar zulke maatregelen hebben ook pas op de lange duur effect. Daarom pleit ik ervoor maatregelen te nemen voordat de populaties tot kritisch lage aantallen individuen zijn gekrompen. En ik adviseer ook populatiegrootten en verjonging nauwkeurig te monitoren.

Tóm tắt các kết quả nghiên cứu chính

Luận văn phân tích động thái quần thể của sáu loài cây bị đe doạ ở trên ba vườn quốc gia và một khu bảo tồn thiên nhiên của Việt Nam, với các mục tiêu nghiên cứu:

1. Phân tích động thái quần thể của sáu loài cây bị đe doạ;
2. Dự đoán triển vọng của sáu loài cây dựa trên hiện trạng và động thái quần thể của loài;
3. Khuyến nghị các biện pháp bảo tồn cho các loài;
4. Đánh giá ảnh hưởng của kích thước ma trận quần thể tới các kết quả thu được từ mô hình.

Luận văn được trình bày trong sáu chương. Chương 1 là phần giới thiệu chung. Chương 2 trình bày một số đặc điểm về rừng Việt Nam, đa dạng sinh học và các loài cây bị đe doạ tuyệt chủng. Chương 3 trình bày kết quả nghiên cứu về động thái quần thể của sáu loài cây. Chương 4 phân tích khả năng tồn tại và phát triển của quần thể sáu loài. Chương 5 xem xét ảnh hưởng của kích thước ma trận quần thể tới các kết quả thu được từ mô hình. Chương 6 trình bày tóm lược các kết quả nghiên cứu và thảo luận chung. Các kết quả nghiên cứu chính của Luận văn được tóm tắt như sau:

Rừng Việt Nam và các loài cây bị đe doạ

Do ảnh hưởng bởi chế độ khí hậu nhiệt đới gió mùa và một địa hình phức tạp, Việt Nam có các loại hình rừng phong phú, từ rừng mưa nhiệt đới, rừng ngập mặn, rừng núi đá vôi tới rừng cận nhiệt đới và cây lá kim (Chương 2). Việt Nam cũng sở hữu một hệ thực vật rất đa dạng về loài, ước tính trên 12000 loài (Thìn 1997, Trừng 1998). Đó là do Việt Nam nằm ở một vị trí địa lý đặc biệt, là nơi tập trung của các loài thực vật bản địa và các loài di cư từ ba hệ thực vật xung quanh: hệ thực vật Himalaya-Yunnam-Guizhou ở phía tây bắc, hệ thực vật India-Myanmar ở phía tây, và hệ thực vật Malaysia-Indonesian ở phía nam và đông nam (Chương 2).

Rừng Việt Nam đã bị suy giảm nghiêm trọng cả về số lượng và chất lượng trong vài thập kỷ vừa qua. Độ che phủ của rừng tự nhiên trên cả nước bị giảm từ 43% năm 1945 xuống còn khoảng 27% vào năm 1980 (Hùng 2004). Nguyên nhân chính của việc suy thoái và mất rừng là do chiến tranh, do việc chuyển hoá rừng và đất rừng sang sản xuất nông nghiệp, do khai thác lạm dụng và du canh (Chương 2). Những năm gần đây, sau những cố gắng rất lớn của Chính phủ trong các chương trình trồng, phục hồi và bảo vệ rừng, độ che phủ của rừng Việt Nam đã tăng lên 36% vào năm 2003, bao gồm khoảng 30% rừng tự nhiên và 6% rừng trồng (Cục Lâm Nghiệp 2004). Tuy nhiên, do bị ảnh hưởng bởi quá trình suy thoái dài, chất lượng rừng tự nhiên của Việt Nam nhìn chung là thấp. Diện tích rừng trồng đã tăng lên đáng kể trong những năm qua, nhưng chất lượng cũng vẫn còn thấp, cần được bổ sung thêm về thành phần loài cũng như cần tiếp tục phát triển và hoàn thiện các biện pháp kỹ thuật lâm sinh và các loại hình rừng trồng (Chương 2).

Đông Nam Á đang phải đối mặt với tỷ lệ mất rừng cao nhất thế giới. Nếu nạn phá rừng không được ngăn chặn, khu vực có thể sẽ mất đi ba phần tư diện tích rừng cùng với khoảng 40% số loài hiện có trong vòng 100 năm tới (Sodhi et al. 2004). Là một nước nằm trong khu vực, Việt Nam cũng có nhiều loài cây bị de doạ tuyệt chủng do bị ảnh hưởng của quá trình suy thoái và mất rừng trong những năm qua. Theo Hiệp hội bảo tồn thế giới (IUCN 2006), Việt Nam hiện có khoảng 260 loài cây bị đe doạ trong đó 150 loài đang hoặc sẽ bị nguy cấp tuyệt chủng. Quần thể của các loài cây bị đe doạ bị suy giảm mạnh cả về mật độ và khu phân bố. Sự tồn tại của các loài này phụ thuộc rất nhiều vào các khu rừng được bảo vệ (Bawa & Ashton 1991). Mặt khác, do quần thể các loài bị đe doạ thường nhỏ và bị chia cắt nên rất dễ bị tổn thương và cũng dễ bị đối mặt với hiểm hoạ tuyệt chủng do sự thay đổi bất thường của môi trường và sự suy thoái từ chính quần thể (Menges 1992, Lande 1993, Oostermeijer et al. 2003).

Nhận biết rõ tầm quan trọng của rừng và đa dạng sinh học đối với đời sống con nguời và sự phát triển của đất nước, Việt Nam đã sớm xây dựng một hệ thống các khu rừng đặc dụng và bảo tồn trên khắp cả nước. Hiện tại, Việt Nam có 126 khu rừng đặc dụng và bảo tồn, chiếm khoảng 8% diện tích cả nước (Cục Phát triển Lâm nghiệp 2004). Thêm vào đó, rừng và thảm thực vật ở một số lưu vực sông quan trọng cũng được bảo vệ và phát triển. Điều này góp phần tăng cơ hội bảo tồn cho các loài cây bị đe doạ cũng như đa dạng sinh học ở khu vực.

Tuy nhiên, để bảo tồn một cách hiệu quả các loài cây bị đe doạ, các khu rừng đặc dụng và bảo tồn cần được cải thiện hơn về cả số lượng và chất lượng. Tỷ lệ diện tích các khu rừng này so với tổng diện tích lãnh thổ còn thấp hơn so với mức chung do IUCN (1997) quy định. Mặt khác, diện tích một số khu bảo tồn còn khá nhỏ (Chương 2) nên có thể làm giảm tính năng bảo tồn của khu. Do vậy, trong những năm tới, đất nước không những cần xây dựng thêm các khu bảo tồn mới mà việc mở rộng các khu bảo tồn nhỏ cũng là một nhiệm vụ quan trọng.

Trong rất nhiều các khu rừng đặc dụng và bảo tồn, các nghiên cứu cơ bản về phân loại thực vật, đa dạng sinh học và động thái quần thể các loài bị đe doạ còn khá hạn chế. Do vậy, một công việc rất cần thiết là tiến hành các nghiên cứu làm cơ sở cho việc xây dựng các kế hoạch bảo tồn. Nghiên cứu được trình bày trong Luận văn này thực hiện một phần mục tiêu trên, nhằm cung cấp thông tin góp phần xây dựng chiến lược bảo tồn hiệu quả các loài cây bị đe doạ.

Động thái quần thể của các loài cây bị đe doạ

Muốn xây dựng một kế hoạch bảo tồn hiệu quả cho các loài cây bị đe doạ, chúng ta cần hiểu rõ động thái quần thể của chúng. Các quần thể có khả năng tái sinh tự nhiên không, và nếu có thì số lượng cây con sinh ra có đáp ứng được cho sự tồn tại và phát triển của quần thể không? Quần thể của loài đang phát triển hay đang suy thoái? Giai đoạn nào trong quá trình sinh trưởng và phát triển của các cá thể là quan trọng nhất cho sự tồn tại và phát triển của quần thể?

Để làm sáng tỏ các câu hỏi trên, chúng tôi tiến hành các nghiên cứu về động thái quần thể của sáu loài cây bị đe doạ trên ba vườn quốc gia và một khu bảo tồn thiên nhiên ở Việt Nam: Chò đãi và Chò chỉ ở Vườn quốc gia Cúc Phương, Bách xanh và Mỡ Ba Vì ở Vườn quốc gia Ba Vì, Tùng Bạch Mã ở Vườn quốc gia Bạch Mã, và Thông Pà Cò ở Khu bảo tồn Hang Kia – Pà Cò. Tại các ô định vị được thiết lập trên khu phân bố của các loài cây nghiên cứu, các chỉ tiêu về sinh trưởng, tỷ lệ sống, khả năng tái sinh của loài được thu thập. Các số liệu sau đó được xử lý, tính toán và sử dụng để xây dựng các mô hình ma trận quần thể (mô hình không biến đổi) cho các loài cây nghiên cứu (Chương 3). Một kết quả quan trọng thu được từ mô hình là tốc độ tăng trưởng của quần thể (λ), được sử dụng để dự đoán tương lai cho quần thể. Nếu λ lớn hơn 1, quần thể đang sinh trưởng và phát triển tốt. Ngược lại, nếu λ nhỏ hơn 1, quần thể đang bị suy thoái và có thể dẫn đến bị tuyệt chủng. Một kết quả có ý nghĩa khác của mô hình là cho chúng ta biết tầm quan trọng của các giai đoạn trong chu kỳ sống của các cá thể đối với sự tồn tại và phát triển của quần thể. Dựa vào các kết quả thu được từ mô hình, các chiến lược bảo tồn hiệu quả được xây dựng (Benton & Grant 1999, Contreras & Valverde 2002, Zuidema & Boot 2002, Kwit et al. 2003).

Chúng tôi kết hợp hai phương pháp để dự đoán triển vọng cho các loài nghiên cứu (Chương 3). Thứ nhất, chúng tôi xem xét tốc độ tăng trưởng của quần thể (λ) thu được từ mô hình ma trận xây dựng cho các loài. Đối với bốn loài Tùng Bạch Mã, Mỡ Ba Vì, Chò chỉ và Thông Pà Cò, chúng tôi không tìm thấy dấu hiệu chứng tỏ rằng quần thể của các loài đang bị suy giảm rõ rệt. Ngược lại, kết quả từ mô hình cho thấy rằng quần thể của Chò đãi và Bách xanh đang bị suy giảm. Số lượng cá thể trong quần thể của Chò đãi và Bách xanh đang bị giảm dần theo thời gian. Thứ hai, chúng tôi xem xét khả năng tái sinh của quần thể và tuổi sinh sản của các cá thể để tính toán xem số lượng cây con sinh ra có đáp ứng được cho sự tồn tại và phát triển của quần thể hay không. Ví dụ, đối với loài Mỡ Ba Vì, chỉ có khoảng 0.1% các cây con sinh ra được ước tính có thể tồn tại tới lúc trưởng thành. Điều này có nghĩa là một cây từ lúc trưởng thành tới khi chết cần phải sinh ra 1000 cây con để có thể tự thay thế bản thân nó. Nếu một cây trưởng thành chỉ sinh được trung bình 1 cây con trong 1 năm thì phải cần tới 1000 năm mới có đủ số cây con để thay thế. Điều này là không thể vì tuổi của Mỡ Ba Vì cao nhất mà chúng tôi tính toán được là khoảng 200 tuổi (Chương 5). Bằng cách tương tự, chúng tôi tính toán khả năng tái sinh của của quần thể cho các loài còn lại. Chúng tôi thấy rằng chỉ có Tùng Bạch Mã, Bách xanh và Chò chỉ là có thể đáp ứng được yêu cầu này. Tuy nhiên, ba loài cây còn lại (Chò đãi, Mỡ Ba Vì và Thông Pà Cò) số cây con sinh ra không đủ để thay thế các cây trưởng thành của quần thể.

Kết quả thu được từ mô hình cũng chỉ ra rằng tỷ lệ sống của các cá thể, đặc biệt là đối với cây nhỡ và cây trưởng thành, là quan trọng nhất cho sự tồn tại và phát triển của quần thể. Tuy nhiên, các đặc tính khác của thể là tốc độ sinh trưởng và tái sinh của các cá thể có có tác động ít hơn tới quá trình sinh trưởng và phát triển của quần thể (Chương 3).

Tóm lại, bằng việc ứng dụng mô hình ma trận trong nghiên cứu động thái quần thể của các loài cây bị đe doạ, chúng tôi dự đoán rằng quần thể của Chò đãi và Bách xanh đang bị suy giảm. Với các loài còn lại, chúng tôi không tìm thấy dấu hiệu rõ rệt về sự suy giảm của các quần thể. Tuy nhiên, khi xét về khả năng tái sinh của các loài, chúng tôi thấy rằng số lượng cây con sinh ra của Chò đãi, Mỡ Ba Vì và Thông Pà Cò không đáp ứng được cho sự tồn tại và phát triển của quần thể. Kết quả thu được từ mô hình cũng cho thấy rằng tỷ lệ sống của các cá thể mà đặc biệt là đối với cây nhỡ và cây trưởng thành là quan trọng nhất đối với sự tồn tại và phát triển của quần thể. Những kết quả này làm cơ sở cho việc xây dựng các phương án bảo tồn cho các loài cây bị đe doạ.

Sử dụng mô hình ma trận biến đổi trong phân tích động thái quần thể các loài cây bị đe doạ

Mô hình ma trận quần thể trình bày ở trên được ứng dụng cùng với giả thiết là tốc độ sinh trưởng, tỷ lệ sống và khả năng tái sinh của các cá thể trong quần thể không thay đổi theo thời gian. Hiển nhiên, giả thiết này sẽ không hợp lý cho những dự đoán về một tương lai dài của quần thể, vì quần thể luôn bị ảnh hưởng bởi những biến động không thể đoán trước của môi trường tự nhiên và của chính quần thể (Menges & Quintana-Ascencio 2003, Munzbergova 2006). Biến động (không thể đoán trước) của quần thể là những biến đổi về động thái của quần thể gây ra bởi những biến đổi độc lập của từng cá thể làm ảnh hưởng tới kích thước quần thể tương lai (Engen et al. 1998, Menges 2000). Bên cạnh đó, biến động (không thể đoán trước) của môi trường cũng sẽ gây ra những biến đổi (không thể đoán trước) về tỷ lệ sống, tốc độ sinh trưởng và khả năng tái sinh của các cá thể, và do đó ảnh hưởng tới quá trình sinh trưởng và tồn tại của quần thể (Menges 2000). Những biến động của quần thể và môi trường có thể làm ảnh hưởng mãnh liệt tới tốc độ tăng trưởng của quần thể và nguy cơ tuyệt chủng của các loài, đặc biệt là các loài bị đe doạ (Menges 1998). Hơn thế nữa, các biến động mãnh liệt của tự nhiên như hạn hán, lũ lụt, giông bão hay lửa rừng có thể làm tổn hại nghiêm trọng hoặc làm tiêu huỷ toàn bộ quần thể của loài, kể cả đối với các loài giầu cá thể (Menges 2000). Do vậy, sẽ khó đưa ra dự đoán chính xác cho tương lai của loài nếu chỉ sử dụng mô hình ma trận quần thể không biến đổi. Tuy nhiên, chúng ta sẽ có câu trả lời chính xác hơn nếu ứng dụng mô hình ma trận quần thể thay đổi, vì các mô hình này cho phép xác định tốc độ tăng trưởng của quần thể dưới tác động của sự biến đổi của môi trường và của chính quần thể.

Chúng tôi ứng dụng mô hình ma trận quần thể biến đổi để xem xét ảnh hưởng của các biến động của môi trường và của quần thể tới sự tồn tại và phát triển của sáu loài cây nghiên cứu. Với những biến đổi của quần thể do tác động của môi trường, chúng tôi ước lượng sự biến động về tỷ lệ sống, sinh trưởng và tái sinh của quần thể từ các số liệu thu thập ngoài thực địa. Những biến động này phản ánh những tác động khác nhau gây ra bởi vị trí không gian khác nhau (ví dụ khác nhau về điều kiện ánh sáng, điều kiện đất đất) giữa các cá thể (Chương 4). Chúng tôi cũng xem xét ảnh hưởng của thời gian tới các biến động của quần thể thông quan sự biến động về sinh trưởng đường kính thu được từ các vòng năm của cây (Chương 5) và sự biến động về số lượng cây con tái sinh giữa các năm (Chương 3).

Kết quả thu được từ mô hình chỉ ra rằng những biến động của môi trường làm giảm số lượng cá thể của quần thể, do đó làm tăng nguy cơ tuyệt chủng của quần thể. So sánh với biến động do thời gian gây ra, biến động về không gian (biến động giữa các cá thể) có ảnh hưởng lớn tới sự suy thoái của quần thể. Biến động của chính quần thể cũng gây ảnh hưởng tới sự tồn tại và phát triển của quần thể. Tuy rằng biến động này không ảnh hưởng nhiều tới các quần thể lớn, nhưng nó làm giảm thời gian dẫn tới tuyệt chủng đối với các quần thể nhỏ. Tuy nhiên, loại biến động này cũng có thể làm giảm nguy cơ tuyệt chủng cho một số quần thể (may mắn) do cơ hội được tăng số cá thể trong quần thể (Chương 4). Chúng tôi cũng thấy rằng nguy cơ tuyệt chủng của quần thể bị ảnh hưởng rất lớn bởi các tham số: tỷ lệ sống (đặc biệt là đối với các cây nhỡ và cây trưởng thành), tốc độ sinh trưởng và tái sinh của các cá thể. Tuy nhiên, sự biến động của các tham số này ảnh hưởng ít hơn tới nguy cơ tuyệt chủng của loài (Chương 4). Điều này cho thấy chúng ta cần quan tâm hơn tới việc thu thập và tính toán các tham số, đặc biệt là tỷ lệ sống của các cá thể để có thể thu được những kết quả chính xác hơn từ mô hình ma trận quần thể biến đổi.

Từ kết quả thu được chúng tôi dự đoán rằng Tùng Bạch Mã và Chò chỉ không bị đối mặt với nguy cơ tuyệt chủng trong vòng 300 năm tới, tuy rằng quần thể Chò chỉ có thể bị giảm xuống dưới 100 cá thể trong vòng khoảng 150 năm tới. Tuy nhiên, tương lai của các loài còn lại không có nhiều hứa hẹn, vì các quần thể được dự đoán sẽ giảm xuống dưới 100 cá thể trong khoảng 100 năm tới. Đặc biệt, mức độ tuyệt chủng đối với Chò đãi, Bách xanh, Mỡ Ba Vì và Thông Pà Cò được dự đoán lần lượt là 65%, 11%, 51% và 93% trong khoảng thời gian 300 năm tới (Chương 4).

Phân tích khả năng tồn tại và phát triển của quần thể (PVA) được sử dụng rộng rãi trên thế giới để đánh giá động thái quần thể và hiểm hoạ tuyệt chủng của các loài bị đe doạ, và cũng là cơ sở để xây dựng những kế hoạch bảo tồn hiệu quả (Boyce 1992, Kaye & Pyke 2003, Boyce et al. 2006). Bằng cách xem xét ảnh hưởng tổng hợp của các biến động (không đoán được) của môi trường và quần thể và các yếu tố xác định như mất nơi cư trú, chia cắt nơi cư trú hoặc bị khai thác lạm dụng, PVA cung cấp những thông tin có độ tin cậy cao về tương lai của loài (Chapman et al. 2001, Beissinger & McCullough 2002). Trong nghiên cứu của chúng tôi, kết quả thu được từ mô hình ma trận biến đổi có độ tin cậy cao hơn so với kết quả thu được từ mô hình ma trận bình thường (không biến đổi). Đó là vì động thái của quần thể được phân tích dưới sự tác động của những biến động của môi trường và quần thể. Tốc độ tăng trưởng của quần thể do đó không bất biến theo thời gian mà thay đổi tuỳ theo mức độ tác động từ các yếu tố môi trường và quần thể. Do đó, từ mô hình ma trận quần thể biến đổi chúng ta có thể dự đoán kích thước của quần thể và hiểm hoạ tuyệt chủng đối với loài cho một tương lai dài (ví dụ cho thời gian 300 năm tới).

Tuy nhiên, nếu sử dụng mô hình ma trận quần thể biến động, chúng ta cần phải có số liệu về ảnh hưởng của sự biến đổi của môi trường và của chính quần thể tới động thái quần thể. Việc thu thập các loại số liệu này thường tốn nhiều thời gian và công sức. Hơn thế nữa, việc tính toán các tham số để xây dựng mô hình quần biến đổi cũng phức tạp hơn nhiều so với khi xây dựng mô hình bình thường (bất biến). Do vậy, tuỳ vào mục tiêu đặt ra cho nghiên cứu mà chọn loại mô hình hợp lý.

Tương lai của các loài cây bị đe doạ và các biện pháp bảo tồn

Dựa vào kết quả thu được, chúng tôi có thể phân các loài nghiên cứu thành ba nhóm với triển vọng khác nhau. Thứ nhất, với hai loài Tùng Bạch Mã và Chò chỉ, kết quả từ mô hình cho thấy tương lai của hai loài khá tốt do tốc độ tăng trưởng quần thể khá ổn định và khả năng tái sinh của hai loài có thể đáp ứng được cho sự tồn tại và phát triển của quần thể (Chương 3). Thêm vào đó, hai loài được dự đoán không bị đe doạ bởi nguy cơ tuyệt chủng trong tương lai 300 năm tới (Chương 4). Thứ hai, với hai loài Mỡ Ba Vì và Thông Pà Cò, tuy chúng tôi không thấy dấu hiệu về sự suy giảm rõ rệt của quần thể hai loài nhưng cả hai đều không đảm bảo khả năng tái sinh để thay thế cho cây trưởng thành. Do vậy, triển vọng của hai loài cây này không được tốt như Tùng Bạch Mã và Chò chỉ (Chương 3). Điều này cũng phù hợp với kết quả thu được từ Chương 4 cho thấy là hai loài có thể phải đối mặt với khả năng tuyệt chủng rất cao (51-93%) trong vòng 300 năm tới. Thứ ba, triển vọng của hai loài Chò đãi và Bách xanh không tốt vì quần thể hai loài được dự đoán đang bị suy giảm (Chương 3). Bên cạnh đó, quần thể của hai loài được dự đoán sẽ giảm xuống dưới 100 cá thể trong khoảng thời gian từ 80-110 năm tới, và hai loài có thể đối mặt với nguy cơ tuyệt chủng chỉ trong vòng 125 năm tới (Chương 4). Tóm lại, các kết quả thu được từ các mô hình quần cho thấy rằng triển vọng của Tùng Bạch Mã và

Chò chỉ là khá tốt. Ngược lại, tương lai của các loài khác không được tốt vì quần thể của các loài này đang bị suy giảm và có thể đối mặt với nguy cơ tuyệt chủng trong tương lai.

Từ kết quả nghiên cứu trên cho thấy cần có biện pháp tổng hợp để bảo tồn hiệu quả các loài cây bị đe doạ. Thứ nhất, với tất cả các loài cần phải bảo vệ nghiêm ngặt các cá thể của quần thể, đặc biệt là đối với những cây nhỡ và cây trưởng thành vì chúng đóng vai trò rất quan trọng đối với sự tồn tại và phát triển của quần thể (Chương 3). Do vậy, cần nghiêm cấm triệt để hoạt động khai thác hoặc các hoạt động gây ra tác động tiêu cực tới quần thể của loài. Với bốn loài (Chò đãi, Bách xanh, Mỡ Ba Vì và Thông Pà Cò) bị dự đoán là đối mặt với nguy cơ tuyệt chủng (Chương 4), cần áp dụng thêm các biện pháp hữu hiệu để làm tăng tốc độ tăng trưởng của quần thể. Chúng tôi thấy rằng việc cải thiện tốc độ sinh trưởng của cây con và cây nhỡ bằng các giải pháp lâm sinh như giải phóng không gian sinh dưỡng sẽ góp phần làm tăng tốc độ tăng trưởng của quần thể. Mặc dù ảnh hưởng của sinh trưởng cá thể tới sự tồn tại của quần thể là nhỏ hơn so với việc tăng tỷ lệ sống của cá thể, nhưng có thể thực hiện dễ hơn rất nhiều so với việc tăng tỷ lệ sống cho cá thể (Batista et al. 1998, Zuidema & Boot 2002, Kwit et al. 2004, Chapter 3). Một biện pháp bảo tồn quan trọng nữa là việc làm giàu quần thể bằng cây con được gieo tạo tại vườn ươm. Nếu quá trình hình thành cây con từ hạt đạt tỷ lệ thấp dưới tán rừng, nguồn hạt này có thể được thu thập và dùng để gieo tạo cây con ở vườn ươm, và sau đó những cây con này được đưa trở lại làm giàu quần thể của loài. Phương pháp này rất quan trọng đối với Chò đãi, Mỡ Ba Vì và Thông Pà Cò, những loài mà khả năng tái sinh không đủ đáp ứng để thay thế cho các cây trưởng thành (Chương 3). So với việc tăng tỷ lệ sống của cá thể, việc làm giàu rừng có tác dụng ít hơn tới tốc độ tăng trưởng của quần thể nhưng việc làm này cũng dễ thực hiện hơn nhiều so với việc làm tăng tỷ lệ sống của các cá thể. Cuối cùng, với các loài có quần thể nhỏ như Bách xanh và Thông Pà Cò (Chương 3 & 4), việc mở rộng khu phân bố của loài thông qua các biện pháp phục hồi tự nhiên sẽ là một biện pháp bảo tồn hiệu quả.

Với một số lưu ý, các kết quả nghiên cứu cho sáu loài có thể áp dụng cho các loài cây bị đe doạ khác với lịch sử phát triển quần thể tương đồng và có sự giống nhau về hiện trạng các quần thể hiện có. Vì động thái quần thể của các loài cây có vòng đời dài có nhiều đặc điểm giống nhau (Chương 3), chúng tôi khuyến nghị một số giải pháp bảo tồn chung cho các loài cây bị đe doạ. Thứ nhất, vì các khu bảo tồn nhỏ, bị chia cắt sẽ tăng nguy cơ tuyệt chủng cho các loài, do vậy cần phải mở rộng các khu này cũng như nghiêm cấm các hoạt động gây chia cắt khu. Thứ hai, cần bảo vệ nghiêm ngặt các cá thể của quần thể, đặc biệt là những cây nhỡ và cây trưởng thành. Do đó, những hoạt động khai thác cũng như các hoạt động mà có ảnh hưởng tiêu cực tới sự phát triển của quần thể phải được nghiêm cấm triệt để. Thứ ba, cải thiện khả năng sinh trưởng của cây con và cây nhỡ của quần thể (ví dụ bằng cách mở rộng không gian sinh dưỡng) cũng góp phần làm tăng tốc độ tăng trưởng của quần thể. Thứ tư, làm giàu rừng cũng là một giải pháp bảo tồn hữu hiệu trong trường hợp mà quá trình hình thành cây con với sự trợ giúp của con người tốt hơn nhiều so với tự nhiên. Thứ năm, với các loài cây có quần thể nhỏ và/hoặc bị chia cắt, việc mở rộng khu phân bố loài thông qua việc phục hồi tự nhiên là một phương án bảo tồn hiệu quả.

Do những loài cây bị đe doạ có vòng đời dài, sự suy giảm của quần thể và thời gian dẫn tới tuyệt chủng của chúng có thể kéo dài. Điều này dẫn tới việc chúng ta có nhiều thời gian để tiến hành các giải pháp bảo tồn cho các loài, nhưng nó cũng có nghĩa là cần có thời gian để các giải pháp bảo tồn phát huy tác dụng. Do vậy, chúng tôi khuyến nghị cần thực hiện các giải pháp bảo tồn hiệu quả trước khi quần thể suy giảm tới mức báo động, và cũng rất quan trọng trong việc giám sát sự biến động về kích thước cũng như khả năng tái sinh của quần thể.

Tài liệu tham khảo

(References in Chapter 6)

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Curriculum vitae

P.D. Chien was born in 1967 in Thai Binh, Vietnam. In 1989, he attended the Forestry University of Vietnam in Xuan Mai, Ha Tay. During this study he specialized in ecology and silviculture. In 1994, he graduated from the university with a Bachelor degree of Science. In the same year, he started working for the Forest Science Institute of Vietnam as a forestry researcher. He carried out several research projects related to ecology and silviculture in Vinh Phuc province and some other areas of the country. In1999, he continued his study at the University of Queensland, where he specially focused on ecology. He obtained his Master degree of Natural Resource Studies at the University of Queensland in 2000. From 2001 onwards, he continued working at the Forest Science Institute of Vietnam and participated in several research projects. One of these was his PhD research project that formed part of the Tropenbos International – Vietnam Programme in cooperation with Utrecht University and the Forest Science Institute of Vietnam. In 2003 he was admitted as a PhD student at the Plant Ecology and Biodiversity Group, Faculty of Science, Utrecht University. He investigated the demography of threatened tree species in Vietnam.