University of Natural Resources and Life Sciences, Vienna

UNIVERSITY OF COPENHAGEN

Regeneration Ecology of *Quercus* species in Gaurishankar Conservation Area, Nepal

Author: Jokin Idoate Lacasia

European Master in Environmental Science – Ecosystems and Biodiversity

University of Copenhagen and University of Natural Resources and Life Sciences, Vienna

Academic supervisors:

Supervisor: Klaus Katzensteiner, Ao.Univ.Prof. Dipl.-Ing. Dr.nat.techn. Institute of Forest Ecology, University of Natural Resources and Life Sciences, Vienna, Austria.

Co-supervisor: Jens-Peter Barnekow Lillesø, Senior researcher. Department of Geosciences and Natural Resource Management, Copenhagen University, Denmark.

Co-supervisor: Georg Gratzer, Ao.Univ.Prof. Dipl.-Ing. Dr.nat.techn. Institute of Forest Ecology, University of Natural Resources and Life Sciences, Vienna, Austria.

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Table of contents

List of Figures

List of Tables

List of Images

List of Maps

List of Equations

List of Acronyms

AIC	Akaike Information Criterion
A	Appendix
A horizon	Mineral horizon
BIC	Bayesian Information Criterion
BU	Bulung VDC
cm	Centimetre
CDM	Clean Development Mechanisms
CF	Community Forest
CFUGs	Community forest user groups
DBH	Diameter at breast height
DF	Degraded forest
°C	Degrees Celsius
DSFG	Dominant Soil Cover Functional Groups
edf	Effective degrees of freedom
OF horizon	Fermented or fibric Organic horizon
FsP	Fixed subplot
FT	Fiste Tunga CF
GAMMs	Generalized Additive Mixed Models
GCA	Gaurishankar Conservation Area
GLMMs	Generalized Linear Mixed Models
GMMs	Generalized Mixed Models
ha	Hectare
HHs	Households
OH horizon	Humic Organic horizon
km	Kilometres
LA	Laduk VDC
LU	Land use
LD	Least degraded forest

OL horizon	Litter Organic horizon
m	Meters
m a.s.l.	Meters above sea level
mm	Millimetres
OR	Orange VDC
OFS	Organic fine substances
O horizon	Organic horizon
PP	Pine plantations
PsP	Pivot subplot
PTM	Potential mother tree
R	Radius
RCD	Root Collar Diameter
$R^2_{Glmm(c)}$	Conditional R^2 values
SD	Sindure Dada CF
SE	Standard error
SP	Sange Pedharo
spp.	Species (plural)
TPD	Tato Pani Dungi CF
TM	Timbu Mahadev CF
TKM	Thado Khola Mahadev CF
VIF	Variance inflation factors
VDCs	Village Development Committees
y	Year

Abstract

Subsistence hill agriculture is widely practise in the mid hill areas of Nepal, which creates a big dependence and pressure on the forests, and on *Quercus semecarpifolia* and *Q. lanata* species in particular. These species have an important provisioning service value due to their capacity of supplying fodder, leaf litter, firewood and timber. They are however being overexploited and moreover, *Q. semecarpifolia* forests are facing an imminent threat due their failure to regenerate. This study aims to provide insight into the ecology of their regeneration, and to assess the condition of selected forests. 42 cluster of plots were established in Gaurishankar Conservation Area (Central Development Region), distributed in different land uses and along different environmental conditions. Each cluster of plots contained 4 subplots ($1m^2$) in which regeneration densities of the studied species, microsite covers, soil characteristics, light availability and distance to the closest potential mother tree were recorded. Furthermore, vegetation surveys were conducted in 20 plots. The least degraded forests of both species had a continuous regeneration, as well as the degraded *Q. lanata* forest. However, regeneration was almost absent in the degraded *Q. semecarpifolia* forest, which had a very dense layer of competing vegetation. Distance to the potential mother tree had a strong negative effect on both species, highlighting a seeds dispersity failure in the study area. Both species favoured thick organic soil horizons. *Q. semecarpifolia* seedlings showed a preference for shadier environments in opposition to *Q. lanata*. Overall, the results corroborate the failure of *Q. semecarpifolia* forests to regenerate under heavy anthropogenic pressure. Furthermore, the high ability of *Q. lanata* to cope with these human-induced disturbances has been confirmed. The results of the microsites variables study were used to develop guidelines for current and future restoration and afforestation projects in the area.

Keywords

Regeneration; *Quercus semecarpifolia; Q. lanata;* Ecology; Light availability; GSF; Hemispherical pictures; Generalized Mixed Models; Microsites; oak forest; seedlings; Nepal

Resumen

La agricultura de subsistencia en laderas es común en las zonas montañosas de Nepal, lo cual crea una gran dependencia y presión sobre los bosques, y sobre las especies *Quercus semecarpifolia* y *Q. lanata* en particular. Dichas especies generan importantes servicios ecosistémicos de abastecimiento debido a su capacidad de suministrar forraje, hojarasca, leña y madera. Sin embargo, están siendo sobreexplotadas y además los bosques de *Q. semecarpifolia* se enfrentan a una amenaza inminente debido a su incapacidad para regenerarse. Este estudio tiene como objetivo proporcionar información sobre la ecología de su regeneración y evaluar el estado de los bosques seleccionados. Se establecieron 42 grupos de parcelas en Gaurishankar Conservation Area (Región Central de Desarrollo), distribuidos en diferentes usos de la tierra y en diferentes condiciones ambientales. Cada grupo de parcelas contenía 4 subparcelas (1 m^2) en las que se registraron las densidades de regeneración de las especies estudiadas, las cubiertas de los diferentes micrositios, las características del suelo, la disponibilidad de luz y la distancia al árbol madre potencial más cercano. Así mismo se realizaron muestreos de vegetación en 20 parcelas. Los bosques menos degradados de ambas especies contaron con una regeneración continua, así como el bosque degradado de *Q. lanata*. Sin embargo, la regeneración estuvo casi ausente en el bosque degradado de *Q. semecarpifolia*, el cual contaba con una capa muy densa de vegetación competidora. La distancia al árbol madre potencial tuvo un fuerte efecto negativo en ambas especies, lo cual muestra que hay un problema en la dispersión de las semillas en el área de estudio. Ambas especies favorecieron suelos con horizontes orgánicos gruesos. Las plántulas de *Q. semecarpifolia* mostraron una preferencia por ambientes más sombríos en contraste con las de *Q. lanat*a. Los resultados corroboran la falta de regeneración en los bosques de *Q. semecarpifolia* sometidos a una fuerte presión antropogénica. Por el contrario, la alta capacidad de *Q. lanata* para hacer frente a estas perturbaciones ha sido confirmada. Los resultados del estudio de las características de los micrositios se han utilizado para desarrollar directrices en proyectos de restauración y reforestación actuales y en proyectos futuros que se desarrollen en el área de estudio.

Palabras clave

Regeneración; *Quercus semecarpifolia; Q. lanata;* Ecología; Disponibilidad de luz; GSF; Imágenes Hemisféricas; Modelos Generalizados Mixtos, Micrositios; Robledal; Plántula; Nepal

Abstrakt

Subsistenzwirtschaft ist weit verbreitet in den mittleren Bergregionen Nepals. Dies schafft eine große Abhängigkeit von und Stress auf die Wälder, insbesondere auf die Arten *Quercus semecarpifolia* und *Q. lanata*. Diese Arten liefern den Menschen Futter, Laub, Brennholz und Holz und haben daher einen großen Wert in der Bereitstellung von Versorgungsleistungen. Der Nutzungsdruck dieser Wälder ist jedoch zu hoch, und außerdem stehen die Wälder *von Q. semecarpifolia* vor einer unmittelbaren Bedrohung, da sie sich nicht regenerieren können. Diese Studie soll Einblicke in die Ökologie ihrer Regeneration geben und den Zustand ausgewählter Wälder bewerten. Im Gaurishankar Conservation Area (Central Development Region) wurden 42 Cluster von Parzellen angelegt mit verschiedenen Landnutzungen und Umweltbedingungen. Jeder Cluster von Parzellen enthielt 4 Teilflächen (1 m^2), in denen die Regenerationsdichten der untersuchten Arten, Microsite-Deckungen, Bodeneigenschaften, Lichtverfügbarkeit und Entfernung zum nächsten potentiellen Mutterbaum aufgezeichnet wurden. Darüber hinaus wurden Vegetationsaufnahmen in 20 Parzellen durchgeführt. Die am wenigsten degradierten Wälder beider Arten hatten eine kontinuierliche Regeneration, ebenso wie der degradierte *Q. lanata* Wald. In dem geschädigten *Q. semecarpifolia*-Wald, der eine sehr dichte Schicht konkurrierender Vegetation aufwies, war die Regeneration jedoch fast nicht vorhanden. Die Entfernung zum potenziellen Mutterbaum hatte einen starken negativen Effekt auf beide Arten, was ein Versagen der Samenverteilung im Untersuchungsgebiet deutlich machte. Beide Arten bevorzugten dicke organische Bodenhorizonte. *Q. semecarpifolia* Sämlinge zeigten gegenüber *Q. lanata* eine Präferenz für schattigere Umgebungen. Insgesamt bestätigen die Ergebnisse die fehlende Regenerierung von *Q. semecarpifolia*-Wäldern unter starkem anthropogenem Druck. Darüber hinaus wurde die hohe Fähigkeit von *Q. lanata* bestätigt, mit diesen vom Menschen verursachten Störungen umzugehen. Die Ergebnisse der Microsites-Variablen-Studie wurden verwendet, um Leitlinien für aktuelle und zukünftige Restaurierungs- und Aufforstungsprojekte in diesem Gebiet zu entwickeln.

Keywords

Regeneration; *Quercus semecarpifolia; Q. lanata;* Ökologie; Lichtverfügbarkeit; GSF; Hemisphärisches Foto; Generalisierte gemischte Modelle; Microsite; Eichenwald; Keimlinge; Nepal

1. Introduction: State of knowledge and research gaps

1.1. Ecology of *Quercus semecarpifolia* and *Q. lanata*

Quercus semecarpifolia Smith. and *Quercus lanata* Smith. (*Q. lanuginosa* D. Don) oak tree species, are members of the *Fagaceae* family. They are highly important for subsistence hill agriculture in the Himalaya region, which is widely practise in the mountainous areas of Nepal. In addition to maintaining and protecting soil fertility, watershed and local biodiversity, they also have an important provisioning service value due to their capacity of supplying fodder, leaf litter, firewood and timber. Unfortunately, the rate at which they are being exploited exceeds any sustainable threshold, making them two of the most overexploited trees in the Himalaya region (Shrestha, 2003; Singh, Rai and Rawat, 2011).

When overharvested trough excessive lopping[1] of the foliage, they lose their crown (see **Image A1** and **Image A2**) and start to resemble a pole in case of *Q. semecarpifolia* (see **Image A3**) or develop a multi-stem shape in case of *Q. lanata* (**Image A4**). For *Q. semecarpifolia* it is assumed that this stops seed production due to the need of allocating resources to produce more foliage and that it is more sensitive towards disturbance intensities than the other species (Shrestha *et al.*, 2004; Rawal, Gairola and Dhar, 2012).

Shresta *et al.*, (2002) have summarized and integrated existing information and literature that attempted to classify the vegetation of Nepal such us the work of Stainton (1972) and Dobremez (1976). It is considered a very instructive classification, and therefore it is the one that has been followed while describing the ecology of the studied species in the following sections. Miehe et al., (2015) has created a more concise vegetation type classification of Nepal using the previously mentioned works, as well as Shresta *et al.*, (2002) and Lillesø *et al.*, (2005) among others. According to this new classification, both species form their own vegetation type. They are classified as *Q. semecarpifolia* forest and *Q. lanata* forest, although pure stands of the second species are rare. These vegetation types provide habitat to a wide number of epiphytes in humid

[1] Understood as the harvesting of branches or parts of branches in a haphazard way, with the main objective of collecting fodder (Geuze and Van Den Ende, 1996)

areas, which in some cases damage the crown and enhance the opening of the canopy, allowing the establishment of light demanding species in the understory and thus transforming it into a diverse and complexly structured forest (Miehe *et al.*, 2015).

The regeneration of oaks is a multifaceted ecological process. It consists in the flowering, fruiting, and the dispersal of the seeds of mature trees, together with the germination of those seeds, seedling establishment and growth (Johnson, Shifley and Rogers, 2002). In the following sections, the known information about the ecology of these oak species (*spp.*) is going to be explained.

1.1.1. *Quercus semecarpifolia*

Distribution

Q. semecarpifolia, also called Kharsu oak is an evergreen, broadleaved tree, widespread along the Himalayan region. It extends from the wettest monsoonal slopes of the south-east Hindu Kush (Afghanistan), to the rain shadowed areas of the Inner Valleys in Bhutan (Miehe *et al.*, 2015) and to south-west China (Polunin and Stainton, 1997). It commonly grows between 2,400 and 3,000 meters above sea level (m a.s.l.), but depending on the amount of rainfall and humidity in the area it can also be found between 1,700 and 3,800 m a.s.l. (Jackson, 1994). Dense *Q. semecarpifolia* forests were recorded up to 3,500 m a.s.l. in Darchula's Chamilaya Valley, Nepal (Elliott, 2012).

Vegetation types in Nepal

In Nepal, it can be found in both the sub-alpine and the temperate zone forming pure forests or being the dominant species in mixed forest. It is very abundant on western Nepal but it occurs sporadically in central and eastern Nepal. The subalpine zone is restricted in the upper limit by the timberline at 4,000 m a.s.l. on average and in the lower limit by the absence of silver fir (*Abies spectabilis*) at an average elevation of 3,000 m a.s.l. It is characterized by frost periods that may last between four to eight months. In this life zone, *Q. semecarpifolia* is found in the Fir-Oak-Rhododendron and Fir-Hemlock-Oak Forests vegetation types, accompanying silver fir on southern aspects. It can also form pure oak stands mainly on southern aspects creating its own vegetation type called Subalpine Mountain Oak Forest.

The temperate zone is located between 3,000 to 2,000 m in elevation. It is very diverse, containing over 40 % of the vegetation types of Nepal. The precipitation distribution varies widely in this zone, ranging from semi-arid in the inner valleys and trans-Himalayan regions to humid conditions on the south of the Himalayan mountain range. On drier southern aspects in western Nepal, *Q. semecarpifolia* is associated with the west Himalayan fir (*Abies pindrow*) forming the West Himalayan Fir-Hemlock-Oak Forest. Also in western dry parts of Nepal it forms a distinctive forest with an abundance of *Rhododendron arboreum* called Mountain Oak-Rhododendron Forest. It also occurs forming pure stands in this zone forming the vegetation type Temperate Mountain Oak forest. Its distribution ends at around 2,500 m a.s.l. being replaced by *Q. lanata* and *Q. incana* (Shresta *et al.*, 2002).

Common accompanying tree species are spruce (*Picea smithiana*), Silver fir (*Abies pindrow*), east Himalayan fir (*A. spectabilis*), Himalayan yew (*Taxus baccata subsp. wallichiana*), blue pine *(Pinus wallichiana*), Himalayan hemlock (*Tsuga dumosa*), *Pyrus spp*, *Prunus padus*, *Acer caesium*, *Juglans regia*, *Rhododendron arboreum* and *Betula alnoides* among others. It forms the climax community and in parts of the Western Himalaya also represents the tree line (Jackson, 1994; Singh, Rai and Rawat, 2011).

Reproduction, seed germination and establishment

It is a monoecious tree, and its flowers are wind pollinated. Approximately 13 months after the pollination the nuts ripen, usually from the end of June till the end of July, but in higher elevation the process can finish in August. The nut falls as soon as it ripens and germinates immediately. It can even start the germination process while it is still on the tree (vivipary), showing a recalcitrant nature (no dormancy) (Troup, 1921). More than 95% of fresh seeds successfully germinate if they are sown immediately after collection (Troup, 1921).

The germination of the acorn coincides with the rainy season or monsoon, which is an unusual behaviour when compared to other tree species of this community that prefer the end of the rainy season for ripening their seeds (between October and January). This unusual behaviour is attributed to the chance of germinating in the absence of predators (Troup, 1921) as well as to germinate in a period in which water is readily available (Singh, 2014). During this season the grasses, other herbaceous plants, and the topsoil cover are increased. The germination is hypogeous, and it includes an abnormal elongation of the cotyledonary petioles, which form a tube that pushes the taproot deep into the soil (see **Figure 1**). The objective is to penetrate successfully into the thick litter horizon (Shrestha, 2006). It invests substantial resources in the growth of the taproot in order to connect the germinating seedling to the soil as soon as possible (Troup, 1921). Nevertheless, thick litter decreases the rate of germination and also, weeds and other herbaceous plants or areas with heavy undergrowth dramatically reduce the ability of the seedling to emerge and survive (Shrestha, 2006; Thakuri, 2010).

Seedlings need fertile soils but they can also grow on poor rocky ridges, although the growth would be poor (Jackson, 1994). Also, they prefer gentle slopes and a soil pH close to 6 (Tashi, 2004). Some studies indicate that *Q. semecarpifolia* seedlings have higher chances of survival in closed canopy, shady areas (Tashi, 2004). Also, other studies highlight the importance of creating canopy gaps in mature forest stands as a requirement for reaching the sapling phase and continue growing, stating that light is a crucial factor for this light demanding species (Troup, 1921; Jackson, 1994; Shrestha, 2003). Based on his results Vetaas (2000) argued that above-ground factors are more important for seedling germination and therefore, survival, than soil variables.

In the Himalayas, the south-facing slopes are warmer and drier in comparison with the cooler north-facing slopes, due to the longer insolation period. The results of a study about the effects of slope aspects on forest compositions, community structures and soil properties in natural temperate forest in the Garhwal Himalaya in India show that the mean soil moisture content as well as the water holding capacity of the soils are lowest on south-west facing slopes and highest on north-east facing slopes (Sharma *et al.*, 2010). The results also show that *Q. semecarpifolia* has highest stem density on south-west aspects but the total basal area cover is higher on north-east facing slopes (Sharma *et al.*, 2010). On the other hand, as shown in another study developed in the same area, density of trees and total basal cover was maximum on north-east and south-east aspects respectively, and minimum in north-west and south-west (Sharma and Baduni, 2000). Generally, *Q. semecarpifolia* grows on all aspects and slope positions, but it is mainly found on southern oriented scarp slopes (Singh, Rai and Rawat, 2011). This slope preference remains an unanswered ecological question. One possible explanation is that it does not withstand heavy anthropogenic pressures and scarps slopes are the only areas where it remains because of their inaccessibility.

Alternatively, *Q. semecarpifolia* might just prefer or have a competitive advantage under those environmental conditions.

Under unfavourable conditions, the above-ground part of the seedling is just a small leafless stem and it produces leaves for the first time during the second season. It is normal that some seedlings die back during the first seasons, and then new shoots are produced. Once favourable conditions are met, shoot growth starts (Troup, 1921). This die back strategy may be an adaptation to the rough conditions in high altitudes and to the strong seasonality of precipitations (Singh, 2014). Furthermore, its seedlings can survive frosts (Jackson, 1994).

Seed production and dispersal

Due to its recalcitrant nature, this species cannot form a long term soil seed bank (Shah, Verma and Tewari, 2015). Therefore, its dispersal ability trough time is more narrow, making it less prepared to cope with future environmental changes when compared to species that are able to produce a soil seed bank (Jackson, 1994; Maarel, 2005). Seeds are dispersed by means of zoochorus, mainly by bears, monkeys, squirrels, mice and birds (Troup, 1921; Vetaas, 2000; Singh, Rai and Rawat, 2011; Shah, Verma and Tewari, 2015).

Masting, which is a reproductive strategy consisting of an intermittent and synchronized production of large seed crops by a plant population (Moreira *et al.*, 2014), happens every 2 to 3 years (Troup, 1921) to 8 to 10 years (Singh, Rai and Rawat, 2011). In masting years, the production of seeds can be up to 10 times higher than in non-masting years and there are around 150 to 200 seeds per kilogram (Jackson, 1994). According to Singh et al. (2011), 2010 was a mast year for *Q. semecarpifolia* in Western Himalaya, which suggests a new mast year could happen in the near future.

Growth

The seedlings grow approximately 5 to 10 cm per year but they can grow faster in nurseries. More than 95% of fresh seeds successfully germinate if they are sown immediately after collection (Troup, 1921). If raised in nurseries, they will need at least two years and an extra-large container due to the rapid taproot development and slow stem growth (Jackson, 1994). Nevertheless, it has been reported that at Solukhumbu (Nepal) seedlings were raised in a nursery and then transplanted, but less than 4% of them survived (Shrestha, 2006). Furthermore, in vitro propagation has been implemented successfully using part of the petiolar tube containing the primary shoot as an explant, but no information has been found about the transplanting success (Tamta *et al.*, 2008).

It is able to reach 25 m and sometimes 30 m in height (Stainton, 1972; Jackson, 1994). Miehe *et al.*, (2015) have also reported a maximum height of 40 m and 1.5 m in Diameter at Breast Height[2] (DBH).

Threats to regeneration

Q. semecarpifolia seedlings are threatened by free grazing domestic livestock (**Image A5**), which can kill up to 75% of the seedlings if the animals stay for 3 months or more (Singh, Rai and Rawat, 2011). Tashi (2004) conducted a study in Bhutan, suggesting that excluding the grazers trough fences increase the survival rate of the seedlings, even if the results were not statistically significant. Nevertheless, its conclusion is consistent with other studies (Troup, 1921; Giri and Katzensteiner, 2013). That study also suggests that seedlings of *Q. semecarpifolia* have higher chances to germinate and survive if they grow protected under a thorny shrub, which may act as nurse plants (Tashi, 2004). At the same time, it may act as strong competitors and thereby, inhibit the growth of the seedlings (Vetaas, 2000).

There is also a growing concern about their failure to regenerate due to excessive lopping (**Image A6**), which force them to allocate resources into producing more foliage, instead of producing seeds (Rawal, Gairola and Dhar, 2012).

[2] Tree diameter at breast height measured at 1.30 m (Maarel, 2005)

FIG. 354. *Quercus semecarpifolia* SEEDLING × ½

a—Acorn b - f— Germination stages g, h Development of seedling during first season

Figure 1: Germination and seedling development of *Q. semecarpifolia*. Troup (1921), figure 354, page 930-931

1.1.2. *Quercus lanata*

Distribution

Q. lanata is also an evergreen broadleaved tree, which forms a multi-storeyed forest. Locally it is known as banjh. It is found mainly in a belt at altitudes ranging from 1,750 to 2,400 m a.s.l., but it can also occur in gullies at elevations as low as 1,200 m. It grows preferably in southern exposed slopes, from Garhwal (India) to Yunnan (South-East China) (Jackson, 1994; Miehe *et al.*, 2015).

Vegetation types in Nepal

In the temperate zone in Nepal it forms the Lower Temperate Oak Forest vegetation type together with other oak species (mainly *Q. incana* and *Q. glauca*). In western Nepal this broadleaved forest is widespread, and its climax formation consists in an association of *Q. lanata* and *Q. incana*, together with *R. arboreum* and *Lyonia ovalifolia*. Nevertheless, *Q. lanata* prefers drier and rocky habitats in comparison with *Q. inacana.* In central Nepal *Q. lanata* is more dominant than the previous one, and in eastern Nepal just *Q. lanata* form forests on southern aspects, even though the before mentioned oak species may also be present as well as *Q. lamellosa* and *Q. oxydon*. When this forest is degraded, *Q. lanata* is also associated with blue pine (*Pinus wallichiana*) forming the Mixed Blue Pine-Oak Forest (Shresta *et al.*, 2002).

In Nepal, the sub-tropical zone lies between 1000 to 2000 m a.s.l. and has warm sub-humid to humid climate. *Q. lanata* is found in the Chir Pine-Broadleaved Forest vegetation type in association with *Pinus roxburghi*, mainly in western Nepal (Shresta *et al.*, 2002).

In general it is commonly associated with evergreen *Rhododendron arboreum, Ilex dipyrena, Symplocos paniculata, Lindera pulcherrima* and deciduous *Rhus wallichii, Lyonia ovalifolia, Carpinus viminea* (Miehe *et al.*, 2015).

Reproduction, seed germination and establishment

It is also a monoecious tree. Flowering and pollination occurs at the end of April and during May and after 8 months at the end of December and till January, the nuts ripen. Under natural conditions, the nut will remain on the soil during the dry season and germinate when the conditions are favourable, usually during the rainy or monsoon season (Troup, 1921). This dormancy allows the seed to avoid germination during unfavourable conditions (Singh, 2014). About 80 % of the fresh seeds germinate (Jackson, 1994).

The germination is hypogeous, and the radicle also descends rapidly to form a taproot. The fleshy cotyledons remain with the seedlings for some time, supplying it with nutrients (see **Figure 2**) (Troup, 1921).

It is a light demanding species, but it can also tolerate some shade as well as frost periods. It is mainly found on dry south-facing slopes, but it reaches a greater height on wetter areas (Jackson, 1994).

Seed production and dispersal

The seeds are also dispersed by means of zoochory (Troup, 1921). Presumably the same wildlife described for the other species dispersed them, but it is believed that smaller animals such us birds, squirrels and mice are the primary dispersers due to the smaller size of the seeds. There are 1,800 seeds per kilogram (Jackson, 1994).

Growth

The seedling grows slowly, but at the end of the first season it can be between 5 and 12 cm in height. It can be successfully cultivated in a nursery and then transplanted, provided the roots are not excessively exposed during the process. A height growth of 50 cm in 4 years was recorded but older trees may grow faster. Direct sowing is also a successful method of artificial reproduction (Troup, 1921).

It can reach 15 to 25 m in height and between 0.6 and 0.8 m in DBH (Tang, no date). Troup (1921) reported the measurement of an individual with a DBH of 1 m and a height of 21 m.

Threats to regeneration

The seeds are prone to be attacked by insects (Jackson, 1994) as well as to suffer a severe predation pressure because of their waiting time on the ground until favourable conditions are met (Singh, 2014).

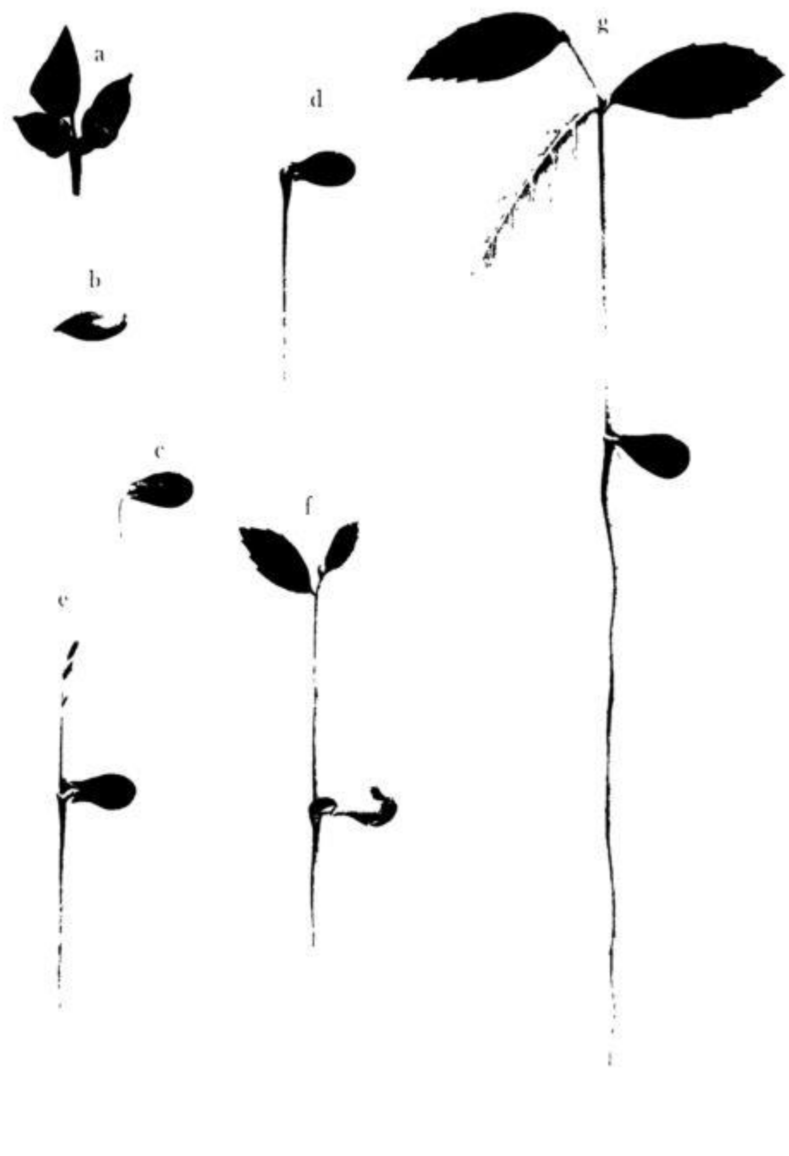


FIG. 356. *Quercus lanuginosa*—SEEDLING ×

a—Acorns b Nut of acorn c - e Germination stages f, g—Development of seedling during first season

Figure 2: Germination and seedling development of *Q. lanata*. Troup (1921), figure 365, page 934-935

1.2. Threats

There is an increasing concern about the failure to regenerate of *Q. semecarpifolia*, and several ecological regeneration studies have already taken place (Vetaas, 2000; Shrestha *et al.*, 2004; Tashi, 2004; Thakuri, 2010; Bisht, Prakash and Nautiyal, 2012; Bisht *et al.*, 2013; Shah, Verma and Tewari, 2015) which fundamentally indicate that it cannot regenerate when subjected to heavy anthropogenic pressure, mainly lopping and grazing. If we consider its economical, ecological and social importance, the state of knowledge on the regeneration of the species is still not sufficient (Måren and Vetaas, 2007). On the other hand, there is an even bigger lack of knowledge regarding the regeneration of *Q. lanata* (Wangda and Ohsawa, 2006).

Overall, *Q. semecarpifolia* and *Q. lanata* forest types are facing an imminent threat due to the ever-increasing human pressure, their failure to regenerate and the climate change related alterations of climatic patterns, such as changes in the monsoon. A change in the timing of the monsoon would impact severely *Q. semecarpifolia* due to the synchronization between the monsoon and the germination of its seeds (Singh, 2014). Increasing temperature is shifting vegetation zones towards higher altitudinal areas, thereby exposing species to harsher conditions such as steeper, more erosive slopes, less fertile soils and pronounced climate fluctuations. These may pose a serious threat to their long-term survival (Shah, Verma and Tewari, 2015). Correspondingly, vegetation types from lower altitudes are encroaching into higher altitudinal areas, and could replace the original forest. The potential habitat of *Q. semecarpifolia* is predicted to shrink 40 % and 76 % with 1°C and 2°C increase in temperature, respectively (Saran *et al.*, 2010). Furthermore, rangelands are becoming more degraded and dry, increasing the dependence on *Quercus spp.* as fodder for cattle (NARMA and Practical Solution Consultancy, 2013). Both forest types are assessed as vulnerable by Miehe *et al.* (2015).

1.3. Research objectives and hypothesis

We can conclude that, even though a growing number of studies about the regeneration ecology of *Q. semecarpifolia* have been conducted, further research is needed to cope with its actual and future threats; especially considering its wide distribution range, the provided ecosystem services, the dependence of local communities on it, and the failure to regenerate under its own canopy when the forests are exploited. As for the *Q. lanata* species, the lack of available data about its regeneration status and regeneration ecology shows the urgent need for research, in order to better understand the actual situation of the species and also for being able to manage it in an optimal and sustainable way.

This thesis focuses on a carbon offsetting project being implemented in the study area (see section **2.1**), called “Carbon offsetting as an opportunity for sustainable rural development in Nepal - a participatory, community based approach”. It is implemented by a consortium of researches from Austrian and Nepalese universities (CDR & IFE - BOKU 2015).

The aim of the present thesis is to increase the knowledge about the regeneration ecology of the studied species, as well as to develop improved guidelines for the above-mentioned carbon offsetting project. The intention is to define where to find seeds, when to collect them and under which conditions they need to be planted in the study area.

Data collection, processing and analysis was conducted with the aim of testing the following hypotheses:

1. There is a lack of regeneration in disturbed *Quercus* forests.

2. The presence and density of seedlings of the two studied *Quercus* species depends on microsite conditions (e.g. light availability, thickness of the organic horizon, microsite cover), and distance to the nearest potential seed-producing tree.

3. There is a relationship between the regeneration success, the different land uses and the degree of human-induced disturbance.

It is predicted that the distribution of DBH size classes in the least degraded forest will follow a reversed J-shape showing that there is continuous regeneration. On the other hand, a bell shaped size class distribution is predicted in the degraded forest showing a lack of regeneration (Vetaas, 2000).

2. Methods

2.1. Study area

2.1.1. Country background information

Nepal is a landlocked country centrally located in the Himalaya. It occupies an area of 147,181 km^2 which represents 0.1% of the world's land area, and despite its small size it hosts 2.2% of the world's natural flowering plants (Shresta *et al.*, 2002). The altitude ranges from 70 m a.s.l. in Kanchan Kalan to 8,850 m a.s.l. at the top of Mount Everest (International Business Publications, 2012) along a short north-south axis, which is the greatest range of any country (Bhattacharjee *et al.*, 2017). This elevation gradient creates remarkable environmental heterogeneity which increases species richness and beta diversity (Sanders and Rahbek, 2012). The different habitats that are present in Nepal are found as narrow bands located to a certain extent parallel to the southern border (Bhattacharjee *et al.*, 2017). It is also considered a biodiversity hotspot because it acts as a junction between the Oriental biota in the lowland south with the Palearctic biota in the montane north (Olson and Dinerstein, 2002). Nepal has a great deal of variation in climate, ranging from cold and dry continental and alpine winter climate to warm and humid tropical summer (Lillesø *et al.*, 2005).

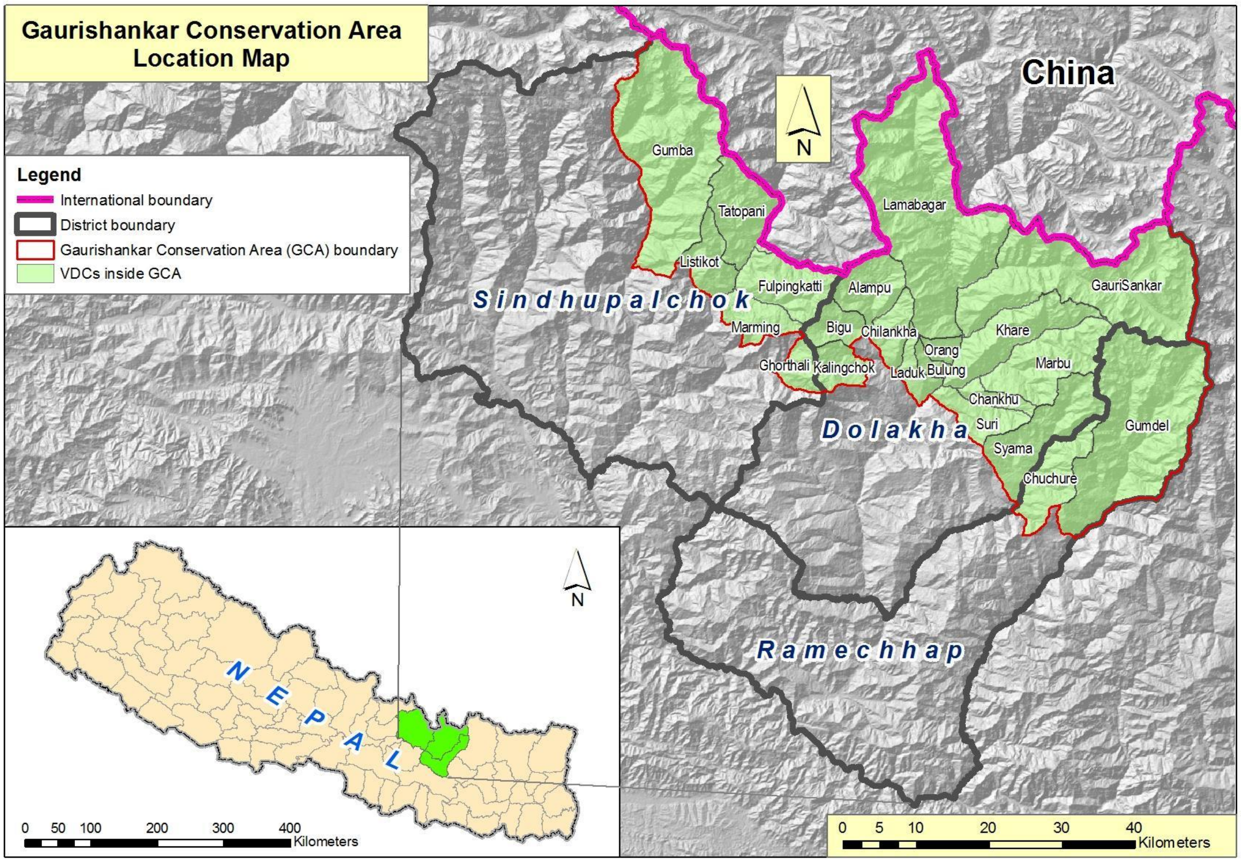
The precipitation in Nepal depends widely on the orography of the country and on the monsoon phenomenon, which is when the higher amount of the precipitation occurs (80% in average). Four seasons can be identified namely, winter (December to February), pre-monsoon (March to May), monsoon (June to August), and post-monsoon (September to November). During the monsoon, air masses advance from east to west across Nepal and generally annual rainfall decreases along this direction. The annual average precipitation in the country ranges between 1,000 to 2,000 mm/y, but in some areas of Eastern Nepal it can be up to 5,000 mm/y (Ichiyanagi *et al.*, 2007). There are three high rainfall pockets in the country. One it is located in the North of Pokhara valley receiving 5000 mm/y. Another one is located northeast of Kathmandu, in the south of Langtang Himalayan range, which coincides with the study area and receives more than 3500 mm/y. The last area that receives more than 3500 mm/y is found east of Mount Everest, in the Num area. There are also areas with very low annual precipitation values, such us Mustang, Manang, and Dolpa regions located on the north of the Annapurna range, which receive less than 200 mm/y. High altitude regions also receive low precipitations. (Karki *et al.*, 2016). There are large rain shadow areas are located in the north of the Himalayan mountain range (Singh, 2014).

There are 29.3 million (by 2017) citizens of Nepal, and 82.4% of them live in rural areas (UN, 2017). Agriculture is the most important economic activity, accounting for one third of the total GDP and employing 80% of the active population. At least one third of the working male population have migrated to other countries from where they send remittances. They are an important source of income, being received by about 56% of the households (IFAD, 2013)

Subsistence hill agriculture is widely practise in the mountainous parts of the country, which suffer from permanent poverty and a lack of access to the market. This creates a big dependence and therefore an intense pressure on the forests of Nepal in general, and on *Q. semecarpifolia* and *Q. lanata* forest in particular (Shrestha, 2006; Singh, Rai and Rawat, 2011).

2.1.2. Gaurishankar Conservation Area (GCA)

It is a newly designated protected area created in January 2010 and located in the northern part of the Central Development Region (CDR) in Nepal Himalayan mountains, 85°46.8’ and 86°34.8’ East longitude and 27°34.2’ and 28°10’ North Latitude (Thapa, Thapa and Poudel, 2014). It occupies an area of 2,179 km^2 and 3 districts, covering 22 Village Development Committees (VDCs). 6 VDCs from Sindhupalchok district, 14 VDCs from Dolakha and 2 VDCs from Ramechhap. It borders Langtang National Park to the west and Sagarmatha National Park to the east, acting as an ecological corridor between those protected areas, some of the most important in the country. To the north, it borders the Tibetan Autonomous Region of the People’s Republic of China (see **Map 1**). Around 66,000 people, consisting of 13,458 households (HHs) with an average HH size of 4.8 live inside GCA (NARMA and Practical Solution Consultancyt, 2013; Thapa, Thapa and Poudel, 2014; Awasthi and Singh, 2015).



Map 1: Location of Gaurishankar Conservation Area and VDCs that compose it (National Trust for Nature Conservation, 2010)

The climate ranges from sub-tropical to artic and the altitude from less than 1,000 to over 8,000 m a.s.l. With every increment of 1,000 m in elevation, the temperature decreases by 6°C. The higher temperatures occur between May to July. The permanent snow line is situated at around 5,300 m a.s.l. There are 6 bioclimatic zones in GCA, specifically tropical, sub-tropical, temperate, sub-alpine, alpine, and nival zones and they are found roughly untill 500 m, 2000 m; 3000 m; 4000 m; 5000 m; and above 5000 m in elevation respectively. The summer monsoon rain occurs from June to September. It is the main source of precipitation, followed by snow fall during the winter in the upper sub-alpine zone. Precipitation is very unequally distributed in the area, being dominated by the aspect, altitude and the presence of rain shadow effect (NARMA and Practical Solution Consultancy, 2013).

Forests, together with shrubs, cover 46 % of the area (96,838 ha). 30 % are managed by the communities (23,000 ha) and the rest by the government. There are 83 community forest user groups (CFUGs), and on average, 1.62 ha of forest land per HHs (NARMA and Practical Solution Consultancy, 2013).

A biodiversity assessment was carried out in 2011 and 695 plant species were recorded, with the highest richness found at 3,400 m a.s.l. The flagship animals of GCA are the Snow leopard (*Panthera uncia*), red panda (*Ailurus fulgens*) and ibisbill (*Ibidorhyncha struthersii*) (NARMA and Practical Solution Consultancy, 2013; Thapa, Thapa and Poudel, 2014).

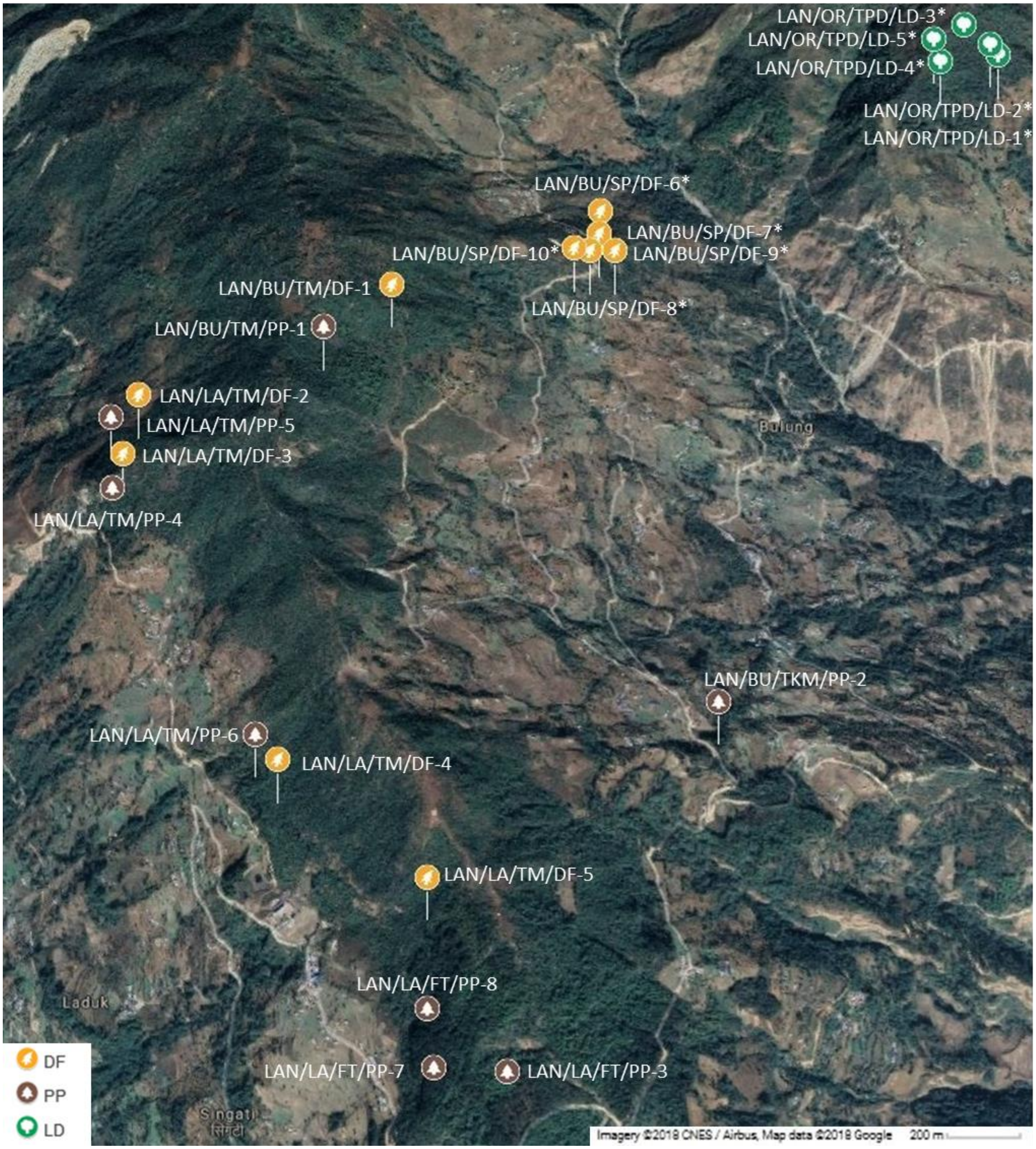
The major economic activity is agriculture, which consists of a mixed farming system of animal husbandry and crop production. Animal husbandry is widely practice by highland dwellers and is one of the main drivers of the degradation of the *Quercus* stands. The trees are mainly lopped to feed yaks, chauris (crossbred of yak and domestic cow), sheep and goats. Tourism is very limited despite the huge potential of the area, being performed by 1.5% of the HHs. Almost a third of the HHs have at least one family member living outside the area and there is a big dependency on their remittances (NARMA and Practical Solution Consultancy, 2013). The area was heavily affected by two large earthquakes in 2015 of magnitude 7.8 and 7.3 respectively, as well as by the quake-triggered landslides (EGU, 2015). The material losses have led to an increment on the use and reliance on forest resources.

2.2. Sampling design

Fieldwork was conducted between April and June 2017 in the Gaurishankar Conservation Area (GCA). It consisted of two parts: vegetation surveys and a study to find out which microsite conditions are favoured by the seedlings of both tree species.

Clusters of plots (see **Figure 3** and **Figure 4**) were distributed in Laduk, Bulung and Orang VDCs, across three different land uses: least degraded forest (LD), degraded forest (DF) and pine plantations (PP) (see **Map 2** for the location of *Q. semecarpifolia* plots and **Map 3** for *Q. lanata* plots and **Table A17** for their coordinates). They were situated in the following community forests: Thado Khola Mahadev (TKM), Timbu Mahadev (TM), Fiste Tunga (FT), Sange Pedharo (SP), Sindure Dada (SD) and Tato Pani Dungi (TPD).

Map 2*:*Location of Q. semecarpifolia plots in Laduk and Bulung VDCs, GCA, Nepal (Google Maps, 2018). *Asterisk* represents the plots where the vegetation surveys were conducted.



Map 3: Location of Q. lanata plots in Laduk, Bulung and Orange VDCs, GCA, Nepal (Google Maps, 2018). * represents the plots where the vegetation surveys were conducted

First of all, forests without human-induced disturbances, containing one of the studied *Quercus spp.* were tried to be located in Bulung and Laduk VDCs. Due to the impossibility of finding forests that were not subject to human pressure, the criteria of forest with absence of disturbance was relaxed and changed to forests with at least 75% of the trees with absence of recent human-induced disturbances signs. One forest was found in Bulung VDC, located in an area difficult to access due to the distance to the nearest settlement and the steep slope. It was dominated by *Q. semecarpifolia* and the majority of the trees lacked signs of recent human-induced disturbances. No *Q. lanata* forest with a small amount of disturbance was found in Laduk and Bulung VDCs, but one was found in the nearby Orang VDC. These two forests were the ones considered as least degraded forests (LD) for the newly designated land uses categories.

The community forests located in Bulung and Laduk VDCs that had signs of being regularly exploited and in which at least one of the studied *Quercus spp.* were found, were considered as degraded forest (DF) for the established land uses categories.

Since the 1980s, large-scale plantations were established in the hilly regions of Nepal in order to recover degraded land, reduce soil erosion and improve the livelihoods of local communities. Since then, more than 370,000 ha have been planted, mainly with *Pinus spp.* (Dangal and Das, 2015). In Dolakha district, the Nepal Swiss Community Forest Project (NSCFP), which was a Swiss Development Cooperation project between 1990 to 2011, helped to plant over 3,900 ha of government land mainly with *Pinus spp.* (Niraula, Maharjan and Pokharel, 2011). Also, the local communities have been planting pines, which has resulted in an abundant of pine forests in the study area (Niraula *et al.*, 2013). These plantations, which in Laduk and Bulung are dominated by the Mexican weeping pine (*Pinus patula*) and the native *Pinus wallichiana*, were the ones considered as pine plantations (PP) for the established land uses categories.

Bradley (2018, unpublished) conducted fieldwork in the same area in 2016 in order to measure carbon content in different land uses categories. During that fieldwork, fixed radius sample plots with 1x1 m soil pits in the centre were randomly distributed across different studied land uses. For the present study, Bradley's soil pits were used as the centres for plot clusters in the case of PP and DF. In these plot clusters, only microsite conditions were recorded. The plot clusters were based on the sampling design created by Pröll *et al.*, (2015), and consisted of two main 5m-radius plots (see **Figure 3**), uphill and downhill from the centre of the cluster. Each contained two 1x1 m subplots. One fixed subplot (FsP) located 5 m uphill and downhill from the centre of the plot clusters, and one pivot subplot (PsP) that was deployed according to 5 different scenarios (see **Figure 5**) depending on presence or absence of regeneration on the FsP and on the 5m-radius plots (Pröll *et al.*, 2015).

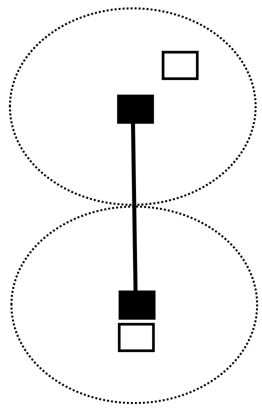


Figure 3: Sampling design using Bradley's (2018) plots as centre on DF and PP. Cluster of 2 5m-radius plots, uphill and downhill from the plot centre, each containing 2 fixed (dark) and pivot (white) subplots. Modification of Pröll et al. (2015)

In the case of LD forest with a low level of human-induced disturbances, which were not part of Bradley's study, just one forest per study species was found. In those two forests, 5 *new* clusters of plots were deployed respectively. Also, for each study species, 5 *new* clusters of plots were deployed in DF in order to increase the sample size.

In these newly deployed clusters of plots (10 per species) a vegetation survey as well as an investigation of microsite conditions was carried out. The location of the centre of these newly established clusters of plots was selected by conducting a positive search for Potential Mother Trees (PMT) along different altitudes and taking into account the accessibility of the areas. A PMT was considered as the least disturbed mature *Quercus* tree in the area, in the case of *Q. lanata* also with presence of flowers.

From the PMT acting as the centre, a vegetation survey was performed in a radius of 2.5m and 5m (see next section **2.3**). Microsite conditions were recorded at the 1x1 m subplot level. In order to establish the FsP, a positive search for regeneration was performed along falling lines (FL) and contour lines (CL). The direction of the CL was determined according to the accessibility of both sides, as well as to a visual estimation of which side was more promising of containing regeneration. Their length was determined by the height of the PMT. If height was between 5 to 10 m, then the FL and CL were 10 m long; if height was between 10 to 15 m, the FL and CL were 15 m long (and so on). Once the length of the lines was calculated, a 1m wide corridor along the line was checked for *Quercus* seedlings. If no regeneration was found along the line, the FsP was deployed in the middle of the line. If regeneration was found along the line, then the FsP was deployed around the regeneration closest to the PMT (see **Figure 4**). The PsP were deployed following the protocol described in **Figure 5**.

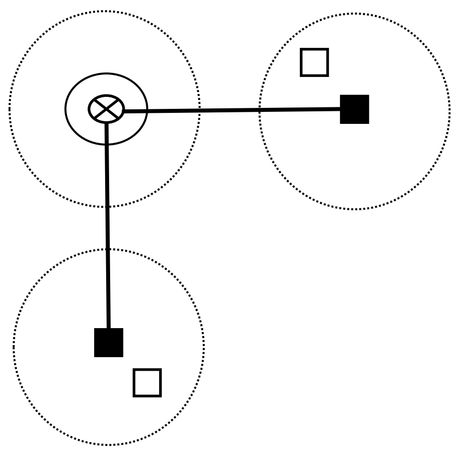


Figure 4: Sampling design of the newly deployed cluster of plots using PMTs as the centre on LD and DF. The PMT is designated by the x, the small solid circle represents the 2.5m-radius and the bigger dashed circle the 5m-radius. The horizontal line represents the CL and the vertical one the FL. The dark and white squares represent the fixed and pivot subplots respectively. Modification of Pröll et al. (2015).

Summing up, the FsP were deployed 5 m down and uphill from the centre of the cluster in the scenario were the plots of Bradley's fieldwork were used, and along the FL and CL in the newly established plots. Finally, the PsP were deployed according to 5 different scenarios (see **Figure 5**) depending on presence or absence of regeneration (Pröll *et al.*, 2015).

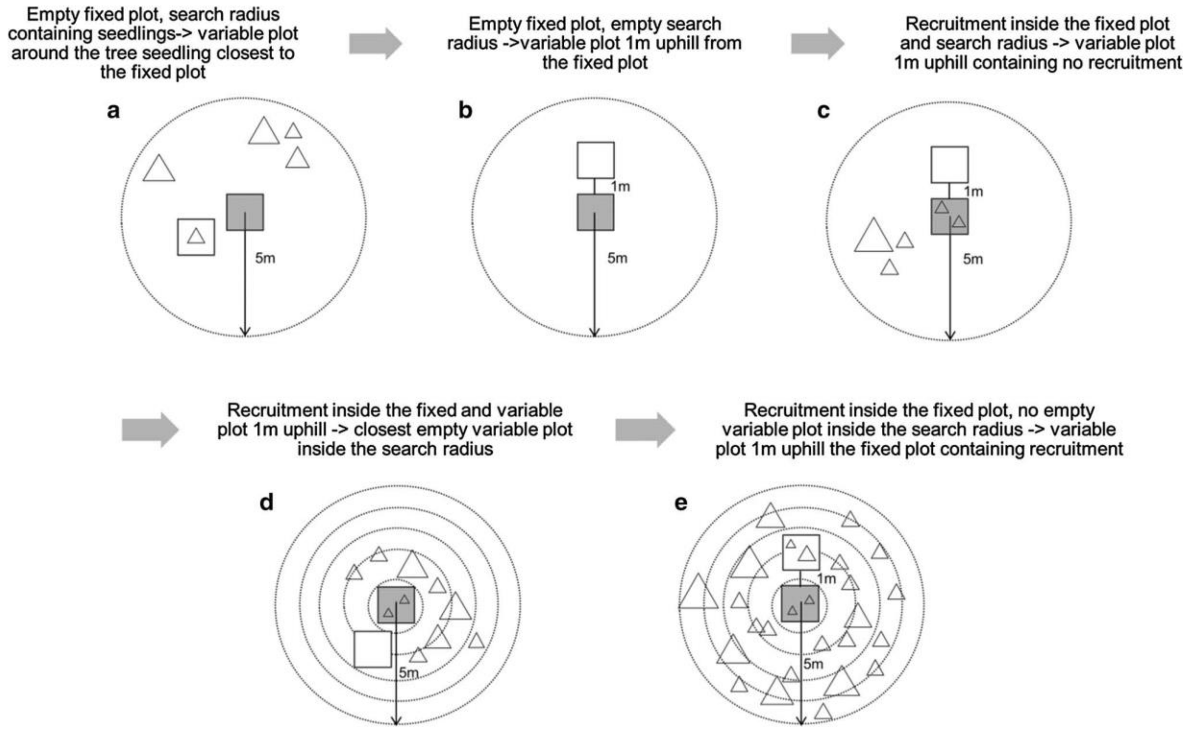


Figure 5*:* 5 different possible scenarios for the deployment of the pivot subplot (Pröll *et al.*, 2015)

In total, 19 (for *Q. semecarpifolia*) and 23 (for *Q. lanata*) plot clusters were created, which consisted of 76 and 92 subplots respectively (see **Map 2** and **Map 3**, as well **Table A17** for their exact location). 10 clusters per species (40 subplots) were newly established using a PMT as the centre, and the rest were established using the plots of a previously conducted fieldwork (Bradley, 2018).

2.3. Vegetation survey

With the objective of analysing the structure and status of the forest, a combination of fixed radii were used, as described in **Figure 6** (Eckmüllner and Hasenauer, 2011). For each species, 5 plots were deployed in LD and another 5 in DF. Fixed 2.5m-radius and 5m-radius used the PMT as the centre for the surveyed.

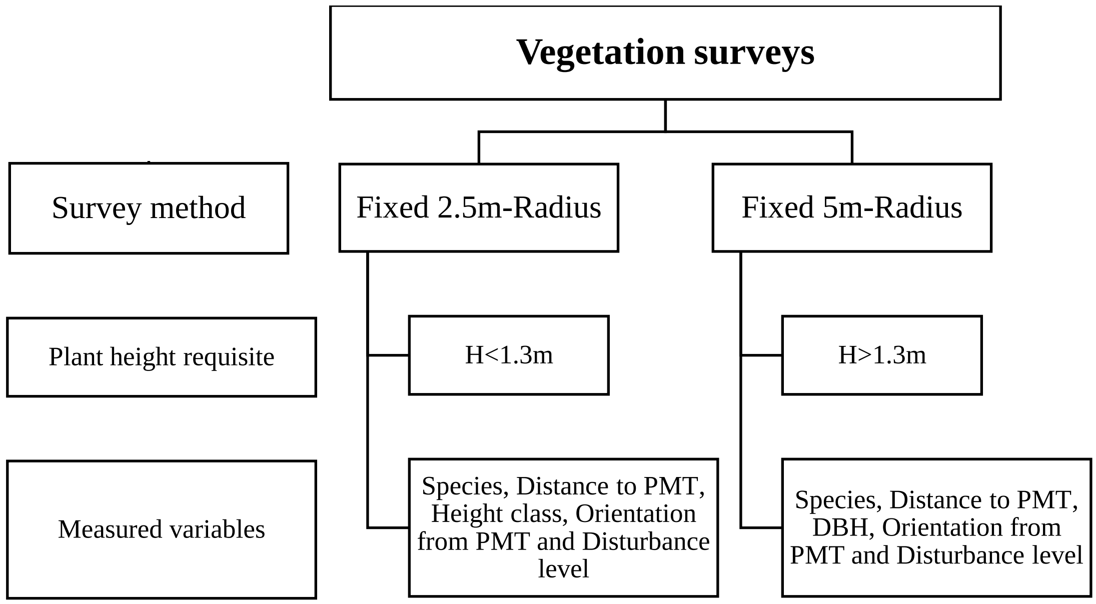


Figure 6*:* Flowchart of the methodology used for the vegetation surveys. 5 plots in LD and 5 plots in DF were surveyed for each Quercus spp.

A fixed radius of 5 m was used for the survey of tree species higher than 1.3 m. The species, DBH, distance to the PMT, orientation from the PMT, and disturbance level of each individual tree were recorded. DBH size classes were created to facilitate the interpretation of the results (see **Table 1**). These results were used to better understand the current structure of the forest community.

Furthermore, a radius of 2.5 m was used for analysing the vegetation smaller than 1.3 m, and species, distance to the PMT, height class (see **Table 2**), orientation from the PMT and disturbance level of each individual plant were recorded. The primary objective was to study the regeneration and understory composition and density of the selected forests.

The distance to the PMT, the height of the plants smaller than 1.3 m (fixed 2.5m-R), and the DBH of the plants higher than 1.3 m (fixed 5m-R) were recorded using a measuring tape. The height of the PMT was recorded using a Vertex IV and Transponder T3 (Haglöf Sweden AB, 2007). The orientation of the recorded individuals from the PMT was measured using a field compass.

Table 1: DBH classes for plant species higher than 1.3m

DBH classes	
1	<10cm
2	10-30cm
3	31-50cm
4	51-70cm
5	71-90cm
6	>90cm

Table 2*:* Height classes for plant species smaller than 1.3m based on Pröll *et al.*, (2015)

Height classes	
0	<10cm
1a	10-30cm
1b	31-60cm
1c	61-90cm
1d	91-130cm

The disturbance level of the recorded individuals was visually estimated and categorized from 0 (absence of disturbance) to 3 (highly disturbed). The created categories for the plants higher and smaller than 1.3 m can be found on **Table A6** and **Table A7** respectively. The considered human-induced disturbance for plants higher than 1.3 m was the degree of lopping of the branches, and for plants smaller than 1.3 m were evidences and degree of trampling and grazing.

The species were identified thanks to the invaluable knowledge of the local research assistants, and the vegetation field guides of Polunin and Stainton (1997) and Fraser-Jenkins, Kandel and Pariyar (2015). As the main aim of the vegetation surveys was to assess the status of the different forests, and to analysis potential competition or facilitation situations for *Quercus* regeneration, the recorded species were clustered into functional groups (see **Table 3**). At least three different species of ferns were recorded, belonging to the genus Microlepia, Drynaria and Polystichum respectively, but the exact species were not identified. Because the three detected genera belong to three different families (Dennstaedtiaceae, Polypodiaceae and Dryopteridaceae respectively), they were clustered together according to their taxonomical order as Polypodiales (Walker *et al.*, 2016). Bamboo was just found in one plot in the LD *Q. semecarpifalia* forest, it was identified to its genus level (Drepanostachyum sp.) and a functional group was created for it.

The functional groups were created based on Tashi, (2004), Pandey (2017) unpublished work and on their traits extracted from Polunin and Stainton (1997). The created categories were: Invasive grasses, Herbaceous species, Shrubs, *Quercus* species, *Rhododendron* species, Pioneers, Framework species, Conifers, Bamboo and *Ilex* species.

Table 3: Plants functional groups. Red background represents spp. that were just found on *Q. semecarpifolia* forest, blue just on *Q. lanata* forest and green represents spp. found on both forests

Functional Groups	Species	
Invasive grass	*Ageratina adenophora*	green
	Gnaphalium polycaulon	blue
Herbaceous	*Piper sylvaticum*	blue
	Vigna unguiculata	blue
	Arisaema tortuosum	red
Shrub	*Gaultheria fragantissima*	green
	Berberis asiatica	green
	Polypodiales	green
	Lyonia ovalifolia	green
	Rhus javanica	blue
	Dichroa febrifuga	blue
	Eurya acuminata	red
	Pyrus pashia	red
	Viburnum nervosum	red
	Myrsine semiserrata	red
	Daphne bholua	red
	Pieris formosa	red
Q. Lanata	*Quercus lanata*	blue
Q. Semecarpifolia	*Quercus semecarpifolia*	green
Rhododendron	*Rhododendron arboreum*	green
	Rhododendron cinnabarinum	red
Pioneer	*Schima wallichi*	blue
	Betula alnoides	blue
	Rhus wallichii	blue
	Acer oblongum	red
Framework spp.	*Ficus neriifolia*	blue
	Docynia indica	blue
	Myrica esculenta	blue
	Phyllanthus emblica	blue
	Prunus cerasoides	blue
	Symplocos pyrifolia	red
Bamboo	*Drepanostachyum sp.*	red
Conifer	*Abies spectabilis*	red
Ilex	*Ilex dipyrena*	red

13 spp. (red)	*Q. Semecarpifolia* forest
14 spp. (blue)	*Q. Lanata* forest
7 spp. (green)	Present on both forest

The indigenous forest species that produce resources that attract seed-dispersing wildlife at an early life-stage were considered as framework species (Elliott *et al.*, 2003)

2.4. Microsite variables

With the objective of describing the conditions in which the seedlings of the studied species germinate and grow, clusters of plots were distributed across the three main studied land uses (PP, DF and LD), based on Pröll *et al.*, (2015) design. As explained (Section **2.2**), each cluster of plots contains two plots of 5m-radius. Each plot contains a fixed subplot (FsP) and a pivot subplot (PvP) of 1x1 m respectively.

At the plot cluster level, the following site variables were recorded: location (coordinates), elevation, aspect, terrain position, slope form and slope pathways, rock content, slope gradient and disturbance level (see **Figure 7**). The coordinates and elevation were recorded using the Thuraya XT-LITE satellite phone (Thuraya Telecommunications Company, 2017). The aspect the slope was facing was recorded using a field compass. The terrain position, rock content and slope form and slope pathways were recorded using the categories and explanations of Barham *et al.*, (2006). The slope gradient was measured using the Vertex IV and Transponder T3 (Haglöf Sweden AB, 2007). Finally, the disturbance level of the site was visually estimated and categorized into four main groups, ranging from 0- least disturbed, to 3- highly disturbed. The created categories can be seen in the **Table A8**.

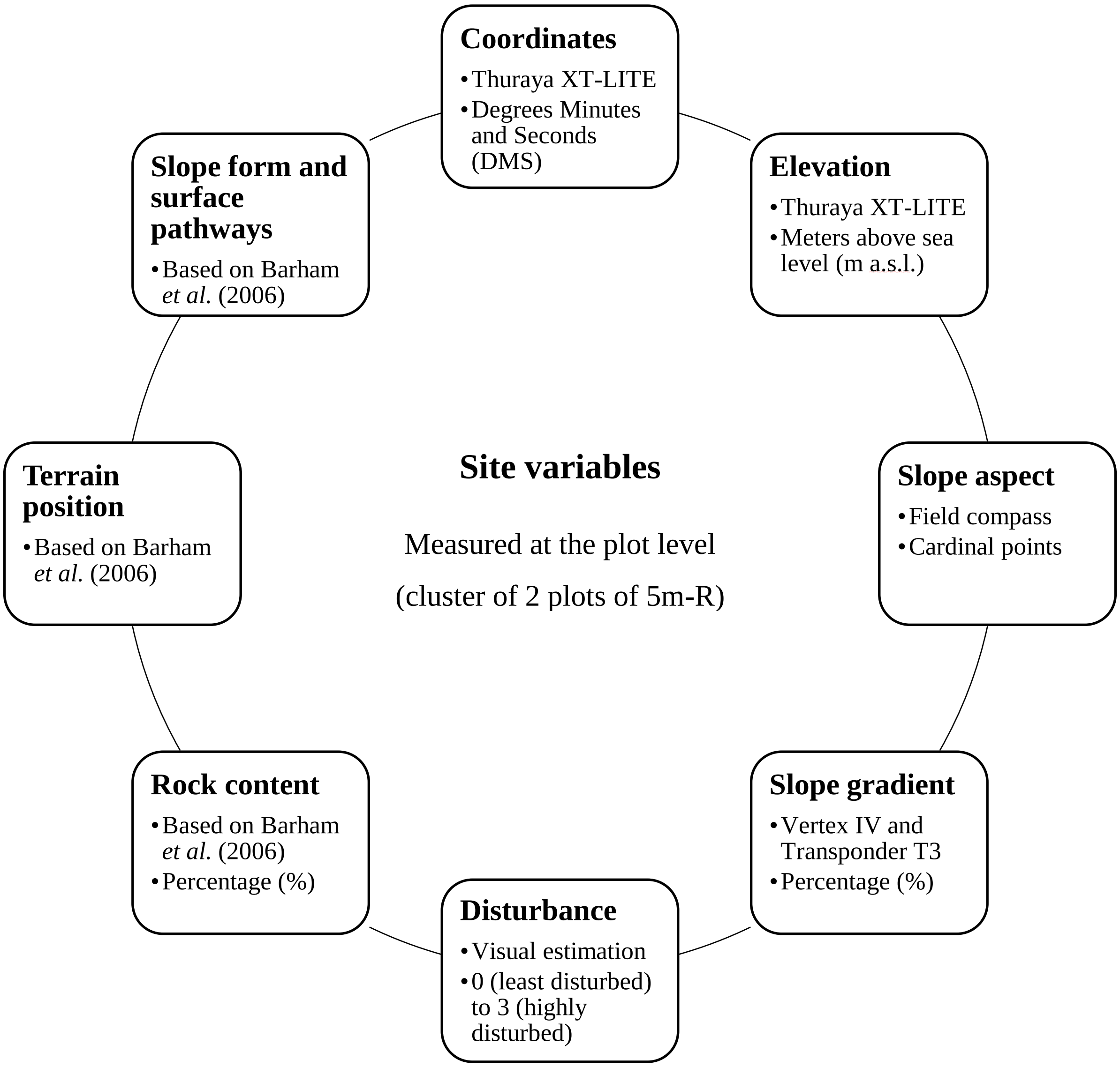


Figure 7: Variables measured at the plot level, as well as the instruments and units used

At the subplot level (see **Image A8**), first presence or absence of *Quercus* regeneration was assessed. In the subplots were regeneration was found, the regeneration density in individuals per square meter (indv/m²) was measured, as well as the percentage of canopy cover. Furthermore, height and root collar diameter (RCD) of the highest *Quercus* seedlings was recorded. The subplots were 1 m² in area, therefore the regeneration density (indv/m²) already indicated the number of individuals located on the subplot. The percentage of canopy cover was measured using a forest densiometer (E. Lemmon, 2008), locating it right above of the highest seedling. Height was measured in centimetres using a folder ruler. RCD was measured in cm as well, using a digital calliper (see **Figure 8**).

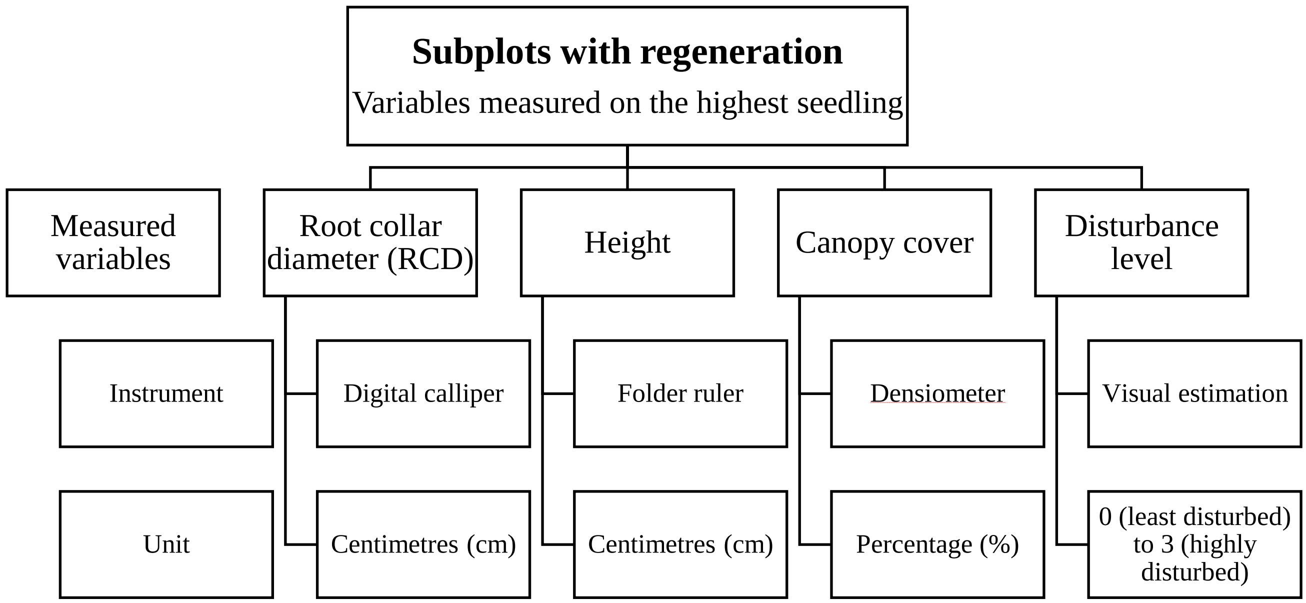


Figure 8*:* Variables measured at subplots where *Quercus* regeneration was found, with instruments and units used

The selected microsite variables were measured on all the established subplots, with presence and absence of regeneration. First of all, Hemispherical images (see **Image A10**) were taken with a fisheye lens camera, a self-levelling mount and a tripod (see **Image A9**). The camera was always located in the middle of the plot, at a height of 1.2 m, and oriented to the magnetic north. It was also levelled to face the vertical with a bubble-level slotted into the self-levelling mount (Beckschäfer *et al.*, 2013). For achieving an even sky condition in all the photographs and avoiding reflections, they were taken during the early morning and late evening, or during overcast sky conditions (Gratzer *et al.*, 2004). Two variables determined the contrast on a picture, the aperture (F) and the shutter speed. The aperture was always fixed (F=5.6) and the shutter speed was determined firstly, taking a picture using the automatic mode of the camera, in order to get the recommended shutter speed. Then, the camera mode was changed to manual and a series of five different photographs was taken on each subplot, reducing constantly the shutter speed, starting with the recommended value obtained on the automatic mode. The final purpose of this was to get a Global Site Factor[3] (GSF). The process followed for calculating it is explained in the next section **2.5.3**.

The occupancy in percentage of each microsite cover was recorded in each subplot. The designated microsites, transformed from Dhendup (2013) were: Herbaceous vegetation, shrubs, boulders, deadwood, moss and lichens, mineral soil, and leaves. Also, the competing vegetation was measured recording the number of individuals of each species, as well as the height of the highest individual of each species. The distance to the closest PMT of each subplot was measured using the diameter tape, if PMTs were present near the study area. In the situation were the PMT was too far away (e.g. some *Q. semecarpifolia* plots in PP), the distance was measured from the subplot to the nearest forest or area were *Quercus* was known to be found using the recorded coordinates and the measuring distance tool from Google Maps (2017).

Furthermore, soil pits of 30 cm were excavated with the help of a shovel and a pick in each subplot. Two main diagnostic horizons were studied, the organic (O) horizon and the organo-mineral (A) horizon. The O horizon is divided into three different horizons according to the rate of recognizable remains and humic components. The first recognisable was the litter (OL) horizon, composed of at least 90% litter with distinguishable origin and less than 10% of volume occupied by humic components. Then follows the fermented or fibric (OF) horizon which contains between 10% to 70% by volume of humic components. The last one is the humic (OH) horizon containing more than 70% of humic components by volume (Zanella *et al.*, 2011). They were studied together and therefore they were clumped in the organic (O) horizon. The last horizon that was recognized was the A horizon, which showed humified organic matter (less than 20 % of organic carbon by mass) mixed with mineral fraction (Barham *et al.*, 2006; Zanella *et al.*, 2011).

In the field, the following soil characteristics were recorded: description of the OL horizon, thickness of the O horizon, and amount of roots and rocks in the A horizon. Thickness was recorded in cm using a folding ruler and the amount of roots[4] and rocks in the A horizon was estimated based on the methodology of Barham *et al.* (2006). Also, soil samples of the O (just OF

[3] GSF is the proportion of global radiation (direct and diffuse) under a plant canopy relative to that in the open (Rich *et al.*, 1999)
[4] Adapted from Barham *et al.*, (2006) classification. Visual estimation, ranging from 0 (no roots), to 3 (many roots).

and OH) and A horizons were taken and kept on plastic zip lock bags for a later on analysis of their pH, colour and texture.

Figure 9 summarizes which variables were measured at the subplot level, as well as which instruments and units were used.

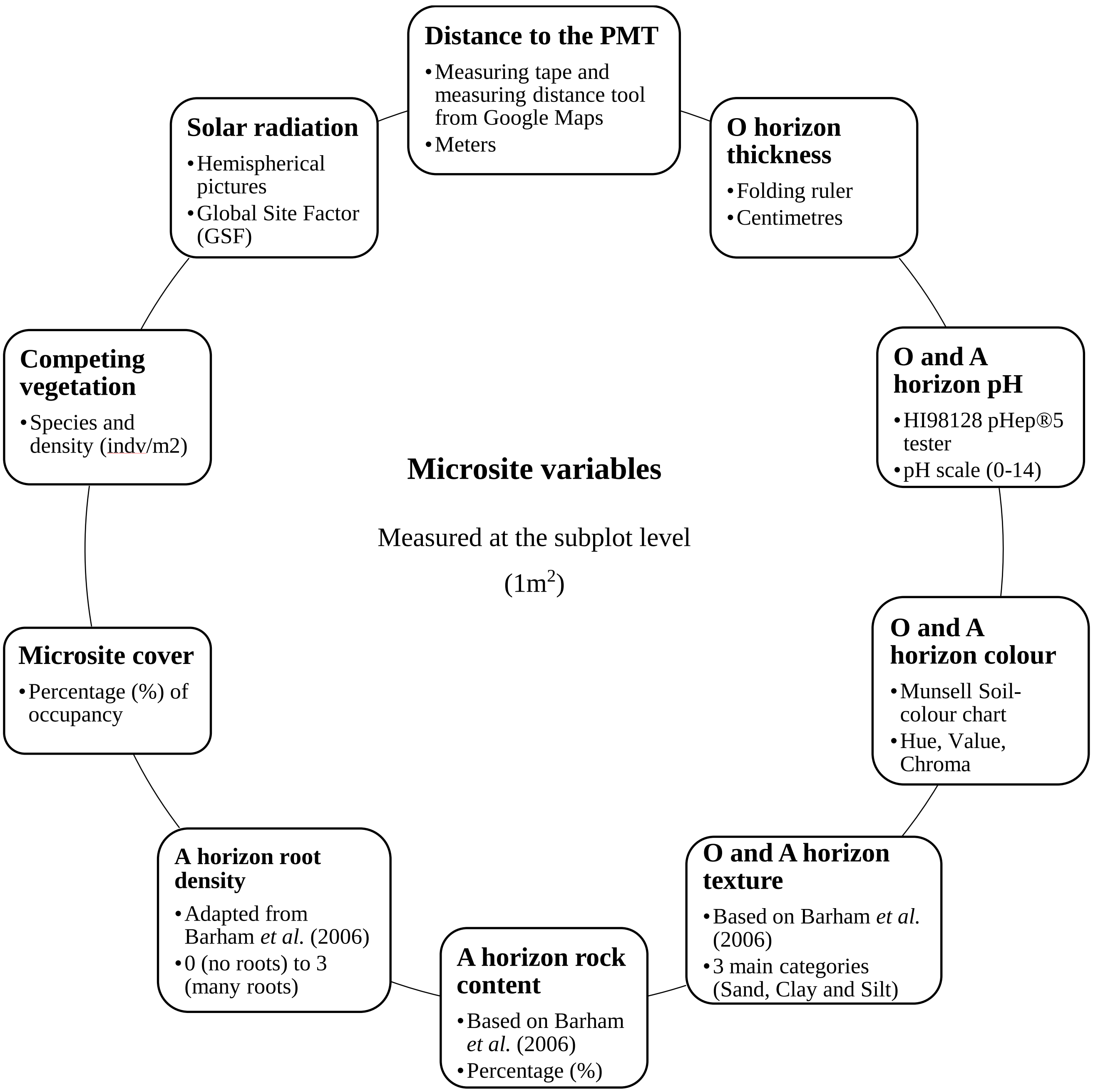


Figure 9*:* Variables measured at the subplot level, with instruments and units used

2.4.1. Soil samples analysis

The soil samples taken at each subplot of the O and A horizon were later analysed for the measurement of the following variables: colour, texture and pH. The soil colour was determined using the standard Munsell soil charts. The soil texture was manually estimated for the three main soil textures categories, using Barham *et al.*, (2006) as a reference. They were identified as Sand, Silt and Clay. Finally, to measure the pH of both horizons, the soil samples were mixed 1:1 with distillate water by volume in plastic pots. They were subsequently stirred before the pH was measured using a HI98128 pHep®5 tester (HANNA Instruemnts, 2016).

2.5. Data processing

2.5.1. Database

First of all, all the variables that were recorded in the field were arrange into two datasets, one per species, using the software Microsoft Excel (2016). Later on, the data from the vegetation surveys and the data from the microsite variables studies were consequently split. The vegetation surveys data was analysed using also the software Microsoft Excel (2016), and the data from the microsite variables was arrange into the required format to be subsequently analysed using R statistical computing software (R Core Team, 2017).

2.5.2. DBH and height classes graphs

In order to interpret and analyse the results of the vegetation surveys, the recorded plant species were clustered into functional groups (FG). Then, the mean density value of each FG was calculated for each height and DBH class as individuals per hectare, as well as their associated standard deviation (SD) and standard error (SE). In total, eight graphs were created, four for each *Quercus* species using the software Microsoft Excel (2016).

The graphs show the mean density values of each FG per height class (2.5m-R, H<1.3m) or DBH class (5m-R, H>1.3m) on the DF and LD surveyed forests. The recorded values showed a high variation between plots, in part due to the limited number of surveyed plots on both types of forests (n=5). The high values of the SD, which show the high variability inside the recorded samples, make the graphs more difficult to interpret. Therefore, SE bars that describe the uncertainty of the accuracy of the sample mean comparing it with the population mean (Nagele, 2003), are shown on the graphs. Nevertheless, the mean density values that are shown on the text are accompanied by their SD value (mean±SD).

2.5.3. Hemispherical pictures analysis

A series of five hemispherical pictures was recorded at every subplot (see **Image A10**), each of them with a different shutter speed and therefore different contrast. The picture with the best contrast between the vegetation and the sky was selected by visual assessment for each subplot and then it was analysed using the HemiView Hemispheric Image Analysis System software version 2.1 (Rich *et al.*, 1999).

First, site details and lens characteristics need to be added into the software. Through the interactive image classification, a threshold intensity value is then selected manually, which determines the parts of the sky visible, and the parts obstructed by landscape features, plant canopies, or human-built structures (Rich *et al.*, 1999).

The use of high contrast images taken under even lighting conditions reduced the subjectivity on the choice of a threshold. Subjectivity was further reduced by a training on image analysis prior to this analysis (Rich *et al.*, 1999).

The outcome of this process was the variable "Global Site Factor", which was later used for assessing the light conditions preference of the *Quercus* seedlings. It is defined as the proportion of global radiation under a plant canopy relative to that in an open area, and it can also be named total site factor. It includes the Indirect Site Factor, as well as the Direct Site Factor and therefore it is believed to be the most comprehensive value for light preferences comparison. Its values range from 0, representing total obstruction, to 1, representing no obstruction for the sunlight reaching the understory (Rich *et al.*, 1999; Cunningham *et al.*, 2011).

2.5.4. Transformation of variables

The transformation of specific variables was necessary for their statistical analysis, as well as for the creation of new ones. Some of the measured variables were transformed into more manageable or into more meaningful ones for the statistical analysis.

Soil colour of the A horizon was transformed into percentage of carbon content using a pedotransfer-function. Firstly, the colour values, which were recorded on the Munsell Soil Color Chart scale (hue, value and chroma), were transformed into the CIE 1931 color space XYZ using the WallkillColor Munsell Conversion Software (WallkillColor, 2018). Then, a pedotransfer-function (see **Equation 1**), which relates colour to measured soil organic carbon content (Katzensteiner and Bradley, 2017), was used to transformed the colour values into carbon content of the A horizon.

$$\ln\,(C\ content\ \%)\ = 0.536 - 0.064 * Y + 1.131 * \ln Z - 0.081 * Z$$

Equation 1: Pedotransfer-function to transformed soil colour measured in the XYZ space, into carbon content (%). Created by Katzensteiner and Bradley, (2017) based on colour and soil organic carbon content measured on the study region.

The density of the different species that were found on the subplots was grouped into one variable called density of competing vegetation (indv/m^2).

The percentage of the different microsite covers were also grouped into broader categories called Dominant Soil Cover Functional Groups (DSFG) (see **Table A9**). This newly created categorical variable was included in the later statistical analysis, together with the other recorded microsite variables.

2.6. Statistical analysis

Once all the measured and calculated variables were prepared and arranged into the required format, statistical analyses were performed with the objective of describing and finding out which microsite variables were the drivers of the density of regeneration of the studied species.

First, a descriptive analysis was performed, in which ranges and mean values of the different measured variables were calculated. When providing the mean of the recorded variables, some authors suggest to present the median and the interquartile range for non-normally distributed variables, as well as the mean ± standard deviation (SD) for the normally distributed variables. (Madadizadeh, Ezati Asar and Hosseini, 2015). In this case, some recorded variables are normally distributed, but others are not, being left or right-skewed. In the following sections, when the mean value of a variable is given, it will be accompanied by its standard deviation (±SD) in order to facilitate an easy reading and interpretation. SD describes the variability between the observations or measurements within the study sample (Nagele, 2003)

In order to compare the influence of different land uses on the density of seedlings, Kruskal-Wallis tests were performed.

The response of the "density of *Quercus* seedlings" towards the different microsite variables was modelled using Generalized Mixed Models (GMMs). At first, Generalized Additive Mixed Models (GAMMs) were created for both species. In the scenario in which the most successful model just contained variables with linear relationships towards the response variable "density of *Quercus* seedlings", Generalized Linear Mixed Models (GLMMs) were used. They were created using R statistical computing software (R Core Team, 2017). The main difference between both models is that GAMMs allow for the modelling of variables that, even if transformed, have a non-linear relationship with the response variable. Mixed models were needed in order to take into account the nested design of the field study, which may have imposed an spatial correlation between subplots in the same cluster of plots (Zuur *et al.*, 2009). Therefore, the variable "plot", that represented the cluster of four subplots, was modelled as the random effect. The GLMMs were created using the R package "lme4" (Bates *et al.*, 2015) and the GAMMs using the R package "mgcv" (Wood, 2004, 2017) and the required R package "nlme" (Pinheiro *et al.*, 2017)

The process to create the models, select the most successful one, and validate it was as follows. Firstly, the studied variables were plotted so that outliers could be identified. An outlier is an observation that has a relatively higher or lower value when compared with the majority of the observations (Zuur, Ieno and Elphick, 2010). Then the response variable "density of *Quercus* seedlings" was plotted against the possible distributions in order to find the most accurate one, using the R package "car" (Fox and Weisberg, 2011) and MASS (Venables and Ripley, 2002). It was the Poisson distribution for both cases, which is the most common one for counting data and because of that, the models included a canonical log-link for Poisson distributed data.

A collinearity test was performed using the variance inflation factors (VIF) created by Zuur *et al.* (2009) for assessing collinearity between the explanatory variables in order to know if some of them should be excluded from the model. In both cases, all the VIF values were lower than 3 (standardized threshold) and therefore, no variables were excluded from the model (Zuur, Ieno and Elphick, 2010).

Then, individual GAMMs were created between the response variable "density of *Quercus* seedlings" and each explanatory variable, in order to gain information about the linearity or non-linearity and the significance of the relationship. With the same objective, individual plots were created between the response variables and all the other explanatory variables. A main model containing all the recorded explanatory variables was not possible to be analysed due to the lack of observations when compare with the number of the recorded variables (limited amount of degrees of freedom). Therefore, the least significant variables were subsequently removed until the model could be run. This was called the "functional model", which contain the higher amount of the most successful variables the statistical software could handle, due to the limited amount of degrees of freedom. A 0.05 level of significance was used.

Afterwards, with the objective of finding the best model, a stepwise model selection was carried out, searching for a significant model with the lowest Akaike Information Criterion (AIC) value. The variance explained by the fixed and random factors was assessed by calculating the conditional R2 values, as proposed by Nakagawa and Schielzeth, (2013), with the R package "MuMIn" (Barton, 2018) for GLMMs, and with the adjusted R^2 for GAMMs.

Finally, the most successful model was validated plotting its residuals. Based on Wood (2006), the raw data against the fitted values, the Pearson residuals against the fitted values and finally raw residuals against fitted values were plotted and assessed.

The same statistical analysis was executed, also using the response variable "density of *Quercus* seedlings", but this time, modelling its changes using the occupancy in percentage of the different microsite covers as the explanatory variables.

3. Results

3.1. Vegetation survey

A total of 11 and 14 species were recorded in the least degraded (LD) and degraded (DF) *Q. semecarpifolia* forest, respectively. And a total of 11 and 19 species were recorded in the LD and DF *Q. lanata* forest, respectively. 20 species were recorded in *Q. semecarpifolia* forest and 21 in *Q. lanata* forest. 13 were exclusively recorded in *Q. semecarpifolia* forest and 14 in *Q. lanata* forest. The remaining 7 species were recorded in both forest, which are species associated to both vegetation types, mainly *Rhododendron arboreum*, common shrub species such as *Berberis asiatica* and an invasive grass called Mexican weed (*Ageratina adenophora*) (see **Table 3**).

In total, 34 different plant species were recorded during the vegetation surveys. It is worthy to mention that on the microsite variables study, one recorded variable was the amount of competing individuals on each subplot. Besides the density, also the different competing species were identified. The total area covered by the microsite conditions study is greater than the one used for the vegetation survey. Summing up for both species, 42 cluster of plots, which makes a total of 168 subplots scatter across three different VDCs, were studied. While recording this variable, 68 different plant species were identified; almost a 10% of the total 695 recorded plant species in the whole GCA (NARMA Consultancy and Practical Solution Consultancy, 2013).

The graphs represent the mean values per FG with their associated standard errors (SE). Nevertheless, in order to check the heterogeneity of the recorded data, the standard deviation (SD) and the mean of each FG on each DBH and height class can be consulted in **Table A10** and **Table A11** for *Q. semecarpifolia* and in **Table A12** and **Table A13** for *Q. lanata*.

3.1.1. *Quercus semecarpifolia*

The surveyed least degraded forest (LD), found between 2,600 and 3,000 m a.s.l. in Bulung VDC, was located in an area of difficult access, with a mean slope steepness of 61.74±7.4%. Probably due to its inaccessibility, it is the only *Q. semecarpifolia* forest in the area that does not shown as much signs of being heavily lopped and grazed as the others do. The highest and thickest individual was recorded in this forest, being 29.3 m in height and 121 cm in DBH.

The forest is clearly dominated by *Q. semecarpifolia*, as the literature suggested (Troup, 1921; Ohsawa, Shakya and Numata, 1986; Jackson, 1994; Elliott, 2012). It is mainly rivalled by *Rhododendron spp.* in the second DBH class (76±69 indv/ha of *Quercus* vs 127±90 indv/ha of *Rhododendron*), mainly *R. arboreum* but also *R. cinnabarinum* (see **Figure 10**).

Bamboo was only found in one plot of this forest and therefore, its standard error bar is very wide. It is important to mention that the bamboo, as well as the *Quercus* acorns are an important part of the diet of red pandas (*Ailurus fulgens*), an iconic Himalayan mammal which is categorized in the IUCN red list as endangered (Glatston *et al.*, 2015).

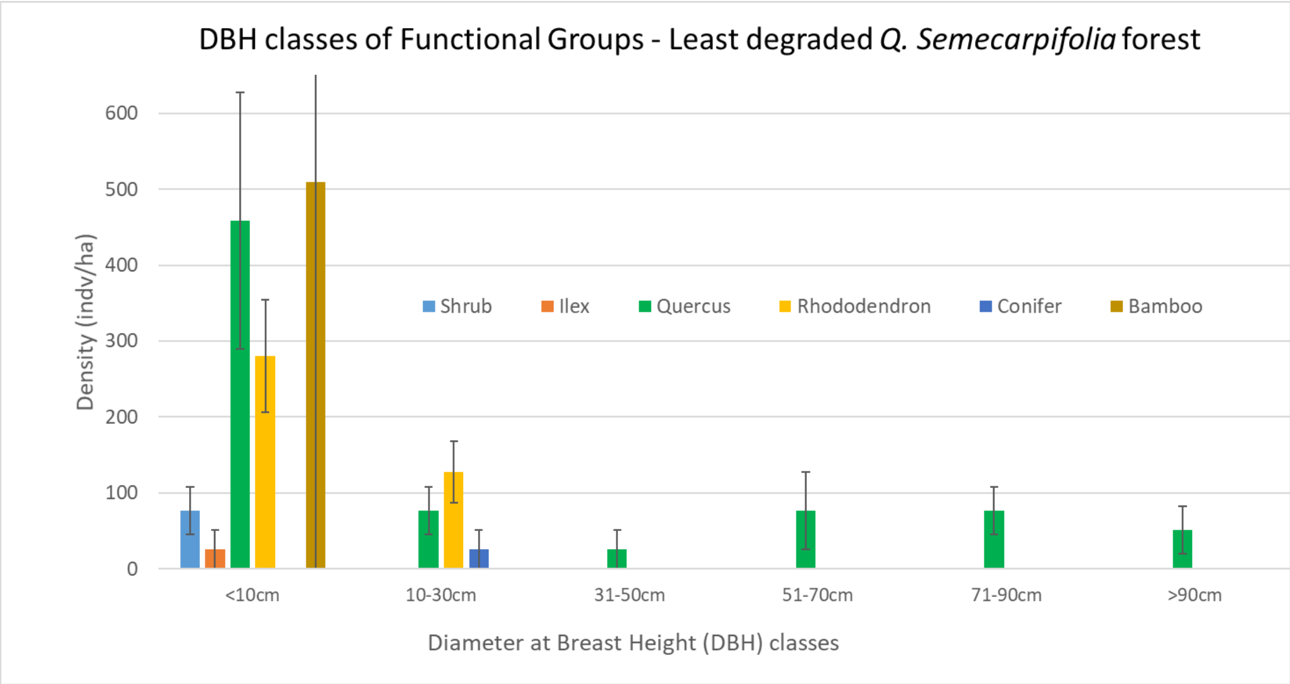


Figure 10: Density of DBH classes of the different functional groups on the LD *Q. semecarpifolia* forest, of plants Height>1.3m. Bars represent mean densities and error bars represent standard error (SE).

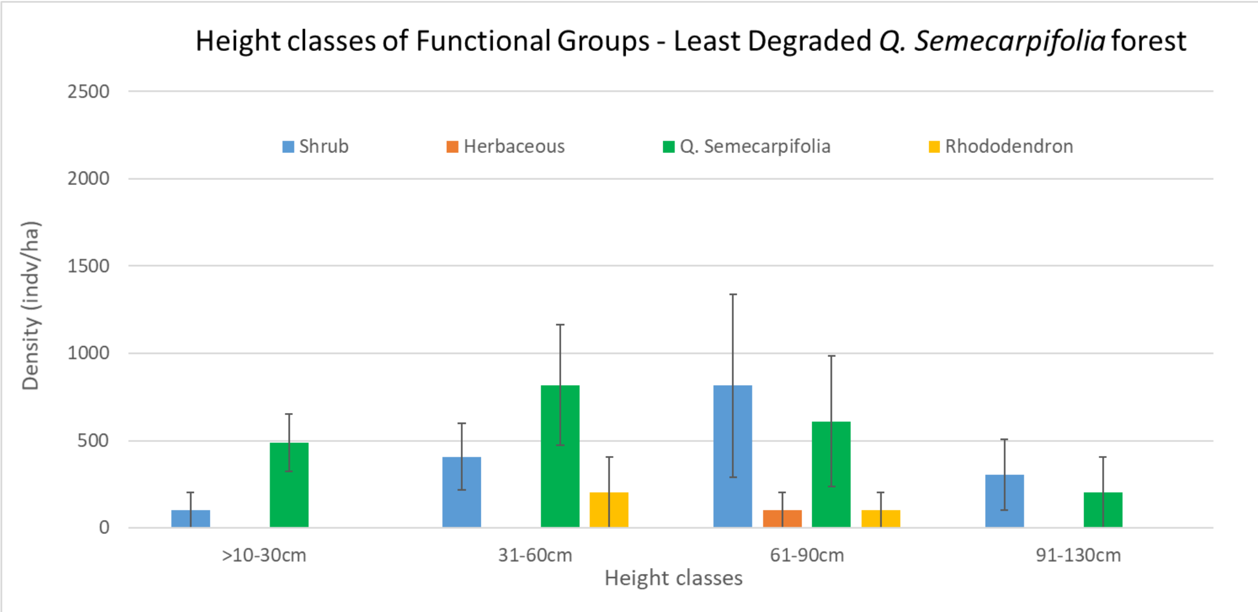


Figure 11: Density of height classes of the different functional groups on the LD *Q. semecarpifolia* forest, of plants Height<1.3m. Bars represent mean densities and error bars represent standard error (SE).

Figure 11 represents the mean densities of each FG per height class. *Q. semecarpifolia* seedlings are very abundant, being just surpass by shrubs in the height class 61-90 cm.

The situation in the degraded *Q. semecarpifolia* forest is very different. It is situated in an area of relatively easy access, in Laduk VDC, between 2,300 and 2,500 m a.s.l. **Figure 12** shows that this forest is a mixed community dominated by *Q. semecarpifolia* and *R. arboreum*, with a big lack of mature old trees. The smallest DBH class (<10 cm) shows very little regeneration of *Q. semecarpifolia* (51±114 indv/ha), in contrast with *R. arboreum* (357±166 indv/ha). It also contrasts with the LD *Q. semecarpifolia* forest, that showed a density of 458±378 indv/ha in the same DBH class.

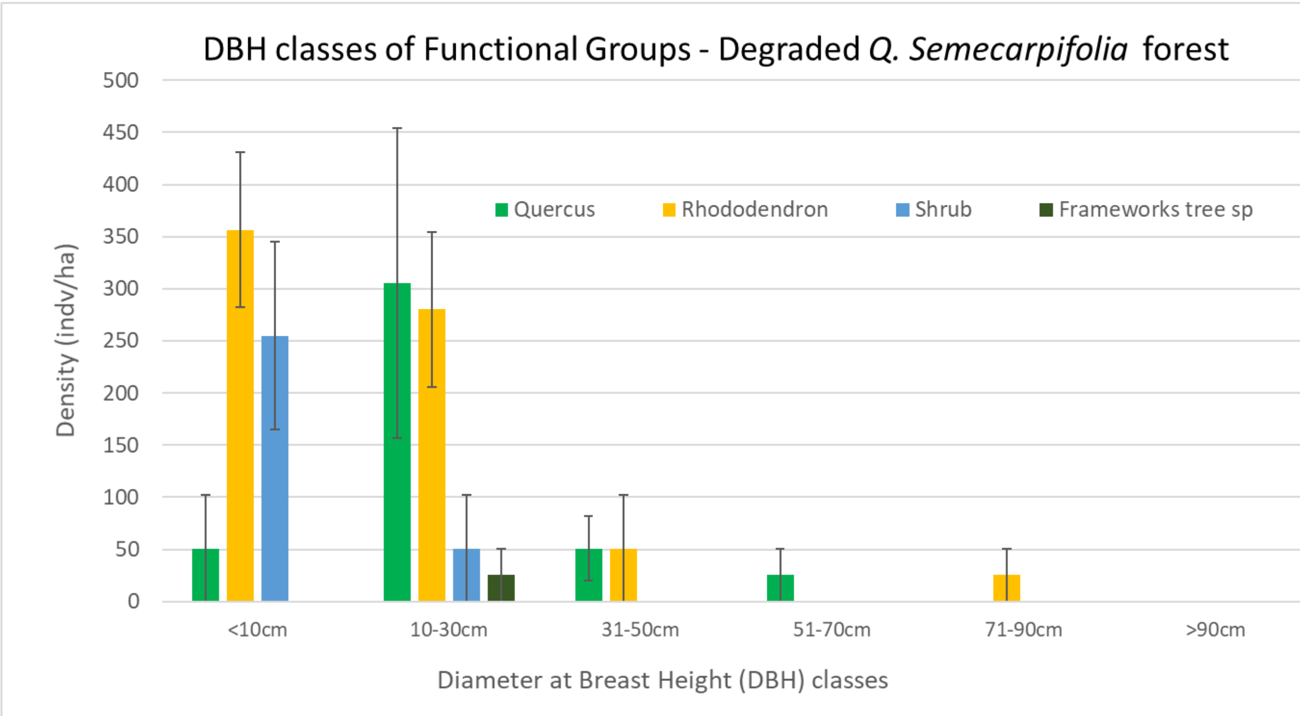


Figure 12*:* Density of DBH classes of the different functional groups on the DF *Q. semecarpifolia*, of plants Height>1.3m. Bars represent mean densities and error bars represent standard error (SE).

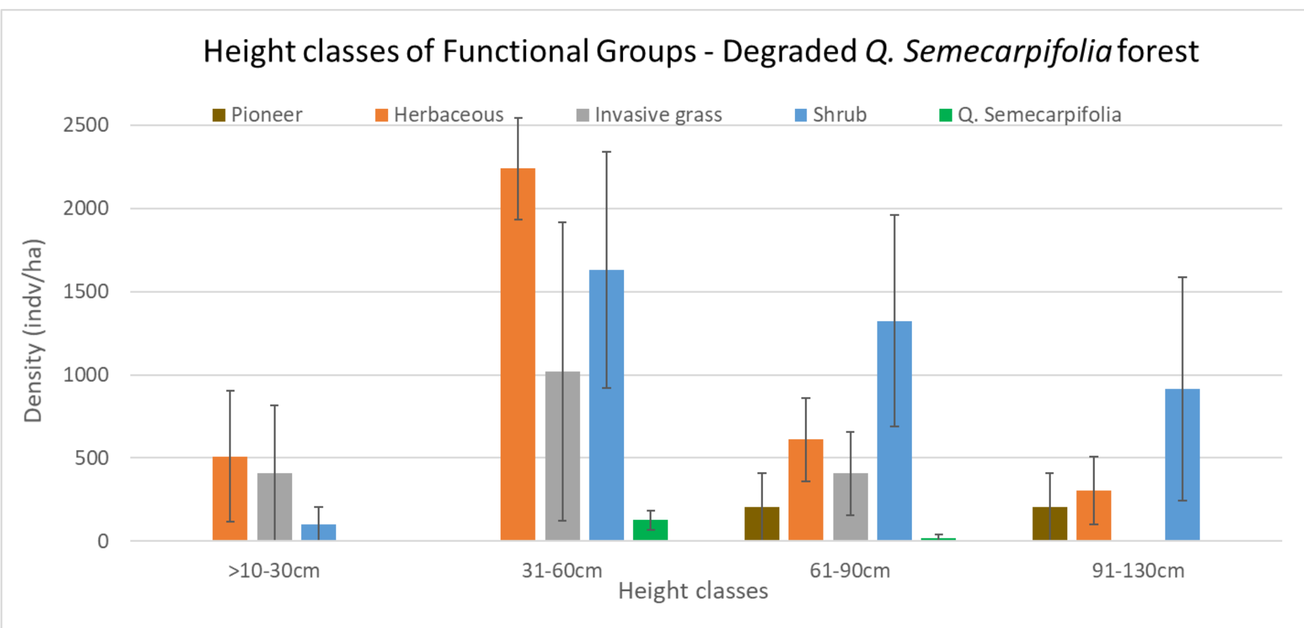


Figure 13: Density of height classes of the different functional groups on the DF *Q. semecarpifolia*, of plants Height<1.3m. Bars represent mean densities and error bars represent standard error (SE).

Figure 13 shows the density of the plants smaller than 1.3 m. Herbaceous vegetation is the dominant FG in the two first height classes, being later on overpass by the shrubs FG. There is very scarce regeneration of *Q. semecarpifolia*, and a complete lack of *R. arboreum* seedlings, even though they are the dominant tree species in the forest.

3.1.2. *Quercus lanata*

No LD forest was found in Laduk and Bulung VDCs, but one was discovered in the nearby Orang VDC inside the Tato Pani Dungi community forest, facing south south-east. It has a remarkably steep slope of 90±6.46%. According to the local villagers, it was protected from human exploitation between 20 to 30 years ago due to its intrinsic beauty, but it may also be due to religious reasons. Occasional cattle grazing is the only activity that is allowed and minor issues with illegal loggers were also reported.

The surveyed plots were located between 2,200 to 2,300 m a.s.l. As suggested by the literature, *Q. lanata* does not form pure stand but mixed forest, in this case mainly with *R. arboreum* (see **Figure 14**). No trees were recorded in the four bigger DBH classes. Even though it is recorded that *Q. lanata* can reach a DBH of 60 to 80 cm (Tang, no date) and extraordinarily to 1 m (Troup, 1921), the thickest individual recorded had a DBH of 22 cm.

Q. lanata clearly dominates the stands, with a density of 815±248 indv/ha in the DBH class 10 to 30 cm, followed by *R. Arboreum* with a density of 357±353 indv/ha in the same DBH class, having a more unequal distribution (see **Figure 14**). At the time of the study, the OL horizon was very thick, mainly dominated by *Q. lanata* and *R. arboreum* leaves.

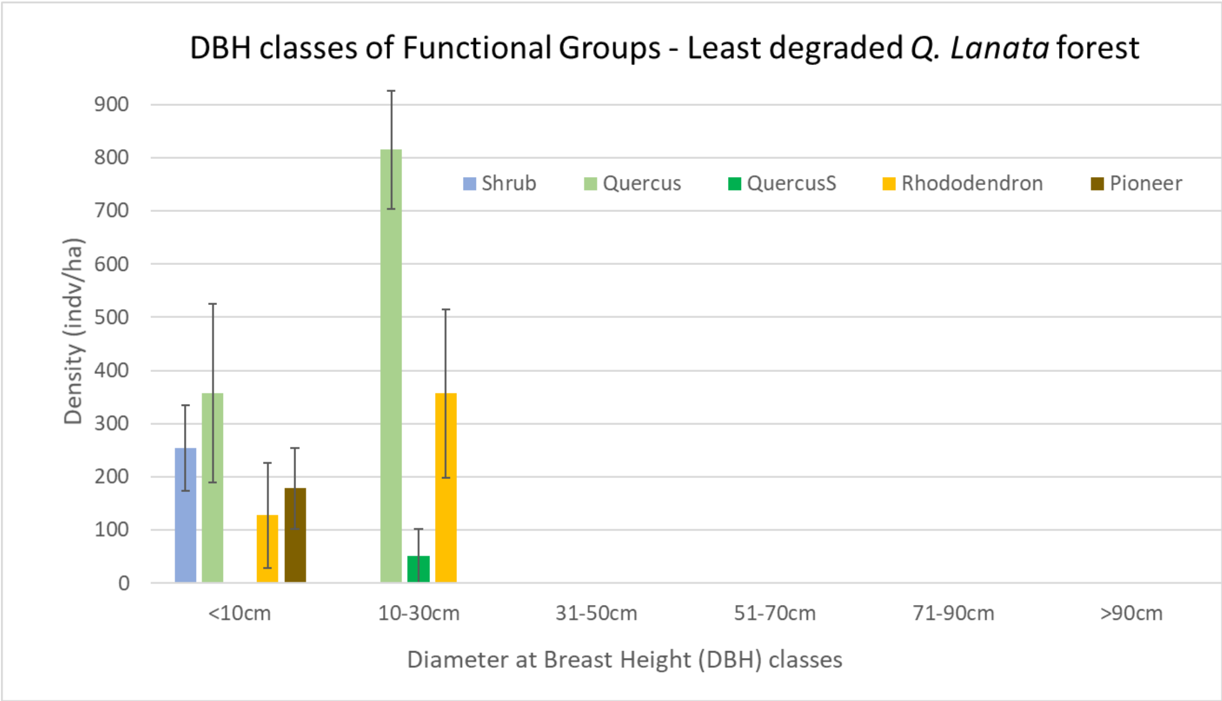


Figure 14: Density of DBH classes of the different functional groups on the LD *Q. lanata* forest, of plants Height>1.3m. Bars represent mean densities and error bars represent standard error (SE).

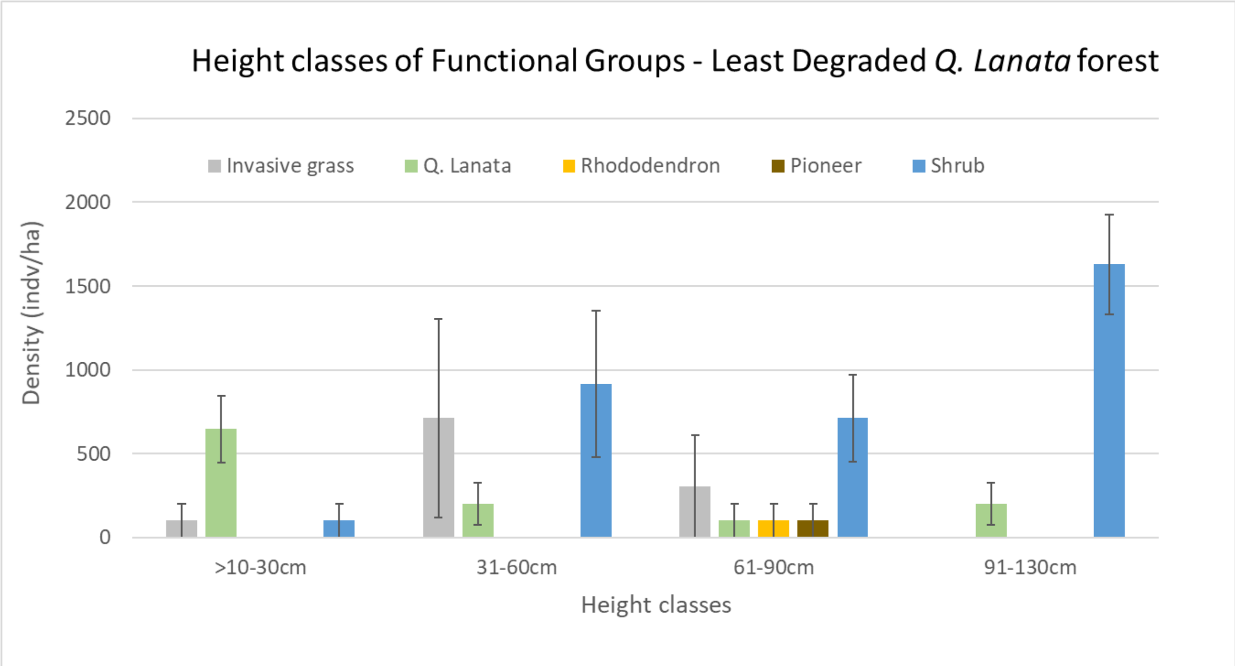


Figure 15: Density of height classes of the different functional groups on the LD *Q. lanata* forest, of plants Height<1.3m. Bars represent mean densities and error bars represent standard error (SE).

Figure 15 shows the height classes distribution of the understory and regeneration in the forest. Even though the density of small *Q. lanata* seedlings is very high (647±449 indv/ha) in the first height class (>10 to 30 cm), it suffers a drastic reduction in the following height classes, which is dominated by the shrub FG. The shrubs dominate the understory of the forest with a density of 1630±279 indv/ha in the bigger height class (91 to 130 cm). The figure also shows the almost complete lack of *R. arboreum* seedlings.

The DF is located in Bulung VDC in the Sange Pedharo forest and also faces south and south-east. It is comparably easy to access from below the main road to Bulungkhani. It comprises both, community forest and privately-owned forest. Some areas used to be abandoned terrace farmlands. The main activities developed there are lopping of branches for fodder, litter and firewood collection, timber logging and cattle grazing. It has a gentler slope than the LD forest, with 67.62±8.22 % steepness.

The surveyed plots were located between 2,150 to 2,250 m a.s.l. As can be deduced from **Figure 16**, there is major difference in the DBH distribution of the recorded functional groups, when compared with the LD forest. The forest is also dominated by *Q. lanata* and the accompanying *Rhododendron spp.* is substituted by a dense layer of shrubs. The presence of framework tree spp. can be attributed to the past used of some forest areas for farming. Surprisingly, a recorded *Q. lanata* individual had a DBH of 37 cm, much larger than the thickest individual recorded on the LD forest (22 cm of DBH). Even though almost all trees showed clear signs of heavy lopping, they had an abundant amount of flowers.

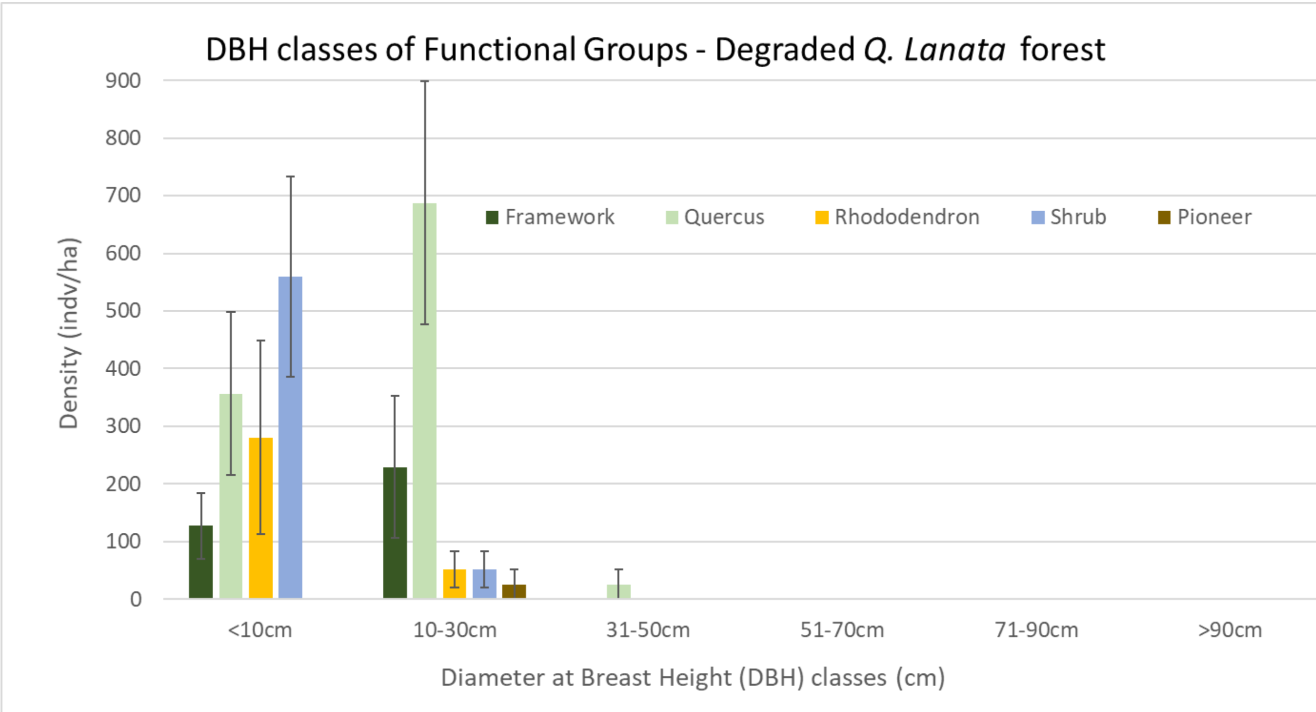


Figure 16: Density of DBH classes of the different functional groups on the DF *Q. lanata*, of plants Height>1.3m. Bars represent mean densities and error bars represent standard error (SE).

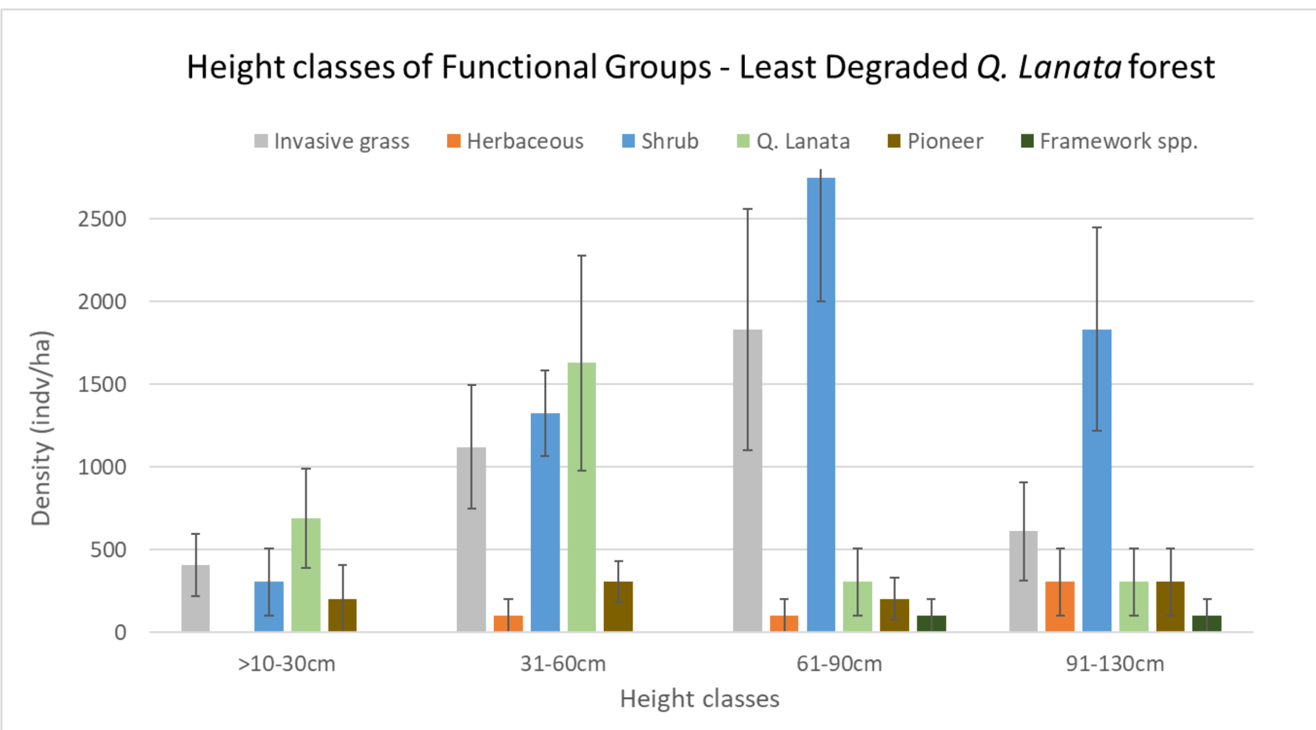


Figure 17: Density of height classes of the different functional groups on the DF *Q. lanata*, of plants Height<1.3m. Bars represent mean densities and error bars represent standard error (SE).

The understory and regeneration of this forest shows differences compare to the LD forest. As can be seen in **Figure 17**, the density of *Q. lanata* seedlings is very high in the first two height classes, being 1623±1458 indv/ha in the height class 31 to 60 cm. It then suffers a descend for the other two, while still being higher in all height classes than the LD forest. The understory layer is even denser compared to the previous forest, reaching a value of 2750±1674 indv/ha and 1833±1635 indv/ha in the height class 61 to 90 cm of shrubs and invasive grass spp. FG, respectively. Shrubs are also the dominant FG in the biggest height class, with a density value of 1833±1376 indv/ha.

3.2.Microsite variables

This research is a Natural experiment due to the use of the natural variation of the variables of interest. Thus, it will be more difficult to tease apart the cause and effect relationships and its conclusions will need to be taken with care.

The other part of the study tries to answer the following research question: which microsite conditions are more adequate for the germination and establishment success of the studied *Quercus spp.* seedlings? In order to answer it, clusters of two plots were established in three different land uses, VDCs, aspects, slopes orientation and elevation. The land uses categories were least degraded forest (LD), degraded forest (DF) and pine plantations (PP). Each cluster of plots comprises four subplots (two pairs of fixed and pivot plots), in which selected microsite variables were recorded.

GLMMs and GAMMs were created in order to better understand the effect of the different recorded variables with the response variable "density of *Quercus* seedlings".

3.2.1. *Quercus semecarpifolia*

A total of 19 cluster of plots were established for this species, which makes a total of 76 subplots. 20 subplots were located in LD, 48 in DF and 8 in PP. 44 seedlings were recorded in total, mainly in the LD forest. A total of 31% of the subplots contained regeneration. **Figure 18** depicts the distribution of the recorded seedlings in the different land uses. As can be seen, no seedlings were found in the PP plots and therefore, those plots were excluded from the main statistical analysis. The black line on the boxplot represents the median, in this case zero for the DF and PP, which highlights the amount of zeros (absence of seedlings) that were recorded. A Kruskal-Wallis test was performed and a significant effect of the different land uses on seedling density was found (H=14.211, df=2, p-value=0.001). The post hoc tests to test pairwise comparisons found that the seedlings density in LD was significantly different to DF (p-value=0.004) and to PP (p-value=0.018). They also indicate that DF and PP were not significantly different (p-value=0.164).

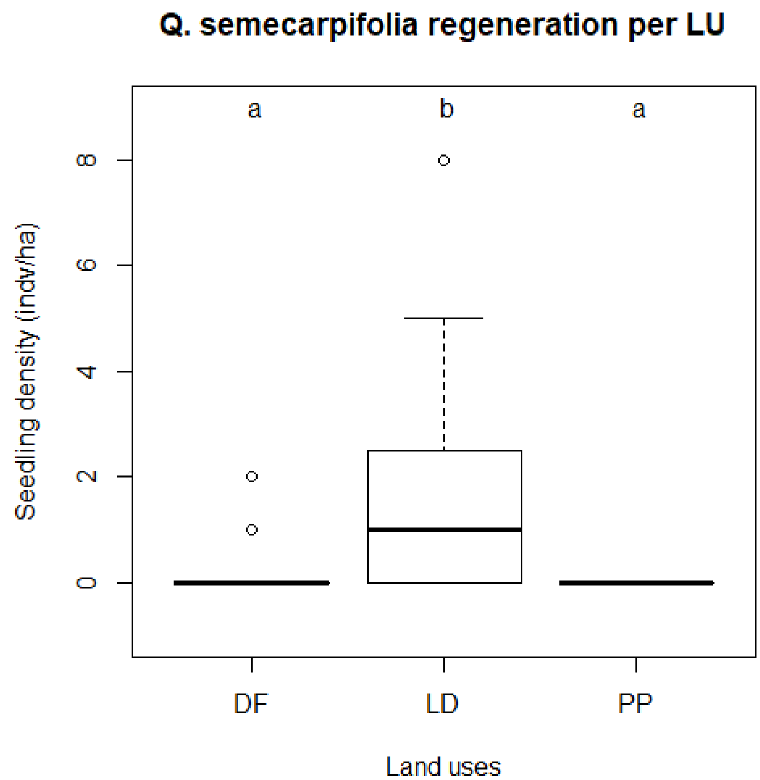


Figure 18: Distribution of *Q. semecarpifolia* seedlings per land use. Different letters mean statistically significant differences (p-value<0.05) between the categories.

The first most successful model, followed the protocol defined in the section **2.6.** It contained the variables “thickness of the soil O horizon (cm)” and “amount of roots in the soil A horizon”, as well as the random effect modelled by the variable “cluster of plots”. Both variables showed a linear relationship with the response variable and therefore, the final version of the model was created using Generalized Linear Mixed Models (GLMMs). Residual plots were created to validate the model but showed a poor fit, especially when the seedling density values were high. Consequently, the process was repeated until a model was found with a good residual structure and the lowest AIC.

The final model contains four variables. “Distance to the PMT (m)” and “density of competing vegetation (indv/ha)” did not have a statistically significant effect on the density of seedlings but it was important to maintain them in the model, as they improve the structure of the residuals. “Thickness of the soil organic horizon” and “amount of roots in the soil A horizon”, are the variables that have a statistically significant effect on the response variable “density of *Q. semecarpifolia* seedlings”, as well as the random effect modelled by the variable “cluster of plots”. The R^2 adjusted value, which is the proportion of variance explained by the model, was 0.329. The model is shown in **Equation 2.**

$$
\begin{aligned}
&gamm\ (Density\ of\ Quercus\ seedlings \sim Distance\ to\ the\ PMT \\
&+ Density\ of\ competing\ vegetation + \ Amount\ of\ roots\ in\ the\ A\ horizon \\
&+ smoother(Organic\ horizon\ thickness), \\
&random = list(Plot = \sim 1), family\ =\ poisson(link = \text{"log"}), data \\
&= SEM2)
\end{aligned}
$$

Equation 2: Most successful GMMs for the response variable “density of *Q. semecarpifolia* seedlings”.

Table 4: Estimates, standard errors (SE), t and corresponding p values of the parametric components and estimated degrees of freedom (edf), F and corresponding p values of the smooth terms for all significant ($p<0.05$) and two non-significant ($p>0.05$) microsite variables from GAMMs of *Q. semecarpifolia* seedlings density per m² plot (n/m²; Poisson distributed data). $R^2_{adjusted} = 0.329$, AIC =333.74, BIC =349.28, *n* = 68 subplots/ 44 individuals

	Parameters	**Estimate**	**SE**	***t value***	***p* value**
Density	Intercept	-3.39583	1.00021	-3.395	0.001211 **
	Distance to the PMT	-0.05929	0.03618	-1.639	0.106381
	Density of competing vegetation	-0.11114	0.0803	-1.384	0.171375
	Amount of roots A horizon	1.90772	0.53369	3.575	0.000693 ***
	Smooth terms	**edf**	**Red. df**	***F value***	***p value***
	Organic horizon thickness	2.968	2.968	2.745	0.0361 *

The residual plots created to successfully validate the model are depicted and interpreted in **Figure A22**.

Both variables, “distance to the PMT” and “density of competing vegetation” showed a negative influence on the “density of *Q. semecarpifolia* seedlings”, but not statistically significance. Even though the effect of the variable “distance to the PMT” was not statistically significant, it is still important because all plots located further than 8 m from the PMT did not contain regeneration.

On the other hand, the variable “amount of roots in the A horizon” showed a significant positive influence on the “density of *Q. semecarpifolia* seedlings” (see **Table 4**). The variable “thickness of the organic (O) horizon” does not follow a linear relationship with the response variable, and the GAMMs cannot provide estimates for it. Nevertheless, its influence on the density of seedlings can be inferred from **Figure 19**. The black line shows the relationship between the variable “thickness of the O horizon” and the modelled “density of seedlings”. The areas in grey colour represents the confidence regions of these non-linear shape. The effective degrees of freedom (edf) of the variable “O horizon thickness” is almost 3, which shows that the fit is similar to a GLMM with a cubic function.

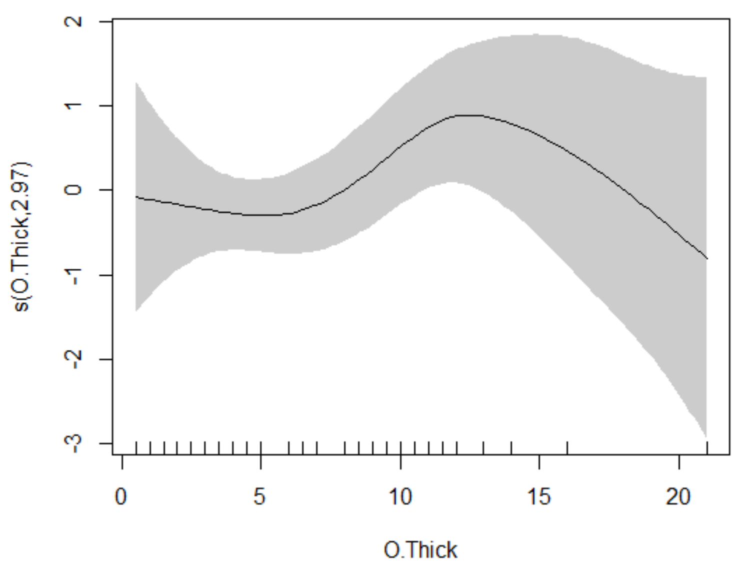


Figure 19: Relationship between the variable Thickness of the organic horizon with the response variable "density of *Q. semecarpifolia* seedlings". Shaded areas represent the confidence regions.

The shape of the response curve in **Figure 19** shows that the “thickness of the O horizon” influences the “density of *Q. semecarpifolia* seedlings” positively, until a certain limit of approximately 14 cm. If the thickness is higher than this limit, the positive effect is reduced. Seedlings were found in soils with a mean thickness of the O horizon of 8.19±4.89 cm.

Furthermore, seedlings were exclusively found in plots with a "pH of the O horizon" between 5.3 and 6.4, with a mean value of 5.73±0.38.

The results of the GAMMs to model the response variable "density of *Q. semecarpifolia* seedlings" using the "coverture of the different microsites" in percentage as explanatory variables, were not statistically significant ($p>0.05$).

3.2.2. *Quercus lanata*

Following the same procedure as for *Q. semecarpifolia*, 23 clusters of plots were established on the different LU. 20 subplots were located in LD, 40 in DF and 32 in PP, which makes a total of 92 studied subplots. 78 seedlings were recorded and as displayed in **Figure 20**, the majority was located in LD and DF subplots. The median density of seedlings was 0 for all LUs, which also highlights the large amount of subplots without regeneration (70%). The results of a Kruskal-Wallis test showed a significant effect of the different land uses on seedling density ($H=10.098$, $df=2$, p-value=0.006). The post hoc tests for pairwise comparisons found the seedlings density on PP to be significantly different to the LD (p-value=0.006) and DF (p-value=0.006). DF and LD were not significantly different (p-value=0.916).

During the survey for *Quercus* regeneration, 18 seedlings were recorded in one subplot (1x1 m) located in a DF, which is a value much higher than the others (see **Figure 20**). Following Zuur *et al.* (2010) recommendations, the observation cannot be considered as an outlier, because it was well registered during fieldwork with confidence that it does not represent a measurement or transcription error, but a genuine variation of the recorded variable.

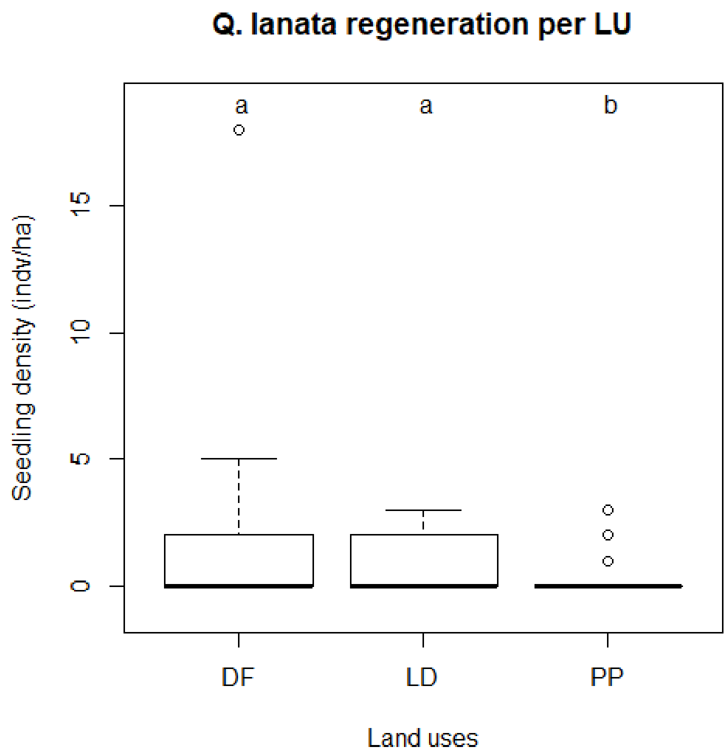


Figure 20: Distribution of *Q. lanata* seedlings per land use. Different letters mean statistically significant differences (p-value<0.05) between the categories

The procedure for creating the model was the same as for *Q. semecarpifolia* (see Section **2.6**).

The most successful GAMM contains three variables. One of them has a linear relationship with the response variable “density of seedlings”, and the relationship of the other two needed to be modelled with smoothers, to account for the non-linearity. The adjusted R^2 value was 0.329. The results are shown in **Table 5** and the model in **Equation 3.**

$$gamm\ (Density\ of\ Quercus\ seedlings \sim Distance\ to\ the\ PMT + smoother(GSF) + smoother(Organic\ horizon\ thickness),\ random = list(Plot = \sim 1), family\ =\ poisson(link = \text{"log"}), data = LA)$$

Equation 3: Most successful GMMs for the response variable “density of *Q. lanata* seedlings”.

Table 5: Estimates, standard errors (SE), t and corresponding p values of the parametric components and estimated degrees of freedom (edf), F and corresponding p values of the smooth terms for all significant ($p<0.05$) microsite variables from GAMMs of *Q. lanata* seedlings density per m² plot (n/m²; Poisson distributed data). $R^2_{adjusted} = 0.329$, AIC =435.22, BIC =452.87, *n* = 92 subplots/ 78 individuals

	Parameters	**Estimate**	**SE**	***t value***	***p* value**
Density	Intercept	0.21009	0.2181	0.963	0.33817
	Distance to the PMT	-0.06684	0.02018	-3.312	0.00137 **
	Smooth terms	**edf**	**Red. df**	***F value***	***p value***
	Organic horizon thickness	2.107	2.107	6.534	0.00168 **
	GSF	4.016	4.016	6.839	6.72e-05 ***

The plots created to successfully validate the model can be seen in **Figure A23**.

The variable "Distance to the PMT" has a negative linear relationship with the response variable "density of *Q. lanata* seedlings", indicating that the further away the subplots were located from a PMT, the lower the recorded density of seedlings was. Even though regeneration was found in a plot located 54 m away from the PMT, 98.72 % of the total regeneration was just recorded between 0.95 and 7.5 m from the PMT.

Moreover, the variables "thickness of the organic horizon" and "GSF" do not follow a linear relationship with the response variable, and the GAMMs cannot provide estimates for them. Their influence on the "density of seedlings" can be interpreted looking at **Figure 21**. The black line shows the relationships between the explanatory variables and the modelled response. The grey area depicts the confidence regions of these non-linear shapes. The effective degrees of freedom (edf) of the variable "O horizon thickness" is just above 2, indicating a similar fit to a GLMM with a square function. The variable "GSF" has 4 edf, showing a fit similar to a GLMM with a quartic function.

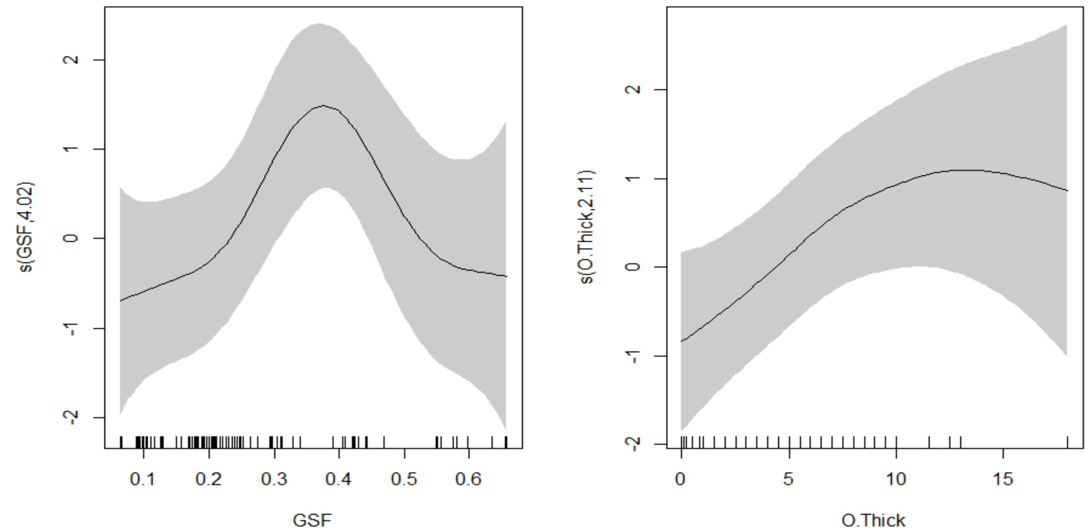


Figure 21*:* Relationship between the variables GSF and Thickness of the organic horizon with the response variable "density of *Q. lanata* seedlings". Shaded areas represent the confidence regions.

The "Global Site Factor" curve has a clearly distinguishable symmetric shape. Seedling density appears to be higher for low-medium GSF values, between 0.25 to 0.5, and maximum around 0.4. This means seedling density will be higher in areas receiving around 40% of the solar radiation the area would receive if no vegetation was present. On both sides of these value ranges, the seedling density is reduced. The range of values in which seedlings were found was wide (between 0.06 to 0.66), with a mean value of 0.27±0.17.

Q. lanata seedlings seem to prefer well developed soils with thick O horizons. After a maximum value of approximately 13 cm however, their density starts to decline. This can be inferred from the negative left-hand skewed curve shape of the "thickness of the organic horizon" variable. Seedlings were found on soils with a mean "thickness of the organic horizon" of 5.67±3.46 cm. Additionally, regeneration was recorded in subplots with an "O horizon pH" ranging between 4.7 and 6.3, having a mean value of 5.4±0.52.

As in the case of the aforementioned species, the results of the GAMMs that tried to model the response variable "density of *Q. lanata* seedlings" using the "covert of the different microsites" as explanatory variables, were not statistically significant ($p>0.05$).

4. Discussion

4.1. Vegetation survey

The highest amount of plant species was found on the degraded *Q. lanata* forest (21 spp.). A reason may be that, in part due to its accessibility, it suffers pronounced human-induced disturbances, such as litter, fodder and firewood collection, and grazing. These disturbances create an open forest, where several light demanding pioneer species can thrive. It may also link to the agricultural past of the surveyed plots. It is assumed that it is related to the high presence of framework spp. (7 spp.), which may have been planted as fodder trees or for provisioning other products.

4.1.1. *Quercus semecarpifolia*

As shown in **Figure 10**, the distribution of *Q. semecarpifolia* trees in the least degraded forest (LD) follows a reversed J-shape, which visibly shows good regeneration and a healthy stand (Wangda and Ohsawa, 2006). *R. arboreum* is the accompanying species, as previously reported (Singh and Rawat, 2012).

Figure 11 shows that *Q. semecarpifolia* seedlings are abundant in the LD forest, and without taking into account the first height class category, their distribution also follows a reversed J-shape. The limited regeneration in the first height class for all functional groups may be attributed to the close canopy of the forest and to the effect of grazing by cattle or wild animals. It may as well be due to the intermittent seed production strategy that the species follows. These results are similar to the ones reported by Vetaas (2000), in which the highest number of seedlings was found in undisturbed plots with high canopy cover.

On the other hand, the results of the DF show that the forest is not just dominated by *Q. semecarpifolia* but also by *R. arboreum.* The diameter distribution does not follow a reversed J-shape. The density of *Q. semecarpifolia* individuals on the smallest DBH class (<10 cm) is very low (51±114 indv/ha), increasing dramatically in the next height class (306±332 indv/ha). Then the density is constantly decreasing until there is a complete lack of individuals in the two biggest DBH classes, which can be attributed to logging. Surprisingly, *Rhododendron spp.* were found in the DBH size class 70-90 cm, even though in very low densities (25±57 indv/ha), probably because its wood is not as valuable. This highlights the lack of old thick trees in the forest (see **Figure 12**). The high density of individuals on the DBH size class 10-30 cm (306±332 indv/ha) could be related to the past logging of bigger individuals and the consequent opening of the canopy and thus sudden growth of smaller ones. The dramatic lack of thick trees could also be related to the intensive lopping pressure that the remaining individuals are facing, which may inhibit their growth.

The results also show that there is a complete lack of regeneration of the two main tree species, probably due to the intense pressure the forest faces. There is a very dense understory of herbaceous and shrubs species (see **Figure 13**) which may be attributed to the openness of the canopy due to the lopping of the branches. It is worth noting that many *Q. semecarpifolia* seedlings may have escaped being recorded due to their leafless stems and their die back strategy when conditions are unfavourable.

While comparing both forests, a clear pattern emerges. On the one hand, if a *Q. semecarpifolia* forest is difficult to access, it faces less human-induced disturbances. Therefore, the canopy is more closed and less light reaches the understory, making it less dense. The reduction of lopping of the branches allows a constant production of seeds, and the reduction of grazing allows the succession of these seeds into seedlings and then into saplings and trees following the natural gap-phase dynamics. Thus *Q. semecarpifolia* continues to be the dominant species of the forest, in accordance with its gregarious nature.

On the other hand, when the *Q. semecarpifolia* forest is easily accessible, it suffers from more human-induced disturbances. The constant removal of biomass from the canopy, especially from this primarily targeted *Quercus* species, reduces the production of seeds. Furthermore, the increment of solar radiation on the forest floor enhances the growth of the understory. This dense layer of herbaceous and shrubs species will have a negative effect on the ability of the *Quercus* seeds to germinate and grow to next life stages, due to the increase of competition and therefore the succession would be arrested. The seeds and seedlings also face the threat of grazing and trampling by the cattle. This situation allows to predict that due to the absence of regeneration of the two dominant tree species, *Q. semecarpifolia* and *R. arboreum* (see **Figure 12**), if these trends continue, the future forest would have a dense understory composed mainly of unpalatable species for cattle, as well as less useful species for the local communities, but a complete lack of mature old trees. Thus, due to their lack of regeneration the current dominant species may be replaced by others in the future (Rawal, Gairola and Dhar, 2012).

The absence of regeneration of *R. arboreum* cannot be attributed to the high grazing pressure because it is unpalatable for grazing animals and furthermore, this disturbance enhance its dispersal (Jackson, 1994). Moreover, almost all the mature individuals were flowering and did not show signs of lopping. Nonetheless, its lack of regeneration may be due to the presence of a thick understory layer of other unpalatable species that may over compete its seedlings, as well as to trampling and litter collection.

4.1.2. *Quercus lanata*

There is an absolute lack of thick trees in the surveyed LD forest. No trees were recorded in any of the four bigger DBH classes. Nevertheless, the density of *Q. lanata* is high in the DBH size class 10 to 30 cm (815±248 indv/ha), and the highest number recorded for a *Quercus spp.* in any of the two surveyed forests. This absence may be linked to occasional illegal logging, the forest management prior to protection, but also to the current high density of stems, which forces individuals to grow taller and thinner.

The density distribution of plants smaller than 1.3 m (see **Figure 15**) per height class shows that there is low regeneration of the main forest tree species. This could be mainly attributed to the lack of light availability due to the closed canopy (mean value of GSF 0.19±0.17), and also to the high density of the other FG that may act as competing vegetation. Nevertheless, even though in low density, there is *Q. lanata* regeneration in all the different height classes, especially in the smallest height class (647±449 indv/ha) which shows a constant production of seeds.

Due to the abundance of mature *Q. lanata* trees and the lack of human-induced disturbances, it is expected that the seedlings will manage to grow and to survive to the next life stage when a natural gap is created in the forest canopy. Therefore, this forest does not suffer from a lack of regeneration despite a lack of seedlings and saplings, because of a continuous production of seeds that could succeed to become trees when the conditions are adequate (e.g. an opening in the canopy).

The density of *Q. lanata* trees in the DF is similar to the one recorded in the LD forest (see **Table A12**). Severe logging could be the cause of the lack of thick individuals. The main findings of this forest include the presence of framework tree species as well as the replacement in dominance from R*hododendron* to shrubs FG, which is the densest FG in the smallest DBH class (560±388 indv/ha with a DBH<10 cm).

In contrast with the LD, the results also show continuous regeneration of *Q. lanata*, with a density peak on the height class 31-60 cm of 1630±1458 indv/ha. They also show a complete lack of *R. arboreum* regeneration. The dense understory and high density of *Q. lanata* seedlings in the first two height classes may be related to the amount of light that is available (mean value of GSF 0.36±0.16) due to the constant opening of gaps on the canopy trough lopping and logging. The sudden descend on the density of *Q. lanata* seedlings from the second height class onwards can be attributed to the litter removal, grazing and trampling pressure, as well as to the high competition with the other understory species.

Even though the trees face a high level of human-induced disturbances in the DF, they are still able to produce flowers and seeds. The fact that the seedlings density is higher than in the LD forest (see **Table A13**) shows that this tree species can cope well with the current human pressure. As in the case of the DF of the other species, the constant removal of biomass from the canopy increases the solar radiation in the forest floor, and enhances the growth of the understory. The highest density values recorded were 2750±1674 indv/ha and 1833±1635 indv/ha in the height class 61 to 90 cm of shrubs and invasive grass spp. FG, respectively in the *Q. lanata* DF. This extremely dense understory may outcompete its offspring, but in some cases and probably due to the high grazing pressure that the study forest had, it was recorded that some thorny shrubs (mainly *Berberis asiatica*) were protecting the palatable seedlings, acting as successional facilitators (see **Image A7**). The positive effect of nurse shrubs has already been reported for *Q. semecarpifolia* (Tashi, 2004) as well as for other oak species from temperate forest (Bakker *et al.*, 2004).

4.2. Microsite variables study

4.2.1. *Quercus semecarpifolia*

The complete absence of regeneration in the surveyed pine plantation plots is closely related to the absence of suitable PMT in those plantations. The mean distance to the PMT of the surveyed PP plots was (57±46.81 m), which contrasts with the mean value for DF (30.25±40.67 m) and even more for LD (2.91±1.24 m).

The fact that no regeneration was found if the plots were located further away than 8 m from the PMT shows the importance of this variable. It indicates a problem with the seed dispersal ability of the tree species in the study area. Dispersal in space is very important in order to avoid intraspecific competition, inbreeding and predation by animals that prefer to feed were seedlings are densely found (Maarel, 2005). A study conducted in Paro Dzongkhag, Bhutan revealed that the mean dispersal distance of *Q. semecarpifolia* is 7.5 m (Dhendup, 2013), due to its heavy weight and its dependence on birds and small mammals for dispersal.

The low number of surveyed plots with presence of regeneration (31%) is nevertheless slightly higher than the ones reported in another ecological regeneration study conducted in Bhutan, in which 18.4 to 25.4% of the plots contained regeneration between the years 2000 to 2003 (Tashi, 2004).

The model results (see **Table 4**) show a negative influence of the variables “distance to the PMT” and “density of competing vegetation” (even though not significant), a positive influence of the variable “amount of roots in the A horizon”, as well as a positive influence of the “thickness of the organic (O) horizon” variable until a certain limit is reached, towards the response variable “density of *Q. semecarpifolia* seedlings”.

For some species a thick O horizon may prevent the successful establishment of seedlings due to their incapability of reaching the mineral horizon, and also for the risk of being buried. However, the result of the model suggests that *Q. semecarpifolia* seedlings prefer soils already developed, with a thick O horizon, up to a limit of approximately 14 cm. This goes in hand with the description of its germination process explained by Troup (1921), especially with the abnormal elongation of the petiolar tube, which allows the seedling to reach the mineral soil even when the O horizon is very thick.

The A horizon of a soil profile is a mineral horizon formed below the O horizon, with accumulation of humified organic matter mixed with the mineral fraction (Barham *et al.*, 2006). The statistically significant positive influence of the “amount of roots” in this horizon suggest (as the previous variable), that seedlings germinate and survive in already developed and undisturbed soils. These are soils in which the horizons have been developed over time, allowing their colonization by different plant species.

Vetaas, O. (2000) and Tashi, S. (2004) reported the optimum soil pH for seedlings to be 6, which is consistent with the obtained mean result of 5.73±0.38 pH value of the O horizon of the subplots with regeneration.

Tashi, S. (2004) results suggested that this tree species prefer gentle slopes, but even though the slope of the studied plots ranged between 20.9 and 90 %, seedlings were just found between 40 and 81.3 % of slope gradient, with a mean value of 64.74±11.49%. These results contrast with Tashi, S. (2004) findings and can be attributed to the special situation of the study area, in which the forest suffers from a lot of anthropogenic pressure. Less accessible forests, in this case forests with steepest slope, likely face less human-induced disturbances.

"GSF" does not have a statistically significant effect either, but even though its value in the surveyed plots ranges from 0.03 to 0.8, seedlings were just found between 6 to 0.46, with a mean value of 0.2±0.12 suggesting that it is a shade tolerant species. On the other hand, Troup (1921) stated that in order to continue to the next plant stage (sapling), seedlings need an abundant overhead light. The results of Tashi, S. (2004) study showed that, although canopy openness neither had an influence in the presence, nor in the survival of *Q. semecarpifolia* seedlings, it had a positive effect in the number of leaves and height of the seedlings.

The results of the created GAMMs using the different microsites covers as explanatory variables were not statistically significant ($p>0.05$). Nonetheless, seedlings were just found in subplots in which the cover of herbaceous vegetation was between 0 to 15% with a mean value of 2.14±1.01%, and the shrub cover between 0 to 35%, with a mean value of 10.71±2.35%. This contrasts with all the recorded values of those two microsite covers, that ranged between 0 to 60% with a mean value of 9.54±1.80% in case of herbaceous vegetation, and between 0 to 65% with a mean value of 13.22±1.67% in case of shrubs. It shows that seedlings have a preference for plots that are not densely covered by other species. These results align with another study that tried to model *Q. semecarpifolia* seedlings density with the different recorded microsites and were also non-significant (Dhendup, 2013).

4.2.2. *Quercus lanata*

The results of the GAMM show that the variables with highest influence on the density of seedlings are “the distance to the PMT”, “thickness of the organic horizon” and “Global Site Factor (GSF)” (see **Table 5**).

The negative influence of the variable “distance to the PMT” shows the low seed dispersal capability of the species, as well as the lack of wildlife in the area.

The symmetric shape of the relationship between “GSF” with the “density of seedlings” has its peak at a value of 0.4, when the influence of the other two significant variables is taken into account. This means that the density of seedlings was higher in the subplots that received 40% of the total global radiation they would have received under open exposure. When compared with the mean GSF value of the subplots that contained *Q. semecarpifolia* regeneration (0.2±0.12), it shows that these seedlings are more light demanding.

The shape of the relationship between the variable thickness of the organic horizon and density of seedlings seems to be a negative left-hand skewed curve. This suggests a positive influence of thick organic horizons until a limit of 13 cm is reached. This preference for thick organic horizons is similar to the tendency shown by the other studied species. Nevertheless, *Q. lanata* seedlings do not produce an abnormal elongation of the petiolar tube as dramatic as *Q. semecarpifolia*. As a consequence, it is predicted that after a certain thickness limit (smaller if compare with the other *Quercus spp.*), the density of seedlings would decrease due to their incapability of reaching the mineral horizon.

The range of the pH values of the organic horizons of the subplots that contained regeneration was wider than the ones of the previous *Quercus.* Also, the fact that the mean pH value is lower shows that its seedlings can grow in more acidic soils.

Even though the surveyed plots were located on slopes with a gradient ranging between 30 to 98.5%, seedlings were exclusively found between 50 to 98.5% gradient, with a steepness mean value of 75.46±13.78%. These range and mean value are higher than the ones recorded for *Q. semecarpifolia*. Slope steepness is associated with the accessibility of an area, which is closely related to the human-pressure that it will receive. It was seen that individual trees can cope well with the current level of human-induced disturbances because they were flowering profusely even when heavily lopped, but the seedlings seem to survive better in less accessible areas, probably due to the less intense grazing and trampling pressure, which seems to be the main deterrent for this species.

As in the case of *Q. semecarpifolia*, the results of the GAMMs that tried to model the response variable “density of *Q. lanata* seedlings” using as explanatory variables the different “microsite covers” were not statistically significant ($p>0.05$). Furthermore, the ranges and mean values of the different “microsite covers” of the subplots on which regeneration was found are very similar to the ranges and mean values of all the recorded subplots.

5. Conclusions

The results of this study has shown that there are differences in the regeneration ecology and in the ability to cope with the current human-induced disturbances between the two studied *Quercus* species. Therefore, different guidelines need to be develop for their successful plantation and for a sustainable forest management strategy.

5.1. Quercus semecarpifolia

The results of the height class diagrams show that regeneration is continuous in the least degraded forest and almost completely absent in the disturbed forest, which may lead to the displacement of this species by other tree species in the future. It also shows that canopy disturbances create a very dense herbaceous and shrub layer, which may outcompete *Q. semecarpifolia* seedlings and saplings.

The findings of the study show that the main variables affecting the regeneration of this species are the “disturbance level” of the individual trees and of the overall forest, the “distance to a PMT”, and how developed the soil is, measured by the “thickness of the O horizon”, and the “amount of roots in the A horizon”.

Seedlings seem to prosper in shady environments but in order to survive to the next life stage (saplings) it has been reported that they need a more open canopy (Vetaas, 2000; Tashi, 2004; Giri and Katzensteiner, 2013). Therefore, this need for a certain amount of canopy removal needs to be taken into account for adaptive forest management purposes.

5.1.1. Guidelines

Seed collection

In order to collect seeds for plantation purposes of this tree species, the phenology of the mother tree needs to be taken into account. In the studied area, 2 different forests, at different altitudes, and with different disturbance levels were surveyed. It is recommended to take the elevation of the areas that are planned to be restored into account, while choosing the forest from which seeds will be collected. If the areas to restore are in Bulung VDC, at high elevations, then the logical choice would be to collect the seeds from the Thado Khola community forest also located in Bulung, which hosts a high density of mature, relatively undisturbed, *Q. semecarpifolia* trees. Therefore, the chances of finding seeds are very high. This forest is relatively difficult to access due to the distance from the closest village (Bulunghkani), its high altitude and its steep slope (61.74±7.4%).

It is also recommended not to collect seeds from just a couple of trees, but from as many as possible, in order to increase the genetic variability of the *Quercus* population of the area to be restored. The facing aspect of the slope in which the forest is located is also an important variable to take into consideration. Both surveyed forests were facing mainly south south-west.

According to the literature, the seeds of this tree ripen during July and August, and once they fall germinate immediately. Some even start to germinate before falling (vivipary). Therefore, it is recommended to visit the forest with the purpose of collecting seeds during that period in order to have the highest chances of success. This period coincides with the monsoon, making it difficult as well as risky to access some parts of the forest. It is also recommended to plant the seeds immediately after retrieval, due to their incapacity of being stored (recalcitrant behaviour) (Troup, 1921; Vetaas, 2000; Orwa *et al.*, 2009).

Planting conditions and forest management

According to the results of the present analysis, the main variables contributing to the successful establishment of the seedlings are the "thickness of the organic (O) horizon" and the "amount of roots in the A horizon."

That the two only statistically significant variables are the ones related to the successful accumulation of organic matter on the topsoil horizons, indicates that human-induced disturbances, such as litter collection, as well as grazing and trampling by the cattle, may pose a serious threat to the germination of seeds, as well as to the survival of the seedlings. Therefore, it is recommended to control such activities in the areas that are going to be restored and where the seeds are planned to be sown.

It is also proposed to sow the seeds on soils with the topsoil already developed. If this is not possible because the area is too degraded, then topsoil may be added from an external source, such as the soil of a surrounding forest. Manure or compost may also be applied to the plant hole.

Few information is available in the literature about the successful transplantation of seedlings from nurseries, but there are positive records in which seeds were planted by direct sowing in contour lines or by dibbing already on the desired area. The main problem, suggested by its germination ecology is that, because it produces thick and numerous roots even in its early life stage, the transplantation would damage the root system, and kill the seedling or sapling in the long term (Troup, 1921). Therefore, it is suggested to sow the seeds already on the area desired to be restored.

The results of the "GSF" variable suggest that the seedlings are shade tolerant, because they are mainly found in low-medium values of the proportion of global radiation, but on the other hand, the literature suggest that they can just reach their next life stage if they receive abundant solar radiation (Troup, 1921; Vetaas, 2000; Tashi, 2004). Therefore, for adaptive management, it is suggested to establish seeds in gaps of different sizes and to monitor their development. It is also recommended to widen the gaps and to thin the stands as the seedlings and saplings grow.

As shown in **Figure 18**, the LUs, which in this case expresses the amount of human-induced disturbances of the area, is one of the most important factors to be taken into account. The lack of regeneration in the PP and the low density of seedlings in the DF, contrast with its high density in the LD. This suggests that in the area planned to be restored, human activities such as collection of litter and firewood, lopping of branches, and grazing and trampling will need to be controlled. The literature suggests that *Q. semecarpifolia* stops producing seeds if the lopping rotation period is shorter than 3-4 years (Orwa *et al.*, 2009). Therefore, another recommended measure is to make sure that in the community forests of the study area this time limit is followed, if continuous regeneration of the forest is desired. To have sustainable management plans implemented on natural forest in which the lopping rotation period is respected as well as grazing is controlled, is as important as restoring degraded areas.

As a final remark, the effect of the variable "distance to the PMT" evidences the problem of seed dispersal in the area. Therefore, it is recommended to protect individual PMT from lopping in order to secure a continues supply of seeds over time. Especially the PMT located inside or near DFs need to be protected. The only completely undisturbed *Q. semecarpifolia* individual that was found in the study area was located near a temple, in a remote area in Bulung VDC, which was protected because it was considered sacred. As expected, the surroundings of that area had abundant regeneration, due to a continuous supply of seeds from the undisturbed PMT. For that reason, one option to protect individual PMTs inside DF from human-induced disturbances with the objective of assuring a continuous supply of seeds, could be to celebrate a tree-adoption event with the local communities and to give a special status to the selected PMTs. This may lead to a more successful protection (Avtzis *et al.*, 2018).

Also, the DBH and height classes distributions of trees in the DF shows that the failure of regeneration is a real problem. If management patterns are not adapted, the DF will become dominated by other less useful species for the local communities.

For these reasons, it is crucial to restore the degraded and unproductive areas, especially the ones located far from the small remnants of LD forest.

5.2. Quercus lanata

The height classes diagrams show that it regenerates well, even under heavy anthropogenic pressure. The dense layer of shrubs and herbaceous vegetation recorded in the DF is associated with the low seedling density in the two bigger height classes, even though it was detected that in some cases thorny shrubs protected the seedlings from grazing animals. Nevertheless, if a continuous regeneration is desired, manual removal of less useful shrubs spp. as well as protection from grazing should be carried out.

It seems to have a more generalist strategy when compared with *Q. semecarpifolia.* The conditions on which it seedlings are found are more diverse. Also, it can withstand human-induced disturbances much better, because in heavily degraded sites the individuals were still flowering, and regeneration was present.

“Distance to the PMT” also affected the density of seedlings of this tree species, which may show a lack of wildlife in the study area that could disperse the seeds of both trees. “Thickness of the O horizon” also had an effect, showing that it prefers it thick but not as much as the other species, probably because it does not elongate the taproot as much. Also, the significant effect of “GSF” showed that it is a light demanding species, and that even when they are at the seedling state, they required an open canopy.

5.2.1. Guidelines

Seed collection

In the study area, the only *Q. lanata* forest that remains little disturbed was found in Orang VDC. The *Q. lanata* forests located in Laduk and Bulung VDC were facing considerable human-induced disturbances. Nevertheless, there wasn’t much difference in the density of trees and the DBH distribution of the studied forests of both disturbances levels. The studied DF even had more regeneration than the LD one, highlighting the ability to cope with disturbances of this tree spp.

As it has been reported by Troup (1921), flowering and pollination occurs at the end of April and during May. The fieldwork was conducted between April and June 2017 and it could be observed that almost all the individuals on both, LD and DF were flowering, even the heavily lopped ones. Therefore, for selecting the forest where seeds will be collected from, it is important to notice that the level of disturbance does not seem to affect the occurrence of seeds. Furthermore, this species does not have a masting strategy, so it is expected to find seeds every year given the proper season.

After 8 months of the pollination of the flowers at the end of December and in January, the nuts ripen. Under natural conditions they will remain on the soil surface during the dry season and germinate during the rainy season, starting in July (Troup, 1921).It is advised to collect the seeds as soon as the nuts ripen because they are very liable to insect attacks and in order to avoid further predation risk, they can be stored until the end of the dry season and the beginning of the rainy season and then planted on the nursery or on the desired plots (Jackson, 1994).

Care will need to be taken while assessing which forest is better for the recollection of seeds, regarding the aspect that both, the forest and the desired plot to be restored are facing. The aspect will strongly determine the conditions in which the seedlings will need to grow. It is important to notices that all the plots on which regeneration was found were facing south, south-east and south-west, which are also the preferred aspects of this species (Shresta *et al.*, 2002; Miehe *et al.*, 2015).

Planting conditions and forest management

"Distance to the PMT", "thickness of the organic horizon" and "GSF" were the variables that explain the best the distribution of the seedlings, as assessed by the GAMM results. Seedlings flourish under medium-low values of "GSF", but the dramatic lack of regeneration in the bigger height classes of the LD forest highlights the importance of having an open canopy for the seedlings to continue growing. The model also suggest that the seedlings prefer a soil organic horizon that is already developed.

It is reported by (Troup, 1921) that this tree spp. can be successfully grown in nurseries and then transplanted to the desired site, taking good care on not to expose and damage the root system. Also, as it is for the other *Quercus spp*. direct sowing on the desired site seems to be the preferred method for artificial reproduction.

In both Laduk and Bulung VDCs, seedlings were observed and recorded growing in old pine plantations of *Pinus patula*. This pine stands were too dense, with some individuals having a high risk of falling. These plantations provide timber to the local community but a *Q. lanata* mixed forest with other useful species for the local communities, like the DF described in Bulung VDC, could provide more ecosystems services besides timber, such as fodder and an increment in biodiversity. It is recommended to protect the *Q. lanata* seedlings found in those plantations, to artificially create gaps in the canopy trough thinning of the stands, and later on make enriching plantations with the desired tree species.

The current management system and its associated level of human pressure does not seem to reduce the ability of the trees to produce seedlings. But on the contrary, it seems to have a positive influence on the establishments of seedlings due to the artificial creation of gaps in the canopy.

Grazing, trampling, litter collection, competing vegetation and especially light availability seem to be the factors that more influence the regeneration success to a greater extent. Therefore, it is recommended to protect individual seedlings from these impacts. Cattle should be excluded trough provisional fencing of the individual plot units or selected seedlings and saplings. On the other hand, individual seedlings and saplings can be protected and the cattle can be used as a tool of shrubs control. In this case it is not as important to protect PMT as it is to protect individual selected seedlings and saplings. The recommended forest management is also adaptive management, in which special focus should be put on the continuous widening of the canopy gaps, due to the major importance of this variable.

Summarizing, the main requirements for a successful establishment of *Q. lanata* seedlings seems to be: enough solar radiation, a well-developed organic horizon, and protection against grazing and trampling.

5.3.Outlook

The study area offers many opportunities for ecological restoration or afforestation projects. Abandoned patches of former agricultural land is available due the massive outward migration that the area has faced (Niraula, Maharjan and Pokharel, 2011). In some of these uncultivated areas natural regeneration is happening, but in some cases it is being arrested due to the high grazing pressure and the presence of a thick layer of shrubs and invasive grass species. Furthermore, the abundance of pine plantations in the area (Niraula *et al.*, 2013) offers a great chance of transforming them into a more diverse mixed forest of native species, that could provide more services to the local communities. *Q. lanata* seedlings and young trees were found in these plantations, but it was not the case for *Q. semecarpifolia*. This suggests that for plantations located in areas suitable for *Q. lanata* assisted natural regeneration may be an easy and successful strategy. In order to bring *Q. semecarpifolia* back to the old pine plantations established in suitable areas for it, a more intense strategy should be developed such us direct sowing of seeds and later on follow the already described adaptive management.

In this study, the excess of subplots with absence of regeneration (69% and 70% for *Q. semecarpifolia* and *Q. lanata* respectively), may have produced biased parameter estimates and standard errors. Therefore for future ecological regeneration studies it is recommended to use zero inflated GMMs (Zuur, Ieno and Elphick, 2010) if this situation is faced. Another important covariate that was not recorded and may have had a big influence on the density of seedlings is distance to the nearest settlement, which is predicted to have a positive correlation with the disturbance level of the forests (Wangda and Ohsawa, 2006). Furthermore, this study has shown the importance of plotting and checking the different residuals, in order to validate or reject the created models.

In order to continue investigating which environmental variables drive the successful establishment and development of the studied species, experiments under controlled conditions need to be done. They can be developed in greenhouses in which the levels of the different possible explanatory variables are known and effect-response relationships can be deduced. Moreover, long term monitoring forest plots could be established with the objective of studying which environmental variables drive the survival of the seedlings and saplings to the next life stage.

As it has already been stated, human-induced disturbances are some of the main drivers on the density of seedlings of these species. Therefore, education programs or workshops could be implemented with the objective of reflecting about the impact of the local communities activities on the regeneration of these valuable and useful tree species and together with them, develop and agree on new management strategies. Furthermore, new technologies could be adopted in order to reduce pressure on the native forest, such us improved cooking stoves. The local communities are the ones with the stronger interest on having healthy forest and, as suggested by the success of numerous community-based forest management projects in Nepal (Nagendra, 2007) and around the world (Stevens *et al.*, 2014), local communities are the best stewards of their forests.

6. References

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Appendix I: Images

Image A2: *Q. semecarpifolia*

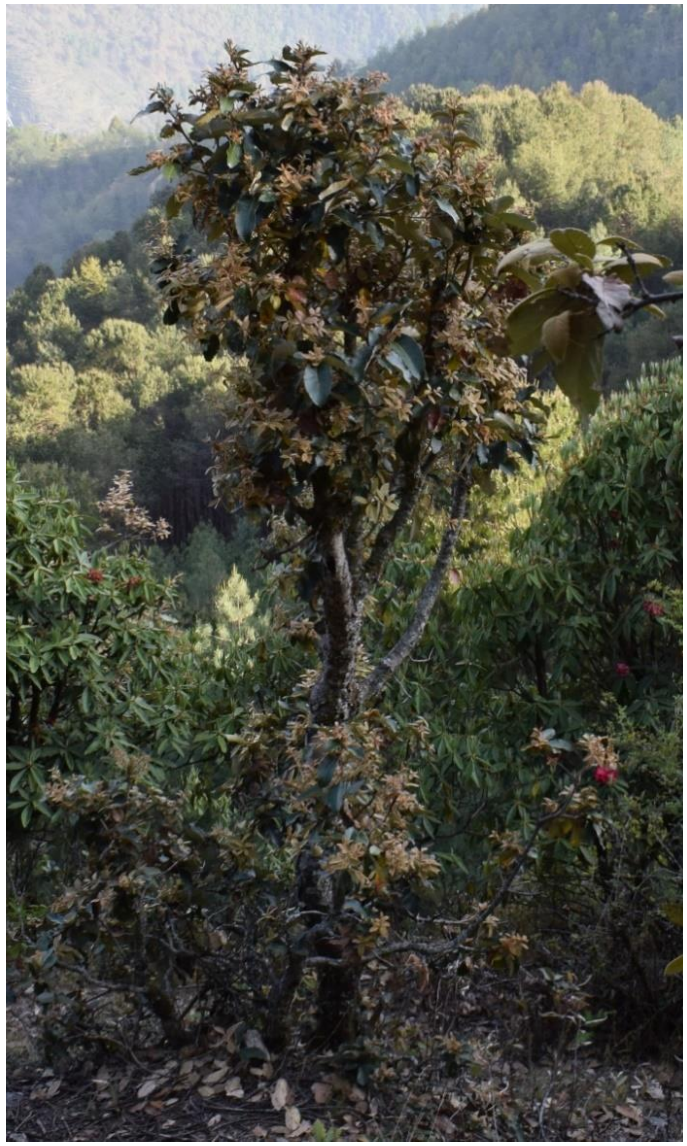

Image A1*: Q. lanata*

Image A3*:* Lopped *Q. semecarpifolia*

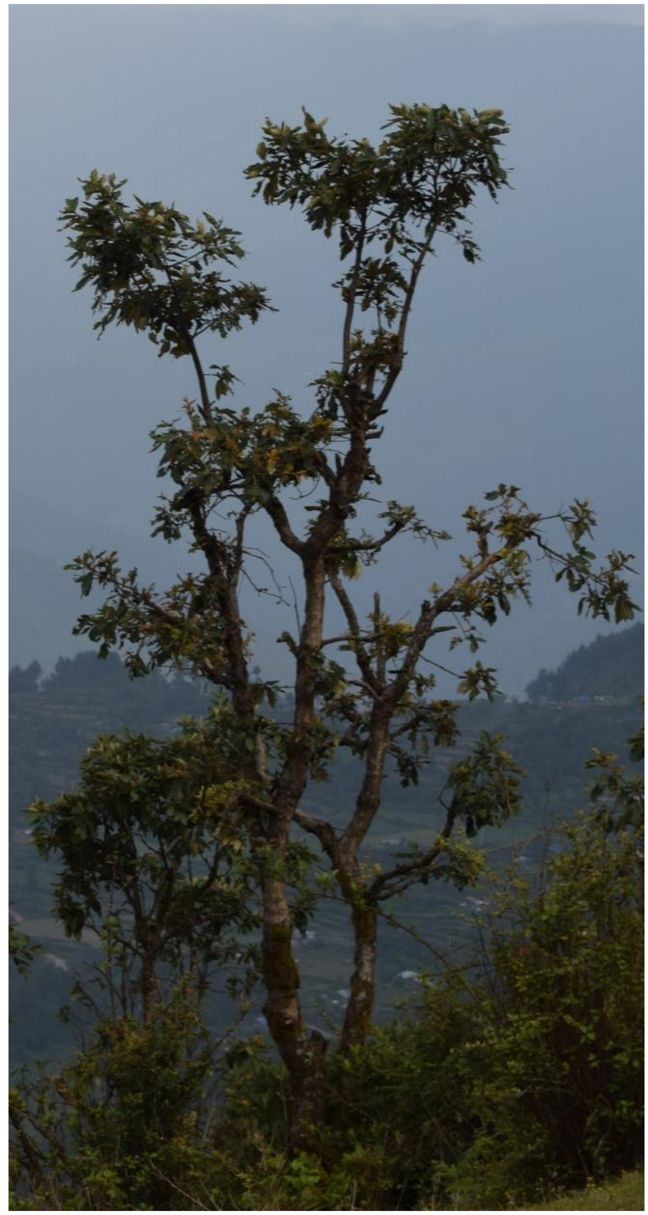

Image A4: Lopped *Q. lanata*

Image A6: Lopping of the branches of a *Q. semecarpifolia*

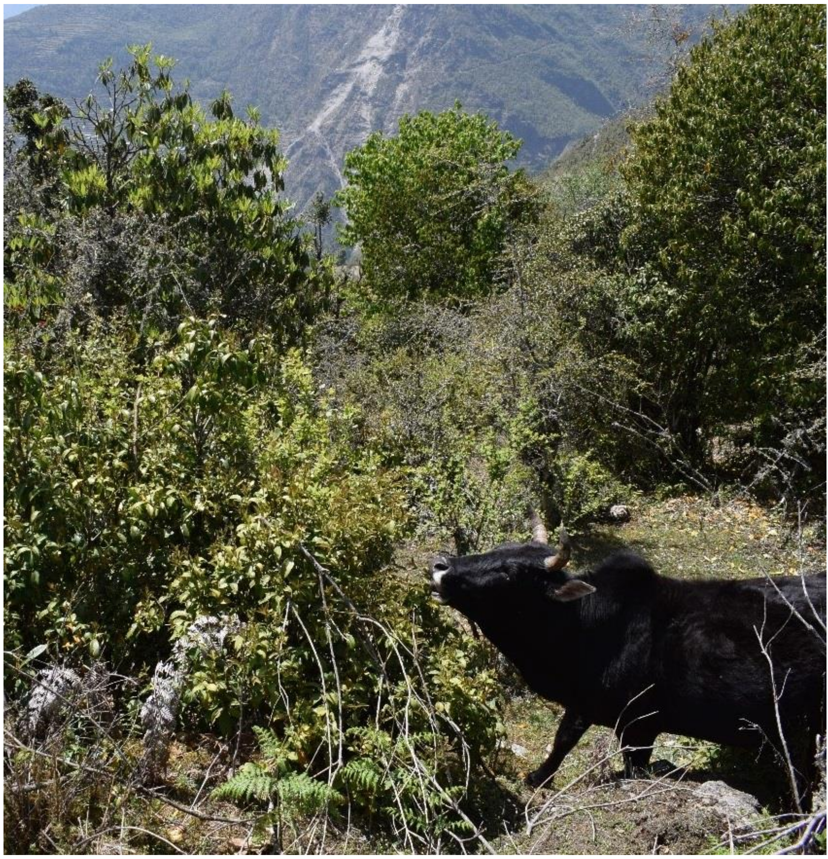

Image A5: Free-grazing cattle

Image A8: Example of a 1x1m frame of the established subplots with presence of *Q. lanata* regeneration

Image A7: *Q. lanata* seedlings and saplings protected by thorny shrubs (*Berberis asiatica*)

Image A9: Fisheye lens camera on the self-levelling mount and tripod

Image A10: Example of a Hemispherical picture

Appendix II: Tables

Table A6: Disturbance levels for plants higher than 1.3 m The human-induced disturbance considered was lopping of branches.

Disturbance levels for plants H>1.3m		
0	Not disturbed	No visible signs of human-induced disturbances (lopping)
1	Lowly disturbed	Artificially reduced crown is appreciated. Loss of less than 20% of it is estimated. Signs of lopping, such as cut branches, are found.
2	Medium disturbed	Artificially reduced crown can be clearly appreciated (more than 20%). Presence of branches without leaves. Sings of a more intensive and repetitive lopping such us cuts on the trunk and more cut branches.
3	Highly disturbed	Extreme cases of individuals heavily lopped, with almost complete absence of branches and foliage. Usually pole-like or multi-stem shape.

Table A7: Disturbance levels for plants smaller than 1.3 m The human-induced disturbances considered were grazing and trampling by cattle*.

Disturbance levels for plants H<1.3m		
0	Not disturbed	No visible signs of human-induced disturbances (grazing or trampling)
1	Lowly disturbed	Less than 20% of the leaves are estimated to be lacking, or to have signs of grazing such us lacking of parts of it
2	Medium disturbed	The lack of leaves is clearly appreciated (more than 20%), as well the presence of broken leaves
3	Highly disturbed	Extreme cases of individuals with an almost completely lack of leaves, and a dominance of broken leaves of the remaining ones

Table A8: Disturbance levels for cluster of plots. The human-induced disturbances considered were lopping, grazing, trampling* and presence of stumps from felled trees.

Disturbance levels for site description		
0	Not disturbed	No visible or minimal signs of human-induced disturbances (lopping, grazing, trampling, and presence of stumps from felled trees)
1	Lowly disturbed	Less than 20% of the trees are estimated to be lopped. Absence of grazing and trampling signs.
2	Medium disturbed	More than 20% of the trees are lopped. Presence of smaller plants with signs of grazing. Presence of clearings that can be linked to lopping, felling and/or grazing.
3	Highly disturbed	The majority of the trees (>75%) have been lopped. Presence of stumps from felled trees. The majority of the smaller plants (>75%) have signs of having been grazed. Presence of clearings that can be linked to lopping, felling and/or grazing.

*It is acknowledged that grazing and/or trampling by cattle, could have instead been caused by wildlife, but it is assumed that the impact is much lower.

Table A9*:* Created Dominant Soil Cover Functional Groups grouping together different microsites.

Dominant Soil Cover Functional Groups (DSFG)		
DC	Densely cover	Herbaceous vegetation >50% or Shrubs>50% or Herbaceous vegetation, Shrubs and Quercus >70%
NS	Nude soil	Boulders>50% or Mineral soil>50% or both>70%
LD	Leaves dominated	Leaves>75%
LC	Leaves & other microsites	Leaves>50%
MX	Combination of microsites	

Table A10: Mean ± standard deviation densities of functional groups per DBH class of plants higher than 1.3 m on the *Quercus semecarpifolia* forest. Units in individuals per hectare.

***Quercus semecarpifolia* DBH classes (H>1.3m)**							
Land Use	Functional groups	<10cm	10-30cm	31-50cm	51-70cm	71-90cm	>90cm
Least Degraded	Shrub	76.39±69.74	0	0	0	0	0
	Quercus	458.37±377.7	76.39±69.74	25.46±56.94	76.39±113.88	76.39±69.74	50.93±69.74
	Rhododendron	280.11±166.01	127.32±90.03	0	0	0	0
	Conifer	0	25.46±56.94	0	0	0	0
	Ilex	25.46±56.94	0	0	0	0	0
	Bamboo	509.3±1138.82	0	0	0	0	0
Degraded Forest	Shrub	254.65±201.32	50.93±113.88	0	0	0	0
	Quercus	50.93±113.88	305.58±332.02	50.93±69.74	25.46±56.94	0	0
	Rhododendron	356.51±166.01	280.11±166.01	50.93±113.88	0	25.46±56.94	0
	Framework tree spp.	0	25.46±56.94	0	0	0	0

Table A11*:* Mean ± standard deviation densities of functional groups per height class of plants smaller than 1.3 m on the *Quercus semecarpifolia* forest. Units in individuals per hectare.

***Quercus semecarpifolia* Height classes (H<1.3m)**					
Land Use	Functional groups	>10-30cm	31-60cm	61-90cm	91-130cm
Least Degraded	Shrub	101.86±227.76	407.44±426.11	814.87±1172.49	305.58±455.53
	Quercus	488.64±363.08	818.24±770.76	611.15±836.86	203.72±455.53
	Rhododendron	0	203.72±455.53	101.86±227.76	0
	Herbaceous	0	0	101.86±227.76	0
Degraded Forest	Shrub	101.86±227.76	1629.75±1586.19	1324.17±1422.39	916.73±1502.21
	Quercus	0	126.14±130.41	19.59±43.81	0
	Pioneer	0	0	203.72±455.53	203.72±455.53
	Invasive grass	407.44±911.06	1018.59±2005.1	407.44±557.91	0
	Herbaceous	509.3±882.13	2240.9±683.29	611.15±557.91	305.58±455.53

Table A12: Mean ± standard deviation densities of functional groups per DBH class of plants higher than 1.3 m on the *Quercus lanata* forest. Units in individuals per hectare.

		Quercus lanata **DBH classes (H>1.3m)**					
Land Use	Functional groups	<10cm	10-30cm	31-50cm	51-70cm	71-90cm	>90cm
Least Degraded	Shrub	254.65±180.06	0	0	0	0	0
	Quercus	356.51±375.55	814.87±248.2	0	0	0	0
	Rhododendron	127.32±220.53	356.51±353.31	0	0	0	0
	Pioneer	178.25±170.82	0	0	0	0	0
	Quercus Sem.	0	50.93±113.88	0	0	0	0
Degraded Forest	Shrub	560.23±388.29	50.93±69.74	0	0	0	0
	Quercus	356.51±317.03	687.55±472.99	25.46±56.94	0	0	0
	Rhododendron	280.11±375.55	50.93±69.74	0	0	0	0
	Pioneer	0	25.46±56.94	0	0	0	0
	Framework tree spp.	127.32±127.32	229.18±276.03	0	0	0	0

Table A13: Mean ± standard deviation densities of functional groups per height class of plants smaller than 1.3 m on the *Quercus lanata* forest. Units in individuals per hectare.

		Quercus lanata **Height classes (H<1.3m)**			
Land Use	Functional groups	>10-30cm	31-60cm	61-90cm	91-130cm
Least Degraded	Shrub	101.86±227.76	916.73±979.65	713.01±580.69	1629.75±278.95
	Quercus	647.26±449.14	203.72±278.95	101.86±227.76	203.72±278.95
	Rhododendron	0	0	101.86±227.76	0
	Pioneer	0	0	101.86±227.76	0
	Invasive grass	101.86±227.76	713.01±1328.08	305.58±683.29	0
Degraded Forest	Shrub	305.58±455.53	1324.17±580.69	2750.2±1673.72	1833.46±1376.04
	Quercus	689.78±672.19	1629.75±1458.4	305.58±455.53	305.58±455.53
	Pioneer	203.72±455.53	305.58±278.95	203.72±278.95	305.58±455.53
	Invasive grass	407.44±426.11	1120.45±836.86	1833.46±1634.51	611.15±664.04
	Herbaceous	0	101.86±227.76	101.86±227.76	305.58±455.53
	Framework tree spp.	0	0	101.86±227.76	101.86±227.76

Table A14: Descriptive analysis of the studied variables in all the *Q. semecarpifolia* plots (n=76)

Variables	**Abbreviation**	**Unit**	**Min**	**Max**	**Mean**	**SD**	**SE**	**Trend**
Response variables								
Density of Seedlings	Seedlings	N°/m²	0	8	0.58	1.36	0.16	
Presence	Presence	No(0)/Yes(1)	0	1	0.28	0.45	0.05	
Site variables - Plot level								
Aspect	Aspect	cos+1	0	2	0.73	0.84	0.1	
Elevation	Elevation	Meters	2338	2915	2552	171.46	19.67	
Slope gradient	Gradient	%	20.9	90	63.92	20.9	1.85	
Disturbance	Disturbance	Value	0	3	1.58	1.1	0.13	
Land Use	LU	Categories						
Position	Position	Categories						
Slope form and Surface pathways	SlopeForm	Categories						
Microsite variables - Subplot level								
Global Site Factor	GSF	Proportion	0.03	0.8	0.21	0.14	0.02	Non-linear
Distance to the Potential Mother Tree	Distance.PMT	Meter	1	125	25.87	38.7	4.44	Decrease
N° of competing vegetation	N.compt	Value	0	18	3.87	4.12	0.47	Decrease
O horizon thickness	O.Thick	Centimetres	0.5	21	6.1	4.16	0.48	Increase
O pH	O.pH	Value	4.5	8.1	5.67	0.6	0.07	Non-linear
O Texture	O.Texture	Categories						
A Carbon content	A.C	%	1.87	5.32	3.72	0.87	0.1	Decrease
A Rock content	A.Rock	%	0	35	9.58	9.98	1.15	Non-linear
A Root	A.Root	Value	0	3	1.57	0.6	0.07	Increase
A pH	A.pH	Value	4	6.6	5.5	0.57	0.06	Non-linear
A Texture	A.Texture	Categories						
Dominant Soil Cover Functional Groups	DSFG	Categories						

Table A15: Descriptive analysis of the studied variables in the *Q. semecarpifolia* plots without the Pine Plantation plots (n=68)

Variables	**Abbreviation**	**Unit**	**Min**	**Max**	**Mean**	**SD**	**SE**	**Trend**
Response variables								
Density of Seedlings	Seedlings	N°/m²	0	8	0.65	1.42	0.17	
Presence	Presence	No(0)/Yes(1)	0	1	0.31	0.47	0.06	
Site variables - Plot level								
Aspect	Aspect	cos+1	0	2	0.7	0.84	0.1	
Elevation	Elevation	Meters	2338	2915	2558	179.75	21.8	
Slope gradient	Gradient	%	20.9	81.3	61.74	15.41	1.87	
Disturbance	Disturbance	Value	0	3	1.59	1.5	0.14	
Land Use	LU	Categories						
Position	Position	Categories						
Slope form and Surface pathways	SlopeForm	Categories						
Microsite variables - Subplot level								
Global Site Factor	GSF	Proportion	0.03	0.8	0.2	0.14	0.02	Non-linear
Distance to the Potential Mother Tree	Distance.PMT	Meter	1	125	22.21	36.31	4.4	Decrease
N° of competing vegetation	N.compt	Value	0	13	3.35	3.35	0.41	Decrease
O horizon thickness	O.Thick	Centimetres	0.5	21	6.26	4.3	0.52	Increase
O pH	OH.pH	Value	4.5	8.1	5.63	0.61	0.07	Non-linear
O Texture	OH.Texture	Categories						
A Carbon content	A.C	%	1.87	5.32	3.66	0.88	0.11	Decrease
A Rock content	A.Rock	%	0	35	8.72	9.93	1.2	Non-linear
A Root	A.Root	Value	0	3	1.632	0.6	0.07	Increase
A pH	A.pH	Value	4	6.6	5.33	0.56	0.07	Non-linear
A Texture	A.Texture	Categories						
Dominant Soil Cover Functional Groups	DSFG	Categories						

Table A16: Descriptive analysis of the studied variables in all the *Q. lanata* plots (n=92)

Variables	Abbreviation	Unit	Min	Max	Mean	SD	SE	Trend
Response variables								
Density of Seedlings	Seedlings	N°/m²	0	18	0.85	2.11	0.22	
Presence	Presence	No(0)/Yes(1)	0	1	0.3	0.46	0.05	
Site variables - Plot level								
Aspect	Aspect	cos+1	0	2	0.66	0.61	0.06	
Elevation	Elevation	Meters	2064	2408	2221	92.23	9.62	
Slope gradient	Gradient	%	30	98.5	62.96	21.23	2.21	
Disturbance	Disturbance	Value	0	3	1.44	0.93	0.1	
Land Use	LU	Categories						
Position	Position	Categories						
Slope form and Surface pathways	SlopeForm	Categories						
Microsite variables - Subplot level								
Global Site Factor	GSF	Proportion	0.06	0.66	0.26	0.15	0.02	Non-linear
Distance to the Potential Mother Tree	Distance.PMT	Meter	0.5	97	22.99	30.26	3.16	Decrease
N° of competing vegetation	N.compt	Value	0	30	6.12	5.91	0.62	Non-linear
O horizon thickness	O.Thick	Centimetres	0	18	4.56	3.22	0.34	Non-linear
O pH	O.pH	Value	4.2	5.37	6.6	0.56	0.06	Non-linear
O Texture	O.Texture	Categories						
A Carbon content	A.C	%	1.28	5.32	3.53	75.12	7.83	Non-linear
A Rock content	A.Rock	%	1	60	12.92	13.88	1.45	Decrease
A Root	A.Root	Value	1	3	1.4	0.56	0.06	Increase
A pH	A.pH	Value	4.5	6.3	5.39	0.38	0.04	Non-linear
A Texture	A.Texture	Categories						
Dominant Soil Cover Functional Groups	DSFG	Categories						

Table A17: Coordinates of the location of the studied *Q. lanata* (n=23) and *Q. semecarpifolia* (n=19) clusters of plots. *Asterisk* represents the plots where the vegetation surveys were conducted.

Q. Lanata plots name	Latitude	Longitude	*Q. Semecarpifolia* plots name	Latitude	Longitude
LAN/BU/TM/DF-1	27.78949	86.16687	SEM/BU/TKM/DF-1	27.795	86.16472
LAN/LA/TM/DF-2	27.78556	86.15917	SEM/BU/TKM/DF-2	27.79278	86.16665
LAN/LA/TM/DF-3	27.78389	86.15889	SEM/BU/TKM/DF-3	27.79917	86.16333
LAN/LA/TM/DF-4	27.77444	86.16528	SEM/BU/TKM/DF-4	27.79778	86.16667
LAN/LA/TM/DF-5	27.77056	86.17028	SEM/BU/TKM/DF-5	27.8075	86.16278
LAN/BU/SP/DF-6*	27.79444	86.17333	SEM/LA/TM/DF-6	27.79389	86.16
LAN/BU/SP/DF-7*	27.79361	86.17333	SEM/LA/TM/DF-7	27.78861	86.16222
LAN/BU/SP/DF-8*	27.79306	86.17306	SEM/LA/TM/DF-8*	27.79639	86.15667
LAN/BU/SP/DF-9*	27.79328	86.17389	SEM/LA/TM/DF-9*	27.79778	86.15611
LAN/BU/SP/DF-10*	27.79306	86.1725	SEM/LA/TM/DF-10*	27.79944	86.155
LAN/BU/TM/PP-1	27.7875	86.165	SEM/LA/TM/DF-11*	27.80111	86.15444
LAN/BU/TKM/PP-2	27.77667	86.17806	SEM/LA/TM/DF-12*	27.80222	86.155
LAN/LA/FT/PP-3	27.76611	86.17278	SEM/BU/TKM/PP-1	27.80254	86.16362
LAN/LA/TM/PP-4	27.78306	86.15861	SEM/BU/TKM/PP-2	27.80778	86.17056
LAN/LA/TM/PP-5	27.785	86.15833	SEM/BU/TK/LD-1*	27.815	86.17583
LAN/LA/TM/PP-6	27.77528	86.16444	SEM/BU/TK/LD-2*	27.81694	86.17611
LAN/LA/FT/PP-7	27.76611	86.17083	SEM/BU/TK/LD-3*	27.81444	86.17806
LAN/LA/FT/PP-8	27.7675	86.17056	SEM/BU/TK/LD-4*	27.81528	86.17861
LAN/OR/TPD/LD-1*	27.80194	86.18806	SEM/BU/TK/LD-5*	27.81556	86.17972
LAN/OR/TPD/LD-2*	27.80222	86.18778			
LAN/OR/TPD/LD-3*	27.80258	86.18672			
LAN/OR/TPD/LD-4*	27.80139	86.18583			
LAN/OR/TPD/LD-5*	27.80194	86.18556			

An interactive map has been created with the exact location of the plots, and can be accessed through the following link (Google Maps, 2018):

https://www.google.com/maps/d/edit?mid=1mDfYggbbGNjTs4NErTgzHnL0IqKbuDab&ll=27.793225236802136%2C86.16915235027272&z=16

Appendix III: Validation plots

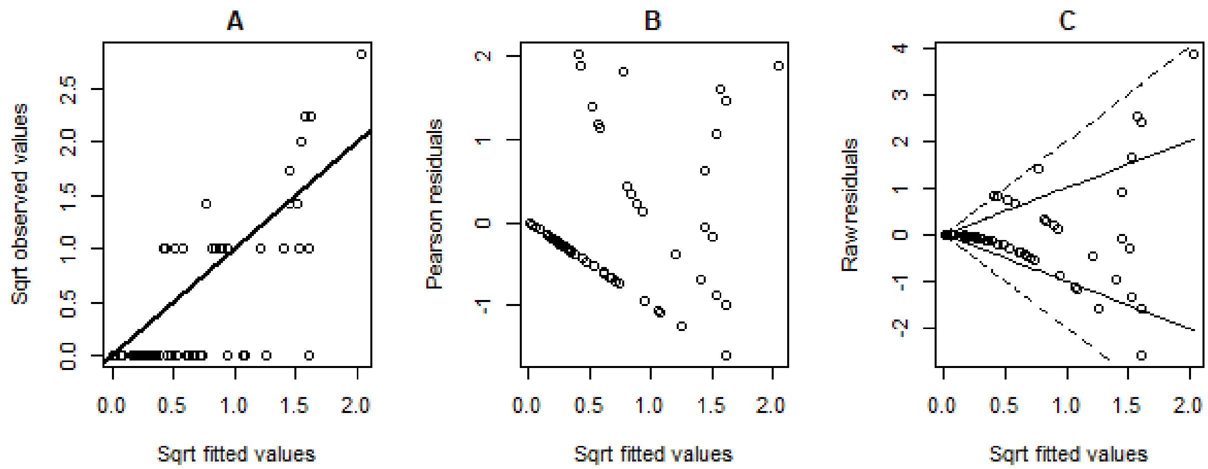

Figure A22*:* Validation plots of the GAMM developed to model *Q. semecarpifolia* seedling density. Plot A shows the relation between raw data and fitted values, which should follow a straight line. Plot B shows the relation between Pearson residuals against fitted values and should show bands with no patterns. Plot C shows raw residuals against fitted values and it should show the shape of a cone. Reference lines display where 1 residual standard deviation and 2 residual standard deviations from the residual mean should lie, for each fitted value. Based on Wood (2006).

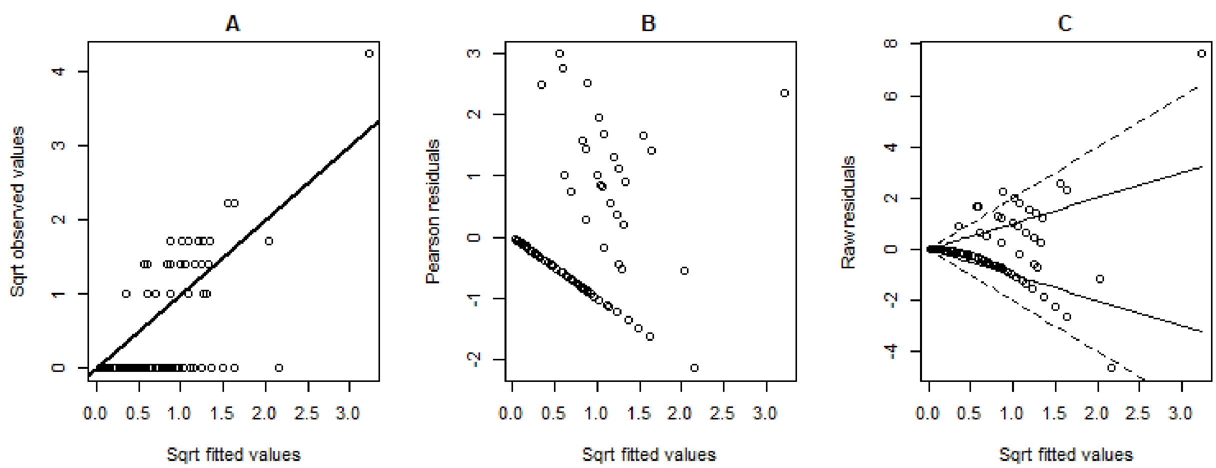

Figure A23: Validation plots of the GAMM developed to model *Q. lanata* seedling density. Plot A shows the relation between raw data and fitted values, which should follow a straight line. Plot B shows the relation between Pearson residuals against fitted values and should show bands with no patterns. Plot C shows raw residuals against fitted values and it should show the shape of a cone. Reference lines display where 1 residual standard deviation and 2 residual standard deviations from the residual mean should lie, for each fitted value. Based on Wood (2006).