Examensarbeten 2016:6

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Institutionen för skogens ekologi och skötsel

Restoration of degraded tropical rainforests through gap and line planting:

Effects on soil and light conditions and seedling performance

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Sveriges Lantbruksuniversitet
Examensarbete i biologi, 30 hp, avancerad nivå A2E
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Restaurering av degraderade tropiska regnskogar genom luck- och linjeplantering:

Effekter på mark- och ljusförhållanden samt plantors överlevnad och tillväxt

Lukas Holmström

Nyckelord / *Keywords:*

Enrichment planting, seedling survival, seedling height, dipterocarp, light / *Stödplantering, plantprestanda, överlevnad, höjd, dipterocarp, ljuskvantitet*

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I denna rapport redovisas ett examensarbete utfört vid Institutionen för skogens ekologi och skötsel, Skogsvetenskapliga fakulteten, SLU. Arbetet har handletts och granskats av handledaren, och godkänts av examinator. För rapportens slutliga innehåll är dock författaren ensam ansvarig.

This report presents an MSc/BSc thesis at the Department of Forest Ecology and Management, Faculty of Forest Sciences, SLU. The work has been supervised and reviewed by the supervisor, and been approved by the examiner. However, the author is the sole responsible for the content.

Abstract

Enrichment plantings are a common way to restore structures and diversity lost through degradation of tropical rainforests. Large areas are degraded every year, and although disturbance over large areas seldom are homogenous, few, if any studies have compared effects of enrichment planting treatments in forests with varying degradation. Therefore the aim of this study was to compare the effects on factors important for seedling performance (i.e. soil and light conditions) under two enrichment planting methods in forests with varying degree of degradation. Further, to compare seedling performance under the two treatments, within and between the levels of degradation. The study was conducted within the INIKEA project area, which is located in the state of Sabah, Malaysia. The experiment forest was classified into three types depending on degradation level and forest structure, 30 years after disturbance. Each forest type were treated with gap planting, line planting as well as liberation (which is not included in this study) and also contained an untreated control. The planting treatments were planted with nursery raised seedlings from 32 species, 24 of which belonged to the *Dipterocarpaceae* family. Inventory and sampling was conducted 22 months after planting; seedling survival and height were recorded on plot level, light measurements (hemispherical photographs) were taken adjacent to each seedling and soil samples was taken in the centre of each plot. The results showed that seedling performance improved with higher light quantity and that seedlings in the gap plantings received higher light levels compared to those in line planting. An interaction between degradation level and treatment were apparent; indicating that in intermediately and heavily degraded forests, gap planting yielded better seedling performance than line planting. However, in the least degraded forests, seedlings in line planting exhibited better performance than those in gap planting. The conclusion from this study was that the degree of degradation should be considered when designing the enrichment planting approach.

Keywords: enrichment planting, seedling survival, seedling height, dipterocarp, light quantity

Sammanfattning

Olika former av stödplantering är vanligt för att återställa strukturer och mångfald som förlorats genom degradering av tropiska regnskogar. Stora områden utsätts varje år för störningar och trots att om störningen och resulterande degradering sällan är homogen har få, om ens några, studier jämfört effekten av stödplantering i skogar med varierande nivå av degradering. Syftet med denna studie var därför att undersöka hur faktorer som påverkar plantors tillväxt och överlevnad påverkads av: två olika stödplanteringsmetoder, i skogar med varierande grad av degradering. Samt att jämföra plantornas tillväxt och överlevnad. Studien genomfördes inom INIKEA projektområdet som ligger i delstaten Sabah, Malaysia. För ungefär 30 år sedan utsattes skogen i INIKEA området för omfattande, men varierande störningar (i.e. plockhuggning, skogsbrand och torka i olika kombinationer). Skogen har sedermera indelats i tre typer beroende på vegetationsstruktur och dess förmodade degraderingsnivå. Varje skogstyp har behandlats med tre metoder; luckplantering, linjeplantering och frigörande huggning av existerande plantor (vilken inte inkluderades i den här studien). Varje skogstyp innehöll även en obehandlad kontroll. Planteringsbehandlingarna planterades med 32 olika arter, varav 24 tillhörde *Dipterocarpaceae* familjen. Dessa plantor kom från en närliggande plantskola. Inventering och mätningar genomfördes 22 månader efter plantering; plantöverlevnad och medelhöjd registrerades på plotnivå, ljusmätningar (Fisheye fotografier) togs i anslutning till varje planta och jordprover i mitten av varje plot. Resultaten visade att plantornas prestanda förbättrades med högre ljusmängd och att plantor i luckplanteringen fick mer ljus, jämfört med dem i linjeplantering. En interaktion mellan behandling och degraderingsnivå fanns, vilket tydde på att i mellan och kraftigt degraderade skogar gav luckplantering bättre plantprestanda än linjeplantering. Men i de minst degraderade skogarna uppvisade plantorna i linjeplantering bättre prestanda än dem i luckplanteringen. Slutsatsen av denna studie blev således att graden av degradering bör övervägas vid utformning av nya stödplanteringar.

Nyckelord: stödplantering, plantprestanda, överlevnad, höjd, dipterocarp, ljuskvantitet

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Introduction

Degradation of tropical rainforests caused by overexploitation and forest fires result in biodiversity loss and changes in ecosystem function (Grainger, 1993; Turner, 1996; Foley *et al.*, 2007; Ghazoul *et al.*, 2010). Although the deforestation rate of tropical rainforest has decreased, degradation of primary rainforests are high (FAO, 2010). The main cause for degradation of primary forests are anthropogenic activities, e.g. logging, shifting-cultivation, etc. (Grainger, 1993). These damages impacts the forests ability to sustain biodiversity and ecosystem services (Turner, 1996; FAO, 2005; Lamb *et al.*, 2005), e.g. climate change mitigation (Foley *et al.*, 2007; Ghazoul *et al.*, 2010). Further, many degraded forests exhibits offset in successional processes (FAO, 2003; Lamb *et al.*, 2005), prohibiting or delaying recovery; reducing the future availability of commercially viable timber. Which may raise incentives to exploit new areas of primary forest.

In order to facilitate the recovery of degraded forests, enrichment planting can be used as an act of supplementing insufficient, or non-existing natural regeneration of desirable species (ITTO, 1989; Lamb *et al.*, 2005). It can be used for different purposes; e.g. under conversion regimes with the aim of transforming forests of low economic value into secondary forests of high economic value or as a means to restore structures and diversity lost through degradation and deforestation (Lamb *et al.*, 2005). The most common way to implement enrichment planting is line planting, where lines are cleared through the forest and seedlings are planted along the lines (ITTO, 1989). Other methods, e.g. gap planting, are also used (ITTO, 1989; Tuomela *et al.*, 1996; Otsamo, 2000), where seedlings are planted in naturally occurring or created gaps. The methods utilized for enrichment planting have been found to differ in light properties reaching seedling height (Bebber *et al.*, 2002). Enrichment planting has been used for rehabilitative purposes with success in some aspects, e.g. recovery of soil microbial biomass and activity (Karam *et al.*, 2012), however, the factors driving seedling survival and growth are complex (Ådjers *et al.*, 1995; Otsamo, 2000; Ashton *et al.*, 2006; Romell *et al.*, 2009; Born *et al.*, 2015).

Whether enrichment planting is successful or not is dependent on the survival and growth of the planted seedlings; however, seedling performance varies with environmental factors (Ådjers *et al.*, 1995; Otsamo, 2000). Light availability and light quality is deemed to play an important role in seedling performance (Lamprecht, 1989; Chazdon & Pearcy, 1991); too much light can stimulate competition from undesirable pioneer species (Tuomela *et al.*, 1996) whilst too little light could result in stunted growth or high mortality (Ashton *et al.*, 2006), possibly enhanced by an increased susceptibility to pathogens (Augspurger, 1984). Water availability, drought and flooding events can have a large effect on seedling survival (Lopez & Kursar, 2007), however, micro topography of the site could either mitigate or worsen the effects of water (Born *et al.*, 2015). Plant growth on tropical soils is assumed to be limited by phosphorus (Dieter *et al.*, 2010) and availability of nutrients seems to positively affect seedling performance (Otsamo *et al.*, 1995). The response to nutrient availability is possibly enhanced if sufficient light is present (Nussbaum *et al.*, 1995; Bungard *et al.*, 2002).

The intensity and character of disturbance may impact several aspects of the residual ecosystem, ranging from effects on soil quality and moisture, to stand structure and canopy closure etc. For example, the intensity of disturbances to forests range from small-scale internal dynamic events with low impact (e.g. a tree fall) to complete disruption of the original ecosystem (e.g. by shifting cultivation or repetitive selective logging (Ådjers *et al.*, 1995; Otsamo, 2000; Romell *et al.*, 2008)).

Logging practices may result in removal of topsoil and severely compacted subsoils leading to increased surface runoff (Malmer & Grip, 1990), and possibly nutrient leaching. The disturbed canopy, in combination with increased amounts of dead biomass on the forest floor (e.g. branches) increases the susceptibility to wild fires (Goldammer & Seibert, 1990). Type and severity of the disturbance results in different successional pathways (Woods, 1989); heavily degraded areas often become dominated by grass and recalcitrant herbaceous vegetation and the less degraded areas contain less obscuring ground vegetation and more trees (Woods, 1989). These effects may all impact the performance of planted seedlings and consequently (due to light regime differences between methods) cause some enrichment planting methods to work better in heavily degraded areas and vice versa.

To understand why and how the forest structure after degradation affects seedling performance is important to design appropriate enrichment planting strategies. Several studies have examined enrichment planting per se, but few, if any, have investigated effectiveness of enrichment plantings in forest successions after varying level of degradation. Therefore, this study examined the response of environmental factors important for plant performance (e.g. light and soil properties) within a forest restoration experiment in Malaysia. The degradation level vary over the area, and the experiment forest have been classified into three types, depending on forest structure after 30 years of succession; open type (extensive herbaceous vegetation with scattered trees, almost no dipterocarp seedlings), macaranga type (existing tree cover with gaps; mainly pioneer macaranga trees and some dipterocarps; few dipterocarp seedlings) and dipterocarp type (dominated by dipterocarp trees of all sizes, including seedlings). Three restoration approaches (liberation, gap- and line planting) have been applied along with an untreated control in all forest types. Depending on forest structure each restoration approach have been assumed to be more or less appropriate. However, there are no studies supporting such assumptions. Furthermore, in both planting treatments (gap- and line planting) seedling response were explored through measurements of growth and survival of the planted seedlings.

Through these measurements and given large differences in developmental history and structure of the forest types, I tested several hypotheses: forest types would differ in both 1) light quantity reaching the forest floor and 2) soil properties. Treatments would mainly affect 3) light quantity reaching the forest floor. Further, given that soil properties and light levels both can impact plant performance, 4) an interaction effect between forest type and treatment would be evident, which would impact seedling growth and/or survival, e.g. the effect of improved light conditions would affect seedling performance differently in different forest types.

Material and methods

Study site

The study was conducted in an experimental area called the Rainforest Restoration Experiment, RRE, within the 18 500 ha INIKEA forest rehabilitation project area (4°36N, 117°12E), which resides on the Malaysian part of Borneo in the state of Sabah. INIKEA is a cooperation between IKEA and Yayasan Sabah Group. The altitude of this area varies between 300 and 700 m.a.s.l. with undulating topography on sedimentary bedrock (Romell *et al.*, 2009). The area had an average annual precipitation of 2 517 mm per year (Gustafsson *et al.*, 2016).

Originally this area was covered by lowland tropical rainforest. During the late 1970's and early 80's selective logging of commercially valuable species were conducted. A subsequent El Niño Southern Oscillation cycle during 1982-83 (Corlett & Primack, 2011) permitted severe forest fires to burn over 1 million hectares in Sabah, Malaysia. (Alloysius *et al.*, 2010). The resulting secondary forest was dominated by pioneer tree species, mostly *Macaranga* spp. (Romell *et al.*, 2009), and a high abundance of climbers, vines, ferns and gingers.

Experimental design

The RRE consisted of 72.9 hectares with different levels of forest degradation. Depending on the forest structure, assumed to correspond to severity of disturbance, the forest was classified into three categories: dipterocarp (dominated by dipterocarp trees of all sizes, including seedlings), macaranga (existing tree cover with gaps, mainly pioneer macaranga trees and some, often damaged, dipterocarps; few dipterocarp seedlings) and open (extensive herbaceous vegetation with scattered trees, almost no dipterocarp seedlings). See table 1, for information about the forest types. Within the RRE, 21 blocks were evenly distributed over the three forest types, i.e. 7 blocks in each forest type (figure 1). Each block was subdivided into four 40x40 m plots which were randomly treated with gap-cluster planting, line planting, liberation or untreated control. The planting material was nursery raised and consisted of 32 different species, 24 of which belonging to the *Dipterocarpaceae* family (for a complete list of species see appendix 1).

In the gap-cluster treatment, here after referred to as gap treatment or gap planting, 20x20 m squares were established. Each 20x20 m square were divided into four equal squares in which four gaps were identified or created, each gap was planted with a cluster of 4 seedlings, the 32 species were randomly distributed among the gaps (figure 2). On average each gap had a 2 m radius and the seedlings were planted 1.5 m from the centre. For the line treatment, a 2 m wide line was cleared through the forest every 10 m and planted with seedlings of randomly chosen species at 3 m intervals (figure 2). The depth of the planting holes were 20 cm (Alloysius, 2016).

Table 1. Averages for all soil variables measured, divided per forest type and depth. As well as basal area measurements, which were acquired from Jansson (2015). Soil measurement were taken in the centre of the RRE-plots within the INIKEA-project on northern Borneo. Table shows averages with standard deviation in parenthesis, n = 28 for all soil samples. MC – moisture content, L.O.I – Loss On Ignition, Organic Carbon, Total Nitrogen, Available Phosphorous, Total Phosphorous. For a description of analyses of soil variables read: Processing, calculations and data analyses.

Forest type	**Depth (cm)**	**pH**	**MC (%)**	**L.O.I (%)**	**Texture**		
					Clay (%)	**Silt (%)**	**Sand (%)**
Dipterocarp	0-5	3.84 (0.24)	2.54 (0.81)	8.66 (3.53)	31.30 (5.69)	25.80 (4.88)	42.91 (10.17)
Dipterocarp	5-15	3.87 (0.17)	2.30 (0.66)	5.48 (1.74)	32.38 (7.15)	26.61 (4.75)	41.01 (11.18)
Macaranga	0-5	4.26 (0.78)	2.18 (0.52)	8.25 (1.26)	30.60 (4.02)	24.35 (5.35)	45.04 (6.87)
Macaranga	5-15	4.12 (0.55)	1.94 (0.45)	5.38 (1.00)	32.53 (4.78)	25.37 (5.61)	42.10 (7.99)
Open	0-5	4.60 (0.58)	2.17 (0.63)	8.37 (2.22)	27.77 (4.01)	27.38 (5.72)	44.85 (8.06)
Open	5-15	4.25 (0.38)	1.85 (0.45)	5.10 (1.26)	29.86 (5.24)	27.50 (5.94)	42.64 (9.27)
		Organic C (%)	**Total N (%)**	**Available P (ppm)**	**Total P (ppm)**	**Bulk density (g/cm3)**	**Basal area[1] (m2)**
Dipterocarp	0-5	1.92 (0.68)	0.20 (0.08)	9.51 (2.51)	215.29 (48.44)	0.93 (0.10)	35.2
Dipterocarp	5-15	0.97 (0.31)	0.09 (0.05)	4.63 (1.69)	172.93 (45.82)	1.07 (0.12)	
Macaranga	0-5	2.04 (0.41)	0.23 (0.07)	13.19 (6.14)	233.50 (63.00)	0.89 (0.10)	43.20
Macaranga	5-15	0.95 (0.36)	0.09 (0.06)	6.15 (5.53)	185.10 (64.80)	1.09 (0.11)	
Open	0-5	1.84 (0.52)	0.22 (0.12)	11.46 (3.43)	262.65 (66.00)	0.95 (0.13)	25.40
Open	5-15	0.81 (0.28)	0.07 (0.04)	4.74 (1.79)	211.52 (69.20)	1.18 (0.10)	

[1]Data acquired from Jansson (2015)

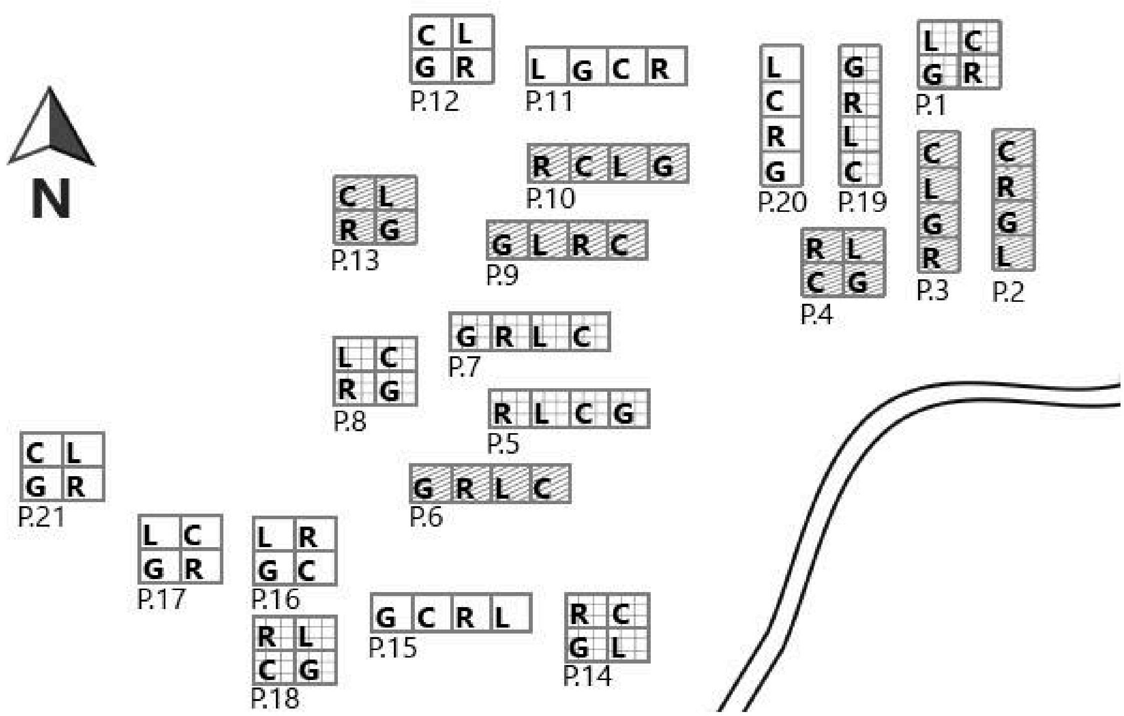

Figure 1. Map depicting the layout of the RRE-plot within the INIKEA-project on northern Borneo. Schematic map depicts the 21 blocks, two treatments and three forest types. Treatment: C = Control, L = Line planting, G = Gap-cluster planting, R = Liberation. Forest types; White = Dipterocarp, Grid = Macaranga, Diagonal stripes = Open.

Data collection

Inventory was conducted 22 months after planting. In order to avoid edge effects, light and seedling measurements were taken only in the eight middle gaps in gap planting and only in the two middle lines in line planting (figure 2). Canopy illumination index, CII, were estimated in all treatments as well as untreated control.

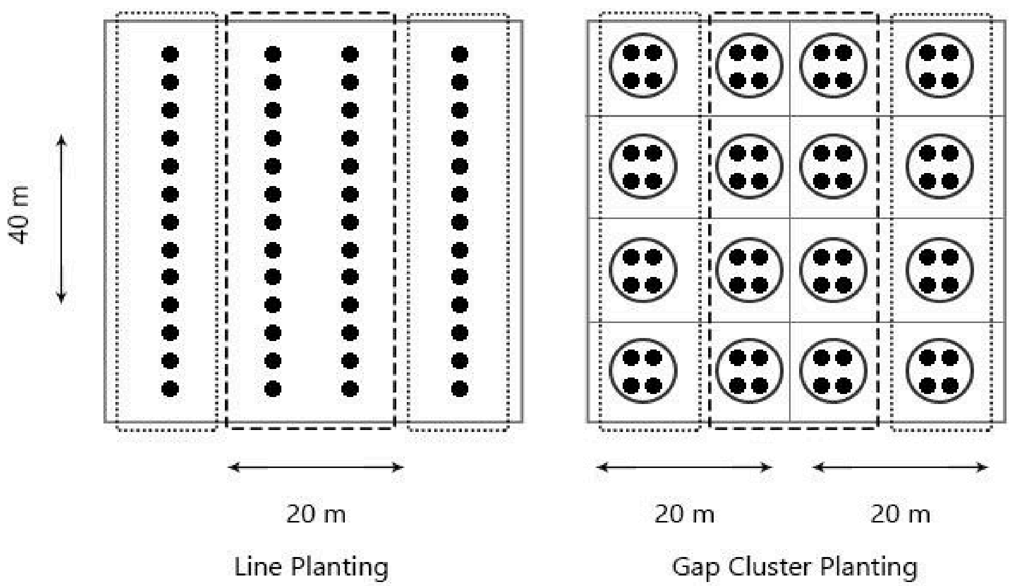

Figure 2. Schematic picture of the planting treatments utilized within the RRE-plots in the INIKEA project on northern Borneo. Line planting to the left and Gap-Cluster planting to the right. The dashed area shows the inventoried area, and the dotted area show the surrounding treatment area.

Hemispherical photographs

Hemispherical photographs were taken using a Canon EOS 50D with a fish-eye lens; Sigma Circular Fish-eye 4.5 mm 1:2.8 FOW 180°. For each picture the histogram was controlled and the exposure adjusted if highlights were present, ISO was set to 400. The camera was held up, 1.3 m from the ground, by a self-levelling frame (SLM-8, Delta-T Service) mounted on a telescopic stand (Manfrotto 680B9). The photographs were saved in RAW and JPEG format, so to maximize the dynamic range of the photo and minimize the risk for lost information in highlights, if present. In order to ensure that all photographs were taken in the same direction the frame had a built in compass and two diodes of different size showing north and south in the resulting photograph. The photographs were taken between the 1^{st} and 10^{th} of September, early in the morning (06 am – 08 am) in order to avoid over exposure by the sun and to avoid gleam from stems and foliage.

Hemispherical photographs were taken in the line and gap treatments in each of the 21 blocks. In line planting, one photograph was taken between every other seedling for seedlings 1-12 in the row and an additional photo between seedlings 12-13, a total of 14 photos were taken in the line treatment. Each photo in the line treatment represented the two nearest seedlings, except the last one, which only represented the last seedling. 8 photographs were taken in the gap treatment, each one represented the seedlings within the gap.

Crown Illumination Index (CII)

Crown illumination index, CII, is a way to assess the illumination of the crown on a tree (Clark & Clark, 1992). The position of the crown and the light reaching the crown are subjectively estimated into 7 different classes (table 2). CII was estimated for every seedling in liberation, gap- and line planting treatments. Since the control treatment did not contain any chosen or planted seedlings, imaginary seedlings organised like in the line planting treatment, were utilised. CII was only used in order to evaluate light regime differences between control, liberation, gap and line planting treatments.

*Table 2***.** Crown illumination index classes and definitions according to (Clark & Clark, 1992).

Index value	Definition
5	Crown completely exposed (to vertical light and to lateral light within the 90˚ inverted cone encompassing the crown)
4	Full overhead light (≥90% of the vertical projection of the crown exposed to vertical light; lateral light blocked within some or all of the 900 inverted cone encompassing the crown
3	Some overhead light (10-90% of the vertical projection of the crown exposed to vertical light)
	Lateral light (<10% of the vertical projection of the crown exposed to vertical light; crown lit laterally):
2.5	High lateral light
2	Medium lateral light
1.5	Low lateral light
1	No direct light (crown not lit directly either vertically or laterally)

Soil sampling

Two soil horizons, 0-5 cm and 5-15 cm, were sampled for each treatment in all 21 plots. A ring corer with a diameter of 5 cm, a height of 5 cm and a volume of 98.2 cm^3, was used to take the samples. The centre of each treatment was identified and five cores were taken for the 0-5 cm horizon and six cores for the 5-15 cm horizon. The 5-15 cm cores were taken 10 m east, west and south from the centre stick, so were also the 0-5 cm cores but additional cores were taken at 1 m and 10 m north of the centre stick. Each sample, consisted of five (0-5 cm) or six (for 5-15 cm) cores, was put in a plastic bag, labelled and sealed.

Seedling survival & height

Seedling survival and height were surveyed in the two planting treatments. Seedling number and species were recorded. In the cases of one or multiple dead/missing seedlings in a gap or line, the 3-month census data was acquired from the INIKEA project, where the species and location of individual seedlings were noted, making it possible to know which seedlings had died. Survival was surveyed at plot level i.e. ($Survival = 1 - (\frac{\#\,of live\ seedlings}{\#\ planted\ seedlings})$), whilst height was measured in cm for every seedling and then averaged per plot.

Processing, calculations and data analyses

Hemispherical photographs

The hemispherical photographs were first edited as RAW files in Adobe Lightroom v6.0, to find a colour balance and exposure which facilitated the subsequent thresholding process in HemiView, where a threshold was set to differentiate between sky and foliage. The photographs were analysed with HemiView 2.1, which was set up according to the site; location was set to 4.60N 117.2E, altitude to 250 m, magnetic declination 0.21 E, lens settings were set to the Sigma Circular Fish-eye 4.5 mm 1:2.8 and the solar model to Simple Solar model, day of photography was adjusted, between 244 and 253 (1^{st} September to 10^{th} of September). The light variables calculated using HemiView are presented in table 3.

Bulk density

Each of the samples were weighted, homogenized by hand and a subsample of 100 g was collected and dried in an oven for 8 hours in 105° C and weighted again. Bulk density was calculated according to equation 1.

$$Bulk\ density = \left(\frac{\left(\left(1 - \frac{Dried\ subsample\ weight}{Undried\ subsample\ weight}\right) * Undried\ sample\ weight\right)}{Sample\ volume}\right) \quad (1)$$

Soil analysis

Chemical analyses of soil samples were conducted by the Forest Research Centre lab in Sepilok. The soil samples were analysed for pH, loss-on-ignition, soil texture, available phosphorous, organic carbon, total nitrogen and total phosphorus. A subsample of each sample were dried at 105° C in order to convert all results to oven-dry weight basis.

A suspension of deionised water and soil (1:2.5 ratio of soil to deionized water) was measured for pH with a glass-calomel electrode. It was done after shaking the mixture on an orbital shaker at 100 rpm overnight followed by standing for 30 min (Landon, 1984). Loss on ignition was calculated by the percentage of weight loss after ignition at 550^{o} C (Grimshaw, 1989), soil texture was determined by following the particle size distribution test by Day (1965). The Walkey-Black method was used to determine the organic carbon content (Nelson & Sommers, 1982). Available phosphorous was extracted by the method of Bray and Kurtz (1945), for total phosphorous each sample was digested the procedure described in Allen (1989) with mixed acid. The phosphorous content was then determined using the molybdenum-blue method in Anderson and Ingram (1993) and read at 880nm on a spectrophotometer (HITACHI UV-VIS, Japan).Total nitrogen was determined by digestion according to the Kjeldahl-method described by Bremner (1965) and measured by a flow injection auto-analyser.

Statistical analyses

For every variable an average was calculated for each 40x40 m plot (table 3). Three species were excluded from the analyses because they did not appear in both treatments, see appendix 1 for a complete species list. The height for one plant was excluded from the average of its plot, its extreme height was reason to believe that the planted seedling had died and been mistaken for a naturally occurring, larger seedling. Some covariates had a non-normal distribution, why they were transformed by natural logarithm.

All statistical analyses were done with a general linear model (equation 2: table 4), in the statistical software MINITAB 17. Backward elimination of covariates and interactions was utilized in order to find the simplest model with significant factors and the highest R^2(adjusted). All covariates and/or interactions that were not significant at the P <0.1 level were eliminated, however factors: forest type and treatment were not excluded regardless of P-value.

Statistical analyses of each covariate was conducted in order to investigate which were affected by forest type and/or treatment. Since the hypotheses were based around effects by treatment and/or forest type and/or an interaction in-between, all covariates not significantly affected by forest type, treatment or an interaction ($P < 0.05$) were removed from the seedling analyses. The remaining covariates were divided into two groups depending on whether they were affiliated with the canopy or the soil. The covariates were checked for correlation by calculating a Pearson correlation matrix using MINITAB 17 (appendix 2). If two or more covariates within each group were correlated ($P < 0.1$), the one which had the highest R^2(adjusted) in its GLM was chosen for further analyses. If covariates were correlated between the two groups one combination were run at a time. $P < 0.1$ was chosen in order to be sure that no correlation existed. Analyses of seedling height and survival explored models with linear relationships of covariates and three-way interactions with forest type and treatment. The simplest model with the highest R^2(adjusted) was chosen for further use in this study. Soil variables were excluded from the seedling analyses due to excessively complicated relationships (appendix 3). Tukey tests were used in order to evaluate differences within factors.

Table 3. Complete list of variables measured for this study in the RRE-plots within the INIKEA project on northern Borneo.

Short form	**Description**
VisSky	Visible sky – Calculated using HemiView
ISF	Indirect site factor – Calculated using HemiView
DSF	Direct site factor – Calculated using HemiView
ISF/DSF	Ratio between ISF and DSF
LAI	Leaf area index – Calculated using HemiView
GSF	Global site factor – Calculated using HemiView
CII[1]	Canopy Illumination index
BD at 5 cm	Bulk density at 0-5 cm depth
BD at 15 cm	Bulk density at 5-15 cm depth
AP at 5 cm[1]	Available phosphorous at 0-5 cm depth
Clay at 5 cm[1]	Clay content at 0-5 cm depth
OC at 5 cm[1]	Organic carbon at 0-5 cm depth
Survival	Average survival in each 40x40 m plot
Height[1]	Average height in each 40x40 m plot

[1]Transformed by natural logarithm

$$Y_{ijl} = \tau_i + \beta_j + (\tau\beta)_{ij} + X_n + (\tau X)_i + (\beta X)_j + (\tau\beta X)_{ij} + X + \varepsilon_{ijl} \qquad Var(\varepsilon_{ijl}) = \sigma^2 \quad (2)$$

Table 4. Explanatory table to General Linear Model, equation 2.

Variable	**Description**
Y_{ijl}	Response variable
τi	Treatment i main effect
βj	Forest types j main effect
(τβ)ij	Treatment and forest type interaction effect
X	Covariate (only used for seedling analyses)
i =1, 2, 3, 4	Treatments (Main blocks)
j = 1, 2 , 3	Forest types
l = 1, 2 , 3… 7	Replications (sub-blocks)

Graphs and diagrams are based on raw and non-transformed values. Analyses are done with transformed values where it is declared.

Results

Light variables

Light variables were clearly affected by treatment, e.g. five of the seven variables were significantly affected by treatment whilst forest type only significantly affected LAI (table 5). However, there is an indication ($0.05 < P < 0.1$) that the ratio between ISF/DSF was affected by forest type. Subsequent tukey tests on significant factors revealed that the CII of seedlings in gap- and line planting treatments was significantly higher than the estimates in untreated control ($P \leq 0.05$), it also showed that CII was not significantly different between the gap and line treatments (figure 3). In contrast, GSF was found to differ significantly between gap and line planting; gap planting had more than 1.3 times higher GSF than line planting (figure 4). The macaranga forest type had a significantly lower leaf area index compared to the dipterocarp forest type but no significant difference to the open forest type.

Table 5. Analysis of variance for light variables measured in the RRE-plots of the INIKEA project on northern Borneo. Table is showing the resulting factors and interactions for each GLM-model after backwards elimination of factors. Initially all models contained three terms; forest type, treatment and forest type * treatment. Forest types are dipterocarp, macaranga and open. Treatments are gap- and line planting. Bold numbers note a p-value below 0.05.

Response	Factors	F-value	P-value	R2(adj)
VisSky	Forest Type	0.86	0.43	14.91
	Treatment	8.46	**0.006**	
ISF	Forest Type	1.23	0.303	19.71
	Treatment	10.6	**0.002**	
DSF	Forest Type	1.69	0.198	20.32
	Treatment	10.08	**0.003**	
ISF/DSF	Forest Type	3.22	0.051	8.18
	Treatment	0.21	0.647	
LAI	Forest Type	3.39	**0.044**	8.89
	Treatment	0.22	0.639	
GSF	Forest Type	1.65	0.205	20.38
	Treatment	10.19	**0.003**	
ln(CII)	Forest Type	2.82	0.066	22.86
	Treatment	7.99	**0.000**	

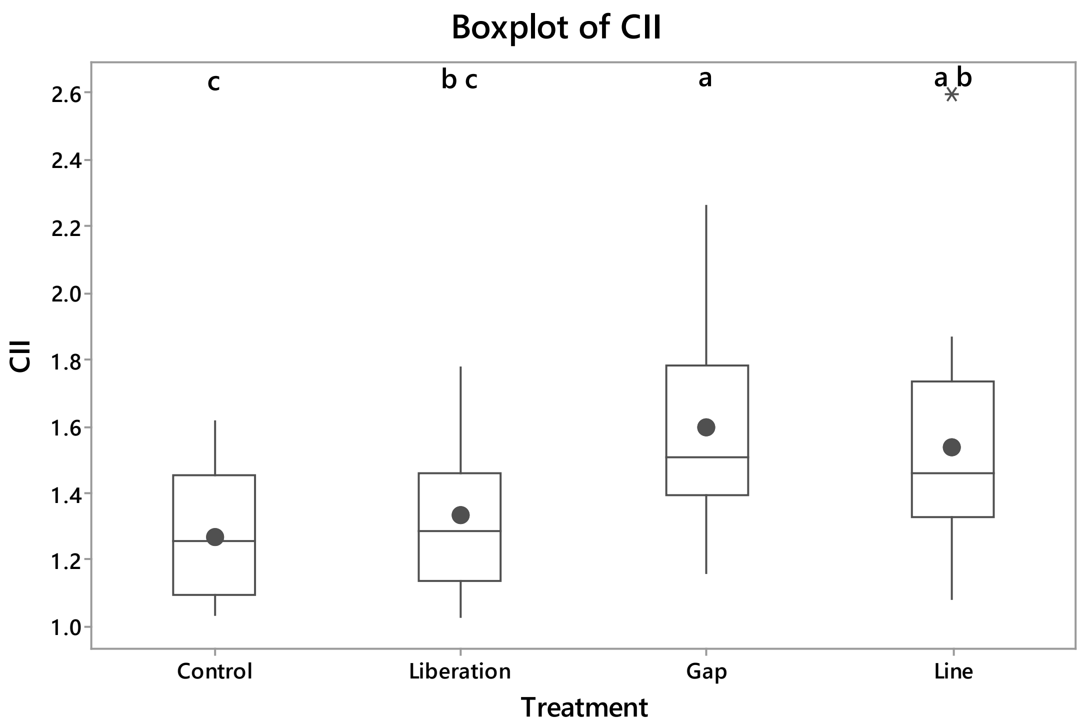

Figure 3. Canopy Illumination Index, CII, for the different treatments and untreated control within the RRE-plots of the INIKEA project on northern Borneo. Filled circles notes mean value, horizontal line notes the median value and an x indicate outliers. Different letters indicate a p-value below 0.05.

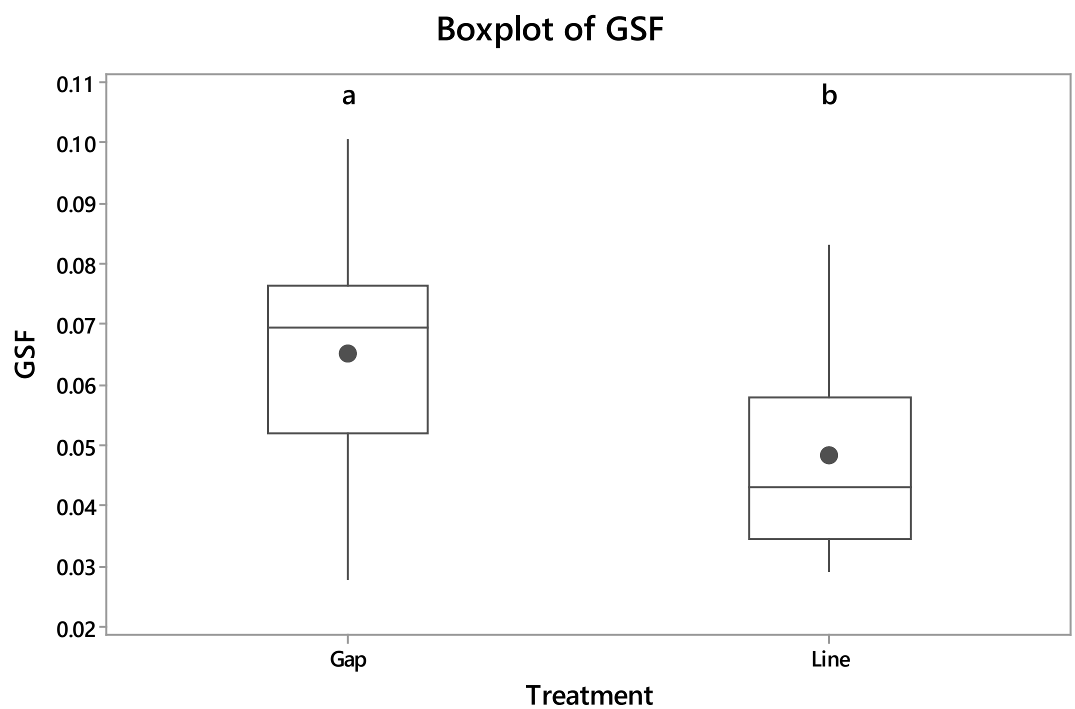

Figure 4. Global Site Factor, GSF, for treatments gap- and line planting within the RRE-plots of the INIKEA project on northern Borneo. Filled circles notes mean value, horizontal line notes the median value. Different letters indicate a p-value below 0.05.

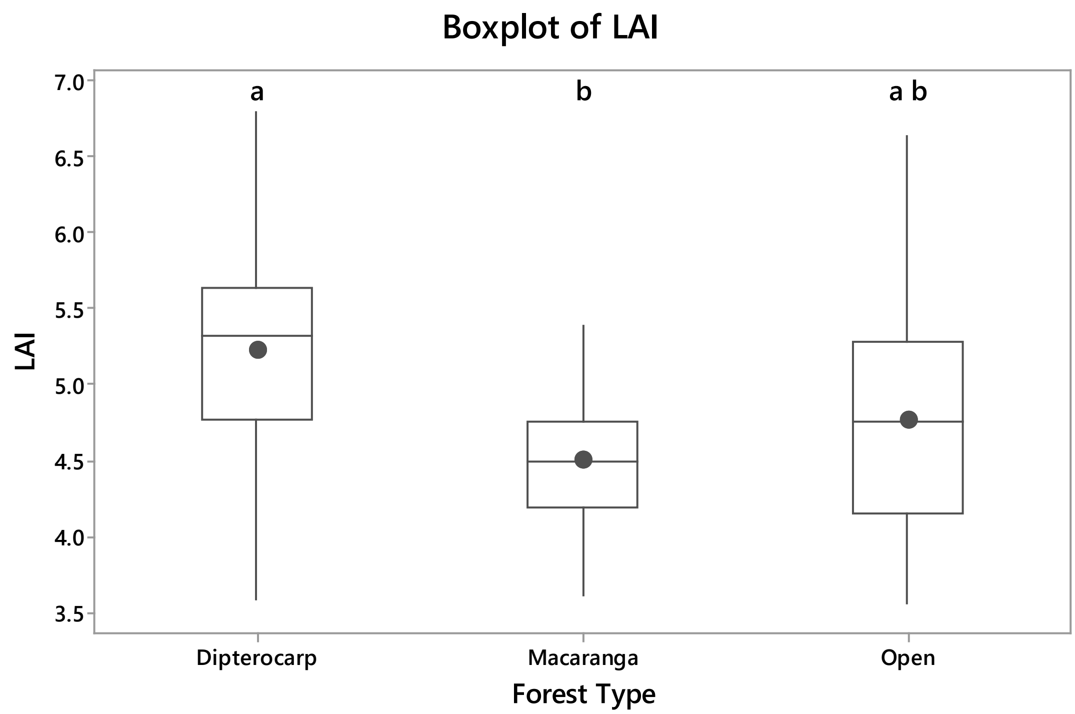

Figure 5. Leaf Area Index, LAI, for the forest types: dipterocarp, macaranga and open, within the RRE-plots of the INIKEA project on northern Borneo. Filled circles notes mean value, horizontal line note median value. Different letters indicate a p-value below 0.05.

Soil variables

Both bulk density at 5-15 cm and available phosphorous at 0-5 cm were significantly affected by forest type ($P \leq 0.05$) but not by treatment. There was an indication ($0.05 < P < 0.1$) that the amount of clay at 0-5 cm depth would be affected by forest type. No other soil variables were significantly affected by either forest type or treatment. Significant factors analysed with post-hoc tests revealed that there was a significantly higher average of available phosphorous at 0-5 cm in the macaranga than in the dipterocarp forest type; average was more than 1.35 times higher, whilst the open forest type appears to be at intermediate levels but not significantly different from either dipterocarp or macaranga (figure 5a). Further, bulk density at 5-15 cm was more than 10 % higher in the open forest type compared to either the macaranga or dipterocarp forest type (figure 5b).

Table 6. Analysis of variance for soil variables measured in the RRE-plots of the INIKEA project on northern Borneo. Table is showing the resulting factors and interactions for each GLM-model after backwards elimination of factors. Initially all models contained three terms; forest type, treatment and forest type * treatment. Forest types are dipterocarp, macaranga and open. Treatments are gap- and line planting. Bold numbers note a p-value below 0.05.

Response	Factors	F-value	P-value	R2(adj)
BD @ 5	Forest Type	1.52	0.232	0.89
	Treatment	0.33	0.569	
BD @ 15	Forest Type	4.78	**0.014**	14.66
	Treatment	0.49	0.487	
Ln(AP @ 5)	Forest Type	4.7	**0.015**	13.83
	Treatment	0.18	0.672	
Ln(Clay @ 5)	Forest Type	2.72	0.079	5.63
	Treatment	0.01	0.904	
Ln(OC @ 5)	Forest Type	1.6	0.216	2.29
	Treatment	0.77	0.386	

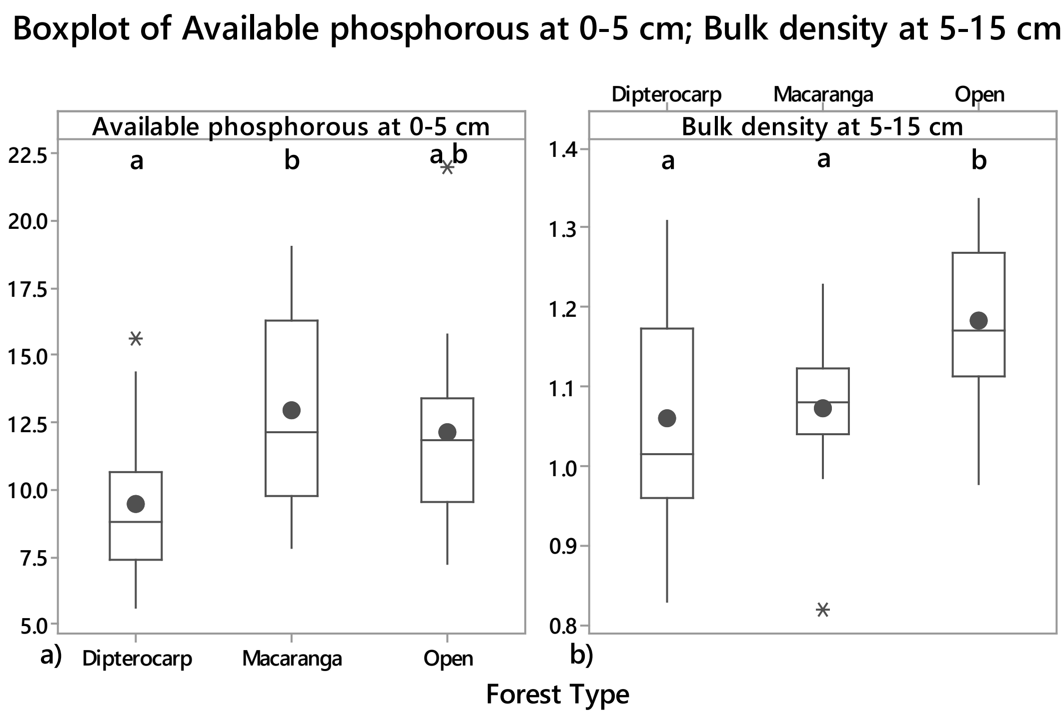

Figure 6. Comparison between the forest types; dipterocarp, macaranga and open in the RRE-plots within the INIKEA project on northern Borneo. Table showing two soil variables. Filled circles notes mean value, horizontal line notes the median value and circles with an x indicate outliers. Different letters indicate a p-value below 0.05. **a)** Available phosphorous at 0-5 cm depth, AP at 0-5 cm. **b)** Bulk density at 5-15 cm depth, BD at 5-15 cm.

Survival

Seedling survival was not significantly affected by any of the factors: forest type, treatment or an interaction (table 7). However, there was an indication (0.05 < P < 0.1) that forest type might have had an effect on survival. A subsequent tukey test further supported that there was no significant difference between forest types (figure 7).

Table 7. Table showing the analysis of variance for the GLM for seedling survival as measured in the RRE-plots within the INIKEA project on northern Borneo. The response variable is survival and the table is showing the remaining terms after backwards elimination; degrees of freedom, adjusted sum of squares, adjusted mean squares, f-values and p-value. Before elimination, three way interactions between each covariate and the factors were included. Forest types are dipterocarp, macaranga and open. Treatments are gap- and line planting. Bold numbers indicate a p-value < 0.05.

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-Value**
Forest Type	2	0.07739	0.03870	2.82	0.072
Treatment	1	0.02504	0.02504	1.83	0.185
Error	38	0.52120	0.01372		
Total	41	0.62364			
Model Summary					
S	R-sq	R-sq(adj)	R-sq(pred)		
0.117114	16.43%	9.83%	0,00%		

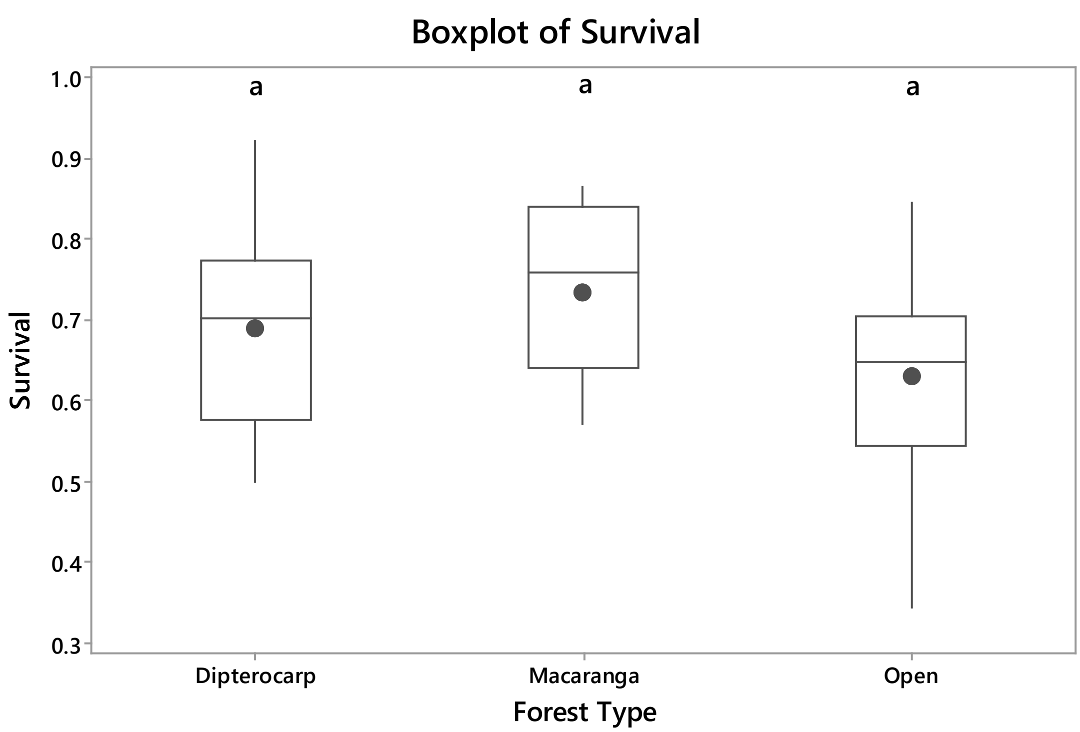

Figure 7. Comparison of survival between forest types; dipterocarp, macaranga and open, within the RRE-plots of the INIKEA project on northern Borneo. Filled circles notes mean value, horizontal line notes the median value. Different letters indicate a p-value below 0.05.

Height

The final GLM for height generated 1 significant term, GSF (table 8). However, the interaction between forest type and treatment revealed a close to significant effect on seedling height (P = 0.064). A tukey test revealed no significant effect of treatment within or between forest types (figure 11). Although not significant, a trend that gap planting yield higher seedlings than line planting in both the open and macaranga forest types can be seen, whilst the opposite is true for the dipterocarp forest type. The covariate GSF significantly influenced height in a positive manner (table 8; figure 11). No interaction between GSF and either of the factors (forest type and/or treatment) were apparent.

Table 8. Table showing the analysis of variance for the GLM for seedling survival as measured in the RRE-plots within the INIKEA project on northern Borneo. The response variable is ln(height) and the table is showing the remaining terms after the backwards elimination; degrees of freedom, adjusted sum of squares, adjusted mean squares, f-values and p-value. Before elimination, three way interactions between each covariate and the factors were included. Forest types are dipterocarp, macaranga and open. Treatments are gap- and line planting. Bold numbers indicate a p-value < 0.05.

Source	**DF**	**Adj SS**	**Adj MS**	**F-Value**	**P-value**
Forest type	2	0.11612	0.05806	2.34	0.112
Treatment	1	0.07559	0.07559	3.05	0.090
Forest type*Treatment	2	0.14817	0.07409	2.99	0.064
GSF	1	0.30615	0.30615	12.35	**0.001**
LAI	1	0.01866	0.01866	0.75	0.392
LAI*Treatment	1	0.07213	0.07213	2.91	0.097
Error	33	0.81793	0.02479		
Total	41	1.36643			
Model Summary					
S	R-sq	R-sq(adj)	R-sq(pred)		
0.157435	40.14%	25.63%	7.32%		

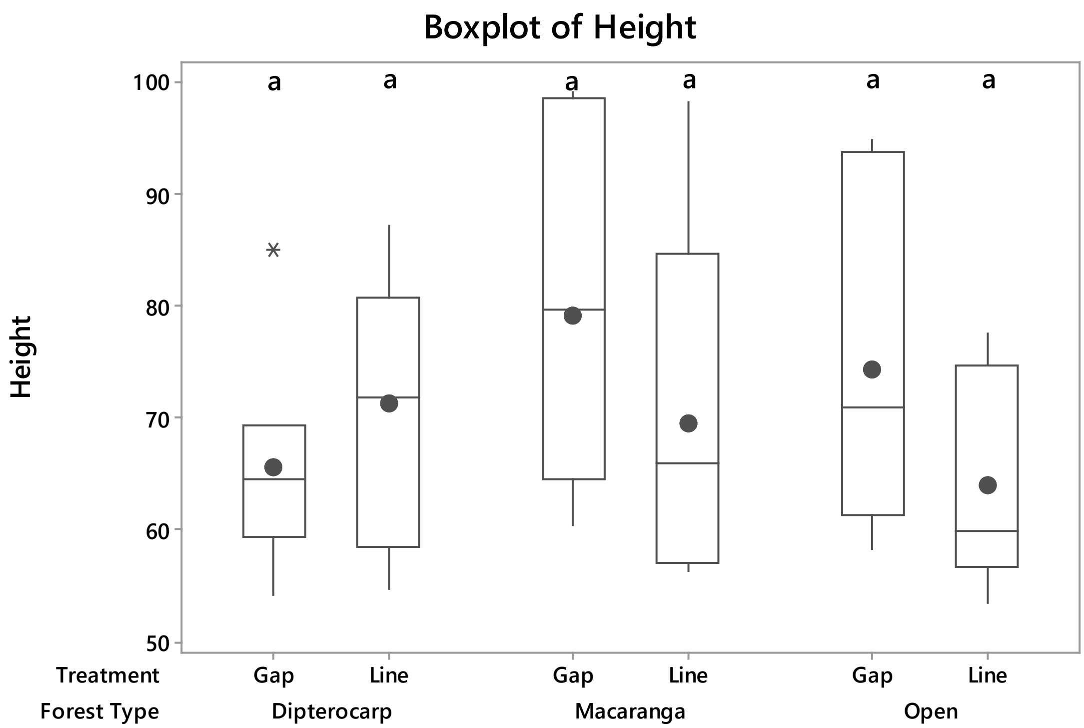

Figure 8. Comparison of height response between the treatments; gap- and line planting within and between the different forest types; dipterocarp, macaranga and open, within the RRE-plots of the INIKEA project on northern Borneo. Filled circles notes mean value, horizontal line notes the median value and an x indicate outliers. Different letters indicate a p-value below 0.05.

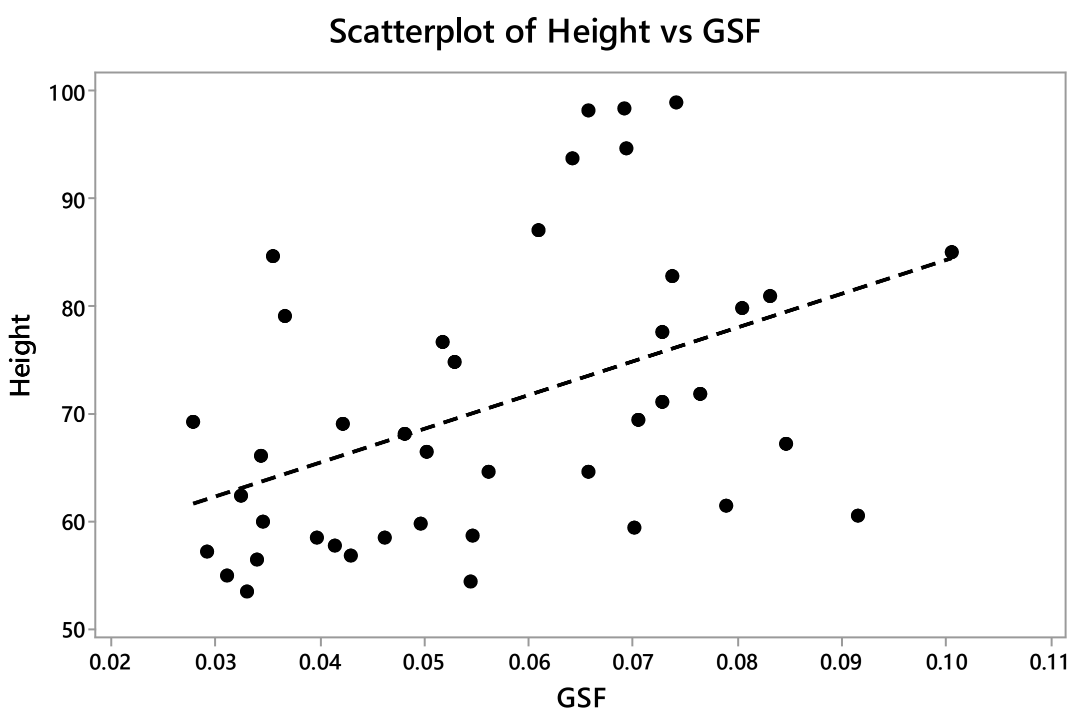

Figure 9. Relationship between height and global site factor, GSF. Measurements taken in the RRE-plots of the INIKEA project on northern Borneo.

Discussion

With this study I wanted to explore how factors important for seedling performance (e.g. light and soil properties) respond to enrichment plantings within tropical rainforests with differing levels of degradation. Further, I wanted to explore how this impacts performance of planted seedlings. I reject the hypothesis that light quantity at the forest floor would be affected by level of degradation, but was rather affected by treatment, showing that light quantity as estimated by CII, were significantly higher in both planting treatments compared to control. Comparing planting treatments revealed that the average of global site factor was roughly 30% higher in gap than line planting. My results also support the hypothesis that soil properties would be affected by level of degradation, showing that the available phosphorous were higher in the intermediately degraded forest type and that bulk density was significantly higher in the heavily degraded forest compared to the least degraded. With the support of these results and the below discussion I argue that degradation level should be considered when choosing enrichment planting strategy.

After 30 years succession, treatment rather than degree of degradation, is governing light quantity reaching young seedlings. The model with the highest explanatory degree had canopy illumination index as its response variable (table 5). It showed that treatment had a highly significant effect on illumination of the seedlings crowns (figure 3); CII was significantly lower in untreated control compared to both the planting treatments. Global site factor showed that there was a significant higher value in gap planting compared to line planting (figure 4), supporting the third hypothesis. The reason behind the higher light quantity in gap compared to line planting might be due to the increased flexibility; within each 10x10 m square you choose the best spot for the gap, i.e. lightest spot. Further, in this study each gap was planted with four seedlings, a brighter than average gap would therefore have had a higher impact on the plot average than a brighter than average planting spot in the line planting. For early seedling performance, the inherent flexibility in gap planting might be favourable.

Although degradation level was close to significant for canopy illumination index, that was not the case for global site factor (table 5). This discrepancy was likely caused by two things; first global site factor was only measured within the planting treatments whilst canopy illumination index were estimated within all treatments and the untreated control. Second, canopy illumination index is a subjective estimate which requires training and calibration in order to be accurate (Keeling & Phillips, 2007). A study by Keeling and Phillips (2007) found that canopy illumination index and global site factor were significantly correlated. However, they conducted their study within a mature tropical rainforest where the height of the canopy likely was somewhat constant across the plots. The discrepancy between CII and GSF found in this study might be due to differences in canopy height between the forest types (Personal observation) making it difficult to estimate CII correctly across the differently degraded areas, possibly making it unsuitable for comparisons between forest types.

Of all aboveground measurements, only leaf area index, LAI, was significantly affected by degradation level rather than by treatment (table 5). That degradation level, and thus forest structure, had significant impacts on leaf area index were likely due to it being a measurement of forest structure rather than light. A tukey test showed that the intermediately degraded forest, macaranga, had the lowest leaf area index (figure 5). That the intermediate forest (macaranga), had lower leaf area index than the least degraded forest (dipterocarp), was expected, due to the higher levels of disturbance it had been exposed to. However, the LAI in the most disturbed forest (open), was not significantly lower than the least disturbed forest (dipterocarp). This result was not in line with the results of Jansson (2015) who found that the most degraded forest had significantly lower leaf area index than the least degraded, and the intermediately degraded forest was an insignificant intermediate. This difference between the studies was likely due to a difference in where the measurements were taken. Jansson (2015) measured his outside of the treatments whilst the measurements for this study was taken within the treatments. This difference in LAI between these studies show that the treatments had an effect on the canopy structure.

More than 30 years after the disturbance event, the degree of degradation (forest type) had significant effects on soil properties. The available phosphorous in the 0-5 cm depth was significantly higher in the intermediately degraded forest type (macaranga), compared to the least degraded (dipterocarp). Due to that tropical soils often are heavily weathered, plants in such areas are often considered phosphorous limited (Dieter *et al.*, 2010), therefore the higher levels of available phosphorous in the intermediately degraded forests might be positive for future seedling performance. However, several factors can cause the available phosphorous to differ between the differently degraded forest types; demand by vegetation, mineralisation rate, soil organic matter and soil texture (Brady & Weil, 2002).

A negative correlation between LAI and available phosphorous in the 0-5 cm horizon was found, (appendix 2), possibly indicating a lower demand for phosphorous in the intermediately degraded forest (macaranga). Increasing level of degradation have been suggested to be followed by an increase in abundance of tree species with pioneer traits (Woods, 1989); high amount of foliar phosphorous is one of those traits (Raaimakers *et al.*, 1995; Gustafsson *et al.*, 2016), possibly causing an increased phosphorous content in the litter fall. However, a healthy decomposer community is needed in order to mineralize nutrients from the litter. Fungal decomposer communities have been shown to be negatively affected by heavy disturbance (Lodge & Cantrell, 1995); decomposer communities in the most degraded forest (open) might not have fully recovered, therefore not exhibiting a significant difference in available phosphorous compared to the least disturbed forests (dipterocarp). Slower mineralization, could contribute to lower amounts of available phosphorous in comparison to levels in the intermediately degraded forests (macaranga). However, clay particles immobilizes phosphorous, a process which is counteracted by organic matter (Brady & Weil, 2002).Although not significant at $P < 0.05$, there was an indication that level of degradation affected the clay content in the uppermost 5 cm, and no effect was apparent on organic carbon in the same horizon. It seems that the most degraded forests (open) had lower clay content than both the other degradation levels (macaranga and dipterocarp), in conjunction with the same amount of organic carbon (table 1) possibly immobilizing less phosphorous; explaining the intermediate levels of available phosphorous.

Due to the time since disturbance (i.e. more than 30 years) it is not surprising that both the organic carbon and the bulk density in the uppermost 5 cm were exhibiting no difference between degradation levels; recovery time for soil organic matter content, in the uppermost 50 cm, are estimated to roughly 40-50 years (Brown & Lugo, 1990) and a study by Paul et al. (2010) showed that topsoil bulk density were recovering within 12 to 30 years depending on restoration measure. Although the uppermost 5 cm might have recovered, the bulk density at the 5-15 cm depth was significantly higher in the most degraded forests (open) compared to both the less disturbed forests (macaranga and dipterocarp) (figure 6a). This was likely due differences in historic disturbance types and intensities. Top soil removal and compaction by crawler tractors on skid trails and log landings are likely the explanation to the higher bulk density (Greacen & Sands, 1980; Jusoff *et al.*, 1986; Jusoff *et al.*, 1987; Jusoff, 1988). Although significantly higher, the average bulk density in the most degraded forests (open) was not excessively high (1.18 g cm^{-3}), studies in undisturbed dipterocarp forest have found bulk densities between 0,98-1,27 g cm^{-3} (Jusoff *et al.*, 1986; Pinard *et al.*, 1996; Hattori *et al.*, 2013b). Soil texture also affect bulk density (Brady & Weil, 2002); higher proportion of sand fraction could contribute to higher bulk density in the most degraded forests (open), however, this is not statistically tested. Given that this forest type (open) was subjected to heavier disturbance in the past this indicates that the bulk density is recovering after 30 years. However, in other areas with a more recent disturbance history, negative effects on seedling performance have been observed, e.g. a study by Nussbaum *et al.* (1995) showed significantly negative effects on seedling survival by high bulk density.

Neither degradation level, nor treatment, was found to be significant for early seedling survival in these forests, planted with multiple species. In comparison to earlier studies in similar areas the survival within this study, 68.6%, are on the low-intermediate end of the spectrum; Romell *et al.* (2008) 72% – 86% after 30 months, Otsamo (2000) 71% – 95% after 19 months. *Ådjers et al.* (1995) 37.5% – 85% after 24 month.

Although no significance were found in this study (table 7), there was an indication that seedlings in heavily degraded forests survived to a lesser extent (figure 7). Early seedling survival have been found to be impaired by high bulk densities; inhibiting lateral root growth as well as causing drought stress due to lower water holding capacity (Nussbaum *et al.*, 1995; Hattori *et al.*, 2013a). Although there was quite a lot of variation in bulk density at 5-15 cm within each forest type, the average bulk density in the most degraded forest type were not extremely high. Further, early seedling survival might be impaired by other factors, such as herbivory or other biotic factors, possibly altered with forest structure. E.g. in a by Romell *et al.* (2008) wild boars caused severe mortality to seedlings, why barbed wire fences were utilized to keep them out; a possible explanation to the pattern in this study might be animal preferences to certain forest types, which is beyond the scope of this study. Damage to seedlings during maintenance of the treated plots could also be a factor; more ground vegetation in the heavily degraded forest would require a more vigorous weeding increasing the chance of damaging the seedlings. It has been suggested that a delayed maintenance could result in damage to the planted seedlings, possibly causing higher mortality (Ådjers *et al.*, 1995).

None of the treatments exhibited any significance, within or between the different levels of degradation. Global site factor was eliminated from the model, due to being highly insignificant, and treatment showed no significant impact on survival. Therefore it can be concluded that at this early stage light quantity do not affect seedling survival. Which is similar to what Ådjers *et al.* (1995) found; increasing line width did not yield differences in survival. Although other studies have suggested that light quantity do have positive effects on seedling survival (Chazdon & Pearcy, 1991; Ashton *et al.*, 2006; Romell *et al.*, 2008); most have examined only a handful of species, making it hard to differentiate between species specific responses and what will yield good results in the field.

Previous studies have found height growth of young seedlings to be positively affected by light availability (Ådjers *et al.*, 1995; Otsamo, 2000; Bebber *et al.*, 2002; Ashton *et al.*, 2006).

Similarly, I found that light quantity, measured as global site factor affected seedling height positively (P = 0.001; table 8 and Figure 12). Although seedling height was not significantly affected by treatment (P = 0.09), it was largely governing the light quantity, as discussed earlier. Therefore, I conclude that treatment affects seedling height, by determining light availability for the seedlings. However, there is an indication that some other factor, determined by treatment, is affecting the seedling height. Tang (1980 as cited by Bebber *et al.* (2002)), suggested that planting multiple seedlings in a group would be beneficial for their performance, i.e. facilitation. That any facilitation would exists between seedlings as young and small as these seems unlikely. It is more likely that this would be a result of the flexibility in gap planting; choosing favourable gaps as well as choosing suitable planting spots within each gap.

The degree of degradation, i.e. forest type, do not exert any main effect on seedling height. Since degradation level significantly affected available phosphorous in the 0-5 cm horizon and the bulk density at 5-15 cm, one could conclude that in this early stage seedling height is not restricted by either phosphorous nor negative effects of slightly higher bulk densities. However, the differences between forest types in available phosphorous are not that large, it is not unlikely that fertilization with phosphorous might cause a growth response. Although early growth was not affected by factors governed by degradation level, it is likely that it might become significant in the future; e.g. high bulk densities in deeper soil profiles may cause inhibition of tap-root elongation (Hattori *et al.*, 2013a).

Although the level of degradation had no effect on seedling height, there is a strong indication that an interaction between degradation and treatment exists. There is a trend in the intermediately (macaranga) and heavily degraded (open) forests that gap planting yields higher seedlings than line planting (figure 11). Whilst in the least degraded forests (dipterocarp), line planting yields higher seedlings than gap planting. The reason for these differences may derive from light quantity or competition from the surrounding vegetation. The higher canopy, combined with little ground vegetation, in the least degraded forests (dipterocarp) could complicate the process of choosing a suitable gap; identifying where on the forest floor a canopy gap might reside is troublesome. Further, canopy height will alter the angle between the seedling and the canopy gap edge; given the same canopy gap size, seedlings below a high canopy would experience a shorter duration of direct overhead sunlight. However, neither indirect (ISF) nor direct site factor (DSF) were significantly affected by the level of degradation (Table 5). Conducting the analysis of global site factor, the interaction between forest type and treatment were highly insignificant and thus removed from the final model, suggesting that the seedlings in the least degraded forests (dipterocarp) might be co-limited by light quantity and other factors. The reason for line planting yielding higher seedlings than gap planting in the least degraded forests (dipterocarp) could possibly be attributed to a larger cleared area; reducing demand for the co-limiting factors by vegetation.

Ideally, the mean relative growth rate per plot should have been used as response variable. However, when calculating growth rates, roughly 20% of the seedlings exhibited negative growth. Rather than including negative growth rates or excluding 20% of the seedlings from the analyses, average height per plot was used instead. Since no information about the accuracy of the earlier measurements were available it seemed the best option. Further, using height rather than the relative growth rate could cause issues; one species might be generally taller at the planting occasion. However, the approach with multiple species and the usage of averages per plot should even this out.

The three categories of degradation used to classify the forest in the INIKEA-project area divides the forest by vegetation structure occurring at the planting occasion. I.e. open forest type consisted of scattered trees, with little to no regeneration of dipterocarp seedlings. Macaranga forest type had a tree cover dominated by pioneer *Macaranga spp.* with very few dipterocarp seedlings. Dipterocarp forest type were dominated by trees of all sizes, including seedlings from the *Dipterocarpaceae* family. It has been assumed that different restoration methods would be more or less suitable depending on degradation level. I.e. line planting would be most effective in heavily degraded forests (open), gap planting in the intermediately degraded forests (macaranga) and the liberation treatment would be suitable for the least degraded forests (dipterocarp).

The variation within the three categories with respect to bulk density at 5-15 cm and available phosphorous at 0-5 cm would indicate that there might be a need for a more detailed classification. Studies have found that slope affects disturbance intensity during logging (Lussetti *et al.*). fire intensity as well as erosion and surface runoff plausibly enhancing nutrient leeching after disturbance (Greacen & Sands, 1980; Malmer & Grip, 1990; Agee, 1996; Granström, 2005). Further, disturbance type would likely differ with slope as well, flatter areas are more likely to have been used as log landings thus having severely compacted soils. Topography also seem to influence growth rates of planted seedlings, e.g. a study by Hattori *et al.* (2013b) found that seedlings grew better on valley floors due to higher nitrogen levels.

The classification scheme was highly subjective, distinguishing between the two most degraded forest types (open and macaranga) seems to be a judgment call; i.e. when do scattered trees become a tree cover? Dividing between the intermediate and the least disturbed types (macaranga and dipterocarp) would seem easier due to the “trees of all sizes, including seedlings from the Dipterocarpaceae family”. It is likely that a more precise division, based upon actual measurements of the forest structures (I.e. basal area, canopy height and proportion of trees from the Dipterocarpaceae family) would yield less unexplained variation and clearer patterns in seedling performance. However, the question how to divide each class remains. With a study similar to this one, but including slope, basal area, canopy height and proportion of trees from the Dipterocarpaceae family one could likely find suitable classes.

Conclusions

Interpretation of these results suggest that the level of degradation should be considered when designing an enrichment planting strategy. Although gap planting yielded better seedling performance within more degraded forests, both long term studies and a cost-benefit analysis must be conducted in order to evaluate which method is most effective. Although the liberation treatment was not included in this study, a comparison between all three methods would be of importance; liberation would likely be less expensive than either planting method, thus allowing larger areas to be restored. However, liberation requires an abundance of naturally regenerated seedlings to be present, making it unsuitable in heavily degraded areas. The classification system seems a suitable guideline for choosing restoration method, as well as estimating earlier disturbance. However, the large variation of some variables indicate that it could be worthwhile to examine if there is a need for clearer distinctions between the intermediate (macaranga) and heavily (open) degraded types.

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Appendix 1

Table 9. Complete list of species planted in the RRE-plots of the INIKEA project on northern Borneo. Table shows scientific name, local name (variation occur depending on area), species with an X were included in this study.

Scientific name	Local name	Included	Scientific name	Local name	Included
Parashorea malaanonan	Urat mata daun licin	X[1]	Dipterocarpus gracilis	Keruing kesat	X[1]
Shorea acuminatissima	Seraya kuning runcing	X[1]	Dryobalanops keithii	Kapur gumpait	X[1]
Shorea gibbosa	Seraya kuning gajah	X[1]	Dryobalanops lanceolata	Kapur paji	X[1]
Shorea leprosula	Seraya tembaga	X[1]	Hopea ferruginea	Selangan mata kucing	X[1]
Shorea macroptera	Seraya melantai	X[1]	Parashorea smythiesii	Urat mata batu	X[1]
Shorea parvistipulata	Seraya lupa	X[1]	Shorea falciferoides	Selangan batu laut	X[1]
Shorea smithiana	Seraya timbau	X[1]	Shorea leptoderma	Selangan batu biabas	X[1]
Parashorea tomentella	Urat mata beludu	X[1]	Shorea seminis	Selangan batu terendak	X[1]
Shorea agami	Melapi agama	X[1]	Artocarpus odoratissimus	Timadang	X
Shorea argentifolia	Seraya daun mas	X[1]	Ficus benjamina	Kayu arah	X
Shorea faguetiana	Seraya kuning siput	X[1]	Heritiera simplicifolia	Kembang	X
Shorea fallax	Seraya daun kasar	X[1]	Koompassia excelsa	Menggaris	X
Shorea ovalis	Seraya kepong	X[1]	Nephelium lappaceum	Rambutan	X
Shorea parvifolia	Seraya punai	X[1]	Baccaurea motleyana	Rambai	
Shorea pauciflora	Oba suluk	X[1]	Mangifera pajang	Bambangan	
Shorea xanthophylla	Seraya kuning barun	X[1]	Pentace adenophora	Tekalis daun bulat	

[1] Species belonging to the dipterocarpaceae family

Appendix 2

Table 10. Pearson correlation matrix for measured variables. The variables were measured in the RRE-plots within the INIKEA project area on northern Borneo. Abbreviations: ISF – Indirect Site Factor, DSF – Direct Site Factor, ISF/DSF – Ratio between Indirect Site Factor and Direct Site Factor, LAI – Leaf Area Index, BD@5 – Bulk Density at 0-5 cm depth, BD@15 – Bulk Density at 5-15 cm depth, GSF – Global Site Factor, AP@5 – Available Phosphorous at 0-5 cm depth, OC@5 – Organic Carbon at 0-5 cm depth, Clay@5 – Clay portion at 0-5 cm depth, VisSky – Visible Sky.

Coefficent P value

	ISF		DSF		ISF/DSF		LAI		BD@5		BD@15		GSF		AP@5		OC@5		Clay@5	
Vis Sky	0.976	0.000	0.894	0.000	0.001	0.995	-0.399	0.009	-0.152	0.337	-0.019	0.904	0.902	0.000	-0.039	0.805	-0.006	0.970	0.003	0.984
ISF			0.952	0.000	-0.110	0.488	-0.264	0.092	-0.131	0.408	0.008	0.961	0.959	0.000	-0.164	0.300	-0.081	0.610	-0.099	0.532
DSF					-0.386	0.011	-0.120	0.450	-0.110	0.489	0.063	0.693	1.000	0.000	-0.228	0.146	-0.133	0.403	-0.144	0.361
ISF/DSF							-0.407	0.007	0.013	0.933	-0.179	0.258	-0.368	0.017	0.247	0.115	0.164	0.299	0.196	0.213
LAI									0.105	0.509	-0.037	0.816	-0.130	0.410	-0.396	0.009	-0.155	0.327	-0.223	0.156
BD@5											0.429	0.005	-0.112	0.481	-0.435	0.004	-0.609	0.000	-0.106	0.503
BD@15													0.059	0.711	-0.112	0.482	-0.525	0.000	-0.492	0.001
GSF															-0.224	0.153	-0.129	0.415	-0.142	0.371
AP@5																	0.533	0.000	0.195	0.217
OC@5																			0.365	0.017

Appendix 3

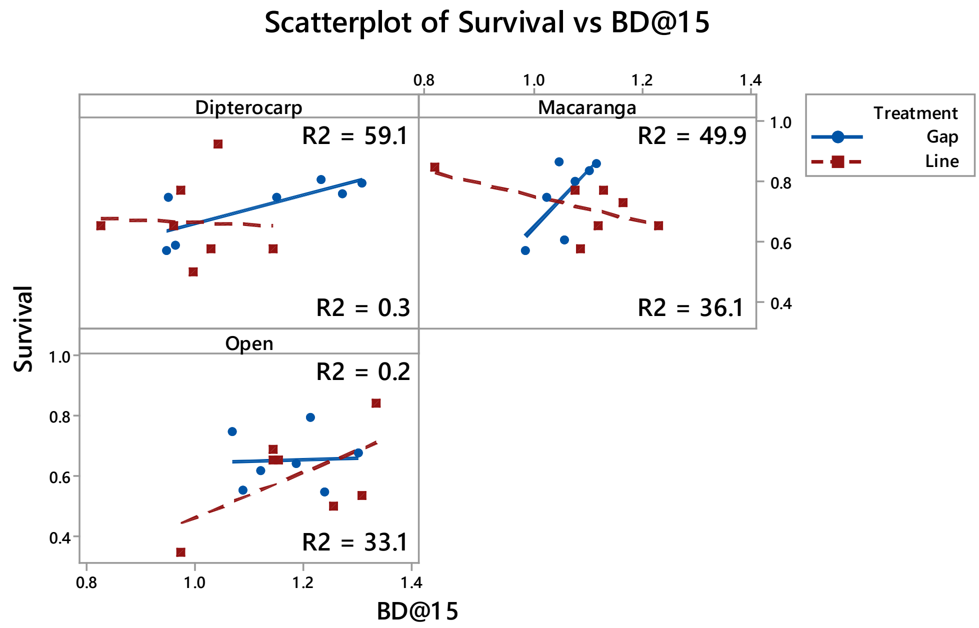

Figure 10. The relationship between seedling survival and BD at 5-15 cm is divided between the three forest types, the blue whole line represents gap planting and the red intermittent line represents line planting. R2-values for regression lines, top value is for the solid line, bottom value for the dashed. Measurements taken in the RRE-plots within the INIKEA project area on northern Borneo.

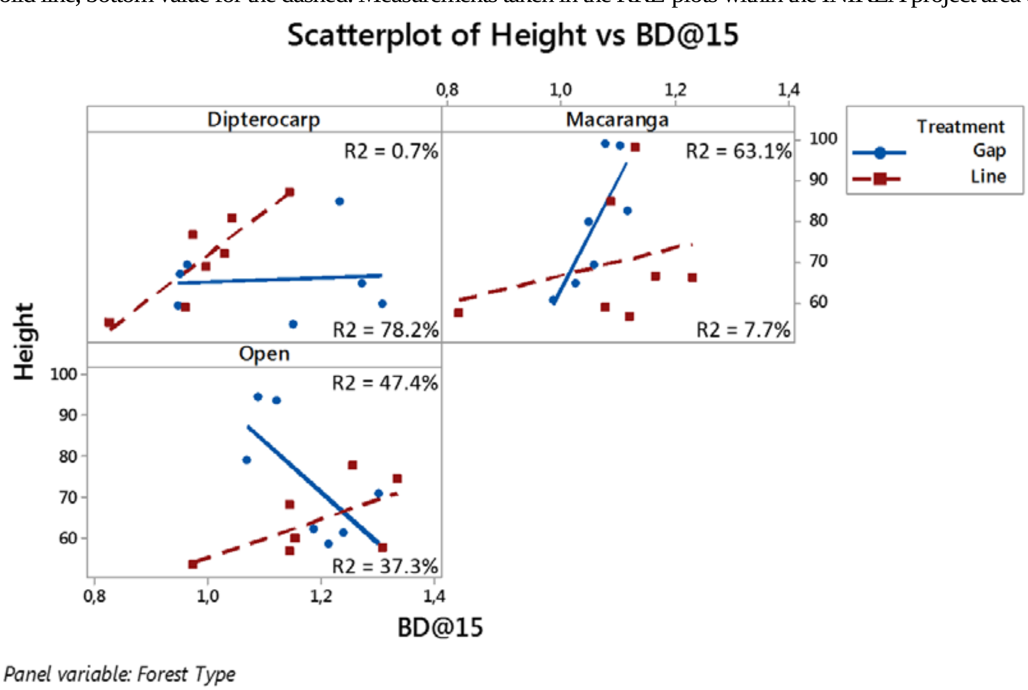

Figure 11. BD at 5-15 cm exhibits different influences on seedling height depending on forest type – treatment combination. Blue circles show individual values for gap planting, red squares for line planting. Dashed line show regression for line, solid line for gap planting. R2-values for regression lines, top value is for the solid line, bottom value for the dashed. Measurements taken in the RRE-plots within the INIKEA project area on northern Borneo.

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