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FACULTY OF AGRICULTURE AND FORESTRY

**Canopy gap characteristics, their size-distribution and spatial pattern in a
mountainous cool temperate forest of Japan**

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<p>Abstract</p> <p>Canopy gaps and their characteristic features (e.g. area and shape) influence the availability of nutrients, moisture and light in a forest ecosystem, and consequently affect the regeneration process and species composition in the forest. Most of the earlier research on canopy gap used field measurement and conventional remote sensing to quantify gap and these methods have limitations and accuracy problems. However, the development in Light Detecting and Ranging (LiDAR) technology has been effective in overcoming limitations and challenges associated with conventional remote sensing. The ability of LiDAR to represent the three-dimensional structure of the canopies and the sub-canopy resulting in high-resolution topographic maps, highly accurate estimated of vegetation height, cover and canopy structure makes it suitable technology for gap studies. LiDAR-based digital surface model (DSM) and digital elevation model (DEM) were used to quantify the canopy gaps over 5124ha of University of Tokyo Chichibu Forests (UTCF) consisting of three forest-types; primary, secondary and plantation forest.</p> <p>Disturbance driven canopy gaps might have spatial and characteristic variation due to differences in disturbance history, nature, frequency and intensity in different forest and land-types. Quantifying gap characteristics and studying variation and size distribution in different forest types and topography help to understand the different gap dynamics and their ecological perspectives. In this study, a gap was defined as an opening with a maximum height of 2m and minimum area threshold of 10m². The minimum area threshold, which represents the gap area created by the death of at least a single tree, was determined through a random sampling of 100 tree crowns at UTCF using high resolution aerial photographs. Gap size distribution was analyzed in different forest types and land types. Spatial autocorrelation of gap occurrence was studied using semivariance analysis and distance to the nearest gap (DNG), which is the distance to the nearest gap for an individual gap. Canopy gap size frequency distribution in different forest-types was investigated using power-law. The negative exponent (α), which is also the scaling component of the power-law distribution, was compared between forest-types.</p> <p>Altogether, 6179 gaps with area 10-11603 m² were found. Gap size distribution in UTCF showed skewness with a high frequency of smaller gaps and a few large gaps. Half of the gaps were smaller than 19 m² and less than one percent of gaps (0.73 %) were larger than 400 m². Primary forest contained high gap density (1.85 gaps per ha), shortest mean-DNG (22m) and second-largest gap-area fraction (0.72 %) after plantation forest area (0.76 %). Secondary forest had the lowest gap density (1.03 gaps per hectare) but had the larger mean gap-area (43 m²) than in primary forest (39 m²). The Kolmogorov–Smirnov test showed differences ($p < 0.05$) in gap size distribution between primary and secondary forest. However, the gap size distribution in primary forest show similarity ($p = 0.59$) with plantation forest area. In primary and plantation forest there was a high frequency of small gaps and few very large gaps (2000-10500 m²), whereas very large gaps (>2400 m²) were absent in the secondary forest.</p> <p>Gap size frequency distribution followed a power-law distribution only in plantation forest area ($p > 0.1$, $\alpha = 2.27$). The scaling parameter in the primary and secondary forest was 2.56 ($p = 0.01$) and 2.20 ($p = 0.02$), respectively. Gap distribution showed some spatial autocorrelation in primary and secondary forest at least with distance up to 1300m. Most of the gaps in the primary forest were concentrated in the valley and middle slope, whereas the upper and middle slope had fewest gaps.</p>		
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1 Introduction

The occurrence and ecological importance of the canopy gaps in a pristine forest was first described by the Finnish botanist Pehr Kalm (1770, cited in Kuuluvainen 1993), however, the importance of the canopy gaps in the forest ecology was firstly investigated by Sernander (1936) in a boreal forest of Sweden (Koukoulas & Blackburn 2004). In the 80s, more foundation research (Runkle 1985; Brokaw 1985; Pickett et al. 1985) showed the importance of canopy gaps, their size and frequency (created by disturbances) in forest ecology. Since then, there have been several canopy-gap studies in relation to biodiversity (Anderson & Leopold 2002), topology (Gale 2000), light regimes (Canham et al. 1990), species regeneration (Sapkota & Odén 2009; Myers et al. 2000) and forest regeneration Sakio (1997). These studies have identified the importance of canopy gaps at different aspects of forest ecosystems, such as structural heterogeneity, tree population dynamics, species composition, variation in micro-topology and thus, accurate canopy-gap quantifying became crucial for forest ecologist and forest managers in order to understand emulate gap dynamics in silviculture activities.

Along with the understanding of canopy gap dynamics (appearance, enlargement, reduction and disappearance of canopy gaps) (Vehmas et al 2011)) and its importance in forest regeneration and species heterogeneity (Kern et al. 2013), the development of advanced remote sensing technology facilitates accurate and efficient gap quantification. Earlier gap research were based on field measurement and conventional remote sensing (aerial photographs, Landsat thematic maps). However, it is a challenging task to delineate gaps using conventional remote sensing because of spatial variation in spectral response due to illumination condition (Koukoulas & Blackburn 2004). On the other hand, field measurements are time-consuming and have small coverage which limits the study to a small extent (Bonnet et al. 2015). More importantly, it might bring biases due to lack of uniform gap measuring and validation system.

Recent developments in Light Detecting and Ranging (LiDAR) technology has facilitated the accurate delineation of canopy gaps overcoming the limitations of conventional remote

sensing methods (Koukoulas & Blackburn 2004). LiDAR measures the three-dimensional structure of the canopies and the sub-canopy topography providing high-resolution topographic maps, highly accurate estimated of vegetation height, cover and canopy structure (Zhang 2008). At present, LiDAR can be used for accurate detection of small gaps (<1 m²) (Vepakomma et al. 2008) or a single tree loss (crown radius ~1 m²) (Yu et al. 2004) from the canopy.

Canopy gaps are consequences of disturbances (Yamamoto 1992), and disturbance in forest ecosystem is a complex process which shows variation in multiple scales (topography, forest typer, species, climate). Thus, canopy gaps also vary accordingly. In one of the very few studies about the relationship between topography and gaps, Lobo (2013) found that gap characteristics differed according to forest and land types. Bigger gaps were most likely to be found in the old-growth forest and on the gentle slope than younger forest or the steeper land. In another study, gap sizes and gap fraction (i.e. ratio of gap area to total area) varied according to topography, elevation and slope (Battles et al. 1995). However, more studies are needed to understand the gap behavior with respect to spatial dimensions such as slope, aspects and land type.

Understanding gap characteristics such as gap size distribution and their impact of species composition, forest regeneration, and other ecological factors, is very important for developing nature-based silviculture through emulation of natural disturbances (Oliver&Larson 1996). Recently, there have been successful efforts to mathematically describe gaps size frequency distribution by a power-law (eq.2). Power-law has been studied in several natural phenomena such as the distribution of species body size, colony size, abundance among species, fire magnitude, island size, lake size, flood size and many other heavy-tailed phenomena (White et al. 2008). However, in gap studies, Kellner & Asner (2009) successfully used it to describe skewed-shaped canopy gap size frequency distribution in a tropical forest. Based on the findings in different forests, authors concluded that gap size frequency distribution in tropical forests can be ubiquitously described by power-law distribution. Research on gap studies (Gaulton & Malthus 2010; Vehmas et al. 2011a; Melloh et al. 2003; Asner et al. 2013) show that canopy gaps in forest comprise of

many small-sized gaps and a few bigger gaps and their distribution can be described by power-law.

2 Literature review

2.1 Disturbance ecology

Disturbance is a physical force or event which disrupt the physical or biological structure of an ecosystem (Pickett et al. 1999). Disturbances can be biotic or abiotic; endogenous or exogenous; intense or weak; severe or mild (Rogers 1996) and vary spatially and temporally (Kuuluvainen 1993). Disturbances differ from each other on their characteristics such as distribution, frequency, rotation period, predictability, magnitude, intensity, severity and synergism. Among others, intensity and severity are important aspects of forest ecology (Lee E. 2002). Intensity refers to the amount of energy released by physical disturbance whereas, severity refers to the amount of mortality of trees and plant populations in disturbed forest. Moderate-severity disturbances may kill some or all over-story and understory vegetation but leave a legacy of intact tree or seedling. High-severity disturbance can wipe out the existing over-story and understory vegetation, whereas small or medium disturbances kill one or a few trees creating openings in the forest canopy (Oliver&Larson 1996).

A stand becomes more susceptible to disturbance as it grows and the magnitude of disturbance required to disrupt the stand decreases with age (Runkle 1984; Oliver&Larson 1996). Therefore, in a forest stand, disturbances frequently show their presence by damaging or killing one or multiple trees. The primary role of disturbances in forest development is to kill the existing vegetation and thus releases the space available for next generation of plants to grow (Oliver&Larson 1996). At first, formed space (gap) modifies local competitive hierarchies, microclimate and resource availability, mainly by increasing the availability of nutrients and moisture and light in a forest ecosystem (Takahashi & Takahashi 2013). Eventually, a gap is occupied by advanced regeneration or recruitment

from buried or disperse seeds (McCarthy 2001) or ingrowths from adjacent trees (White and Pickett 1985). Thus, disturbances in the forest initiate a series of dynamic events in the forest ecosystem called gap dynamics (Yamamoto 2000).

After the disturbance, both surviving and new plants have a chance to occupy the open space. Individuals try to capitalize on the growing space and grow rapidly before the available space is closed. However, several factors such as soil, climate, competition, and species growth characteristics play a crucial role to decide which species have a competitive advantage to take over the new space (Oliver&Larson 1996). If soil, climate, and other conditions do not favor other species, these species which occupy the space, can dominate the space for decades or century.

2.1.1 Disturbance agents

As tree ages and increases in size, it becomes more susceptible to smaller and more common disturbances (Oliver&Larson 1996). Consequently, trees are damaged or killed by disturbances. Disturbance can be either one or in-combine of fire, winds, floods, erosion, siltation, landslides, avalanches, glaciers, volcano, ice storms, mammals, insects, and diseases. Each geographical area has characteristic disturbance types and frequencies based on its topography, climate, soil, vegetation, animals and other factors. For example, temperate broad leaves forest are susceptible to moderate-severity disturbances such as cyclones, thunderstorm, drought, ice storms and heavy rain (Greenberg & Collins 2016). Similarly, most of the insect damages are frequent and intense in the temperate forest of North America (Lierop et al. 2015).

Wind is one of the most common disturbances in the mountainous region. Topography has a great influence on forest damage caused by wind (Lee E. 2002). Wind speed can be strong at the top of a slope if the wind angle is at a right angle to a ridge, at the mid-slope if the wind blows at an acute angle to a ridge, and at the valley if the wind blows parallel to the ridge. Trees on the windward sides of ridge face the strong wind, whereas trees on the lee slopes are damaged by the violent downslope wind created by wind motions of wind

moving over the summit (Barry, 1981 cited in Oliver&Larson 1996). Thus, the impact of disturbance can vary according to the altitude, slope and aspect. The damage from a single windstorm might have a specific pattern but will be invisible when numerous storms hit a forest over time. However, in the case of high-intensity disturbances such as cyclone or typhoon, there can be a strong relationship between damage and aspect as the damaging wind may come from the same direction (Oliver&Larson 1996).

Strong typhoons are associated with high wind and rainfall and are a common form of natural disturbance in both temperate and tropical forest (Lin et al. 2010). Typhoon is a major form of natural disturbance in forest ecosystem which can cause snapping, defoliation and uprooting of trees. The most notable impact of the typhoon in the forest is defoliation which significantly increases the light flux into the forest floor (Lin et al. 2010). However, typhoon can uproot trees creating big gaps in the forest canopy.

Floods, erosion, and siltation are normally associated with heavy rains and snowmelt. In the mountainous topography, landslide, flood and erosion are common disturbances, and depending on the magnitude, impact of these disturbances can be uprooting of single to multiple trees. High rain and steep slopes increase the chance of erosion. However, poor forest management practices and poor construction (roads) also can trigger erosion. Beside tree mortality, erosion and landslide can reduce growing space by removing nutrient, water holding capacity and physical pore space for root penetration. At the same time, it can expose buried seeds to the environment and might initiate the germination process. In such case, only species which can survive extreme of soil condition are likely to grow and occupy that space [Oliver&Larson 1996].

Biotic disturbance agents include insects and diseases and mammalian herbivores, and they often disturb forest for food and habitat (Stanturf 2004). Mammals cause disturbances through grazing and browsing. In this process, mammals can eat leaves, branches, seeds, roots and tree bark causing partial damage to tree-death. These disturbances by mammals are unique to other disturbances created by physical forces. For example, in the temperate mountain forest of Japan, Takahashi & Takahashi (2013) found that black bears create

unique disturbances by their feeding habits, which creates a unique light regime distinct from that created by tree fall.

People impact and manipulate forest through technology, economics and population migration (Oliver&Larson 1996). In most cases, human beings create disturbances by thinning, selective logging, burning, land clearing and clear-cutting and most of the time these activities can mask or reduce natural disturbances or reduce the frequency of natural disturbance in a forest in some period (Oliver&Larson 1996). In managed forests, human disturbances can be more frequent than natural disturbances. For instance, clear-cutting of forest can repeat every 40 years in a stand, whereas forest fire with similar magnitude would take 400 or longer years to reoccur (Oliver&Larson 1996). The impact of such silvicultural practices is that it might avoid the large natural disturbance and reduce the number of small disturbances. For example, a young regenerated forest after clear-cutting can be more resistive to natural disturbances, and thus very few disturbances can be seen in young forests.

One disturbance can increase the susceptibility to other disturbances (Oliver&Larson 1996). For instance, dead trees make forest more susceptible to forest fires, overgrazing might cause soil erosion and earthquakes can trigger landslide by reducing the friction between soil particles. A weakened tree by climatic changes, fires and overcrowding are susceptible to insect attack and diseases. Similarly, one disturbance can increase the resistance to other disturbance. Death of a tree might open the canopy and increase photosynthate available for neighbor trees. Consequently, trees can develop into bigger diameter and become more resistant to wind storms.

Disturbance regime in a forest is not solely controlled by disturbance agents, but it is controlled by the interaction between topography, soil type and disturbance history. (Lobo 2013). For example, the effect of wind varies across different topographic land type, thus the disturbance created by wind might differ in land type. Similarly, landslides and erosion depend on slope and soil type. Thus, the disturbance regime in a forest is a consequence of several abiotic and biotic factors that interact in many ways.

2.2 Disturbance dynamics in the temperate forests of Chichibu Mountains

Chichibu Mountains, the focal area of this thesis, have complex topography with steep slopes and a network of mountain streams. In the steeper landscape, valley floor landforms are affected by fluvial processes and various mass soil movement processes (landslide and erosion) from tributaries and adjacent hillslopes (Sakio and Tamura 2008). In the riparian forest of Chichibu mountains, flood and landslide are common types of disturbances. Natural disturbance in the Chichibu mountainous varies between small to large disturbance (Sakio and Tamura 2008). Small disturbances occur in the ground level without altering light condition in the forest ecosystem. In the rainy season, sedimentation and erosion of sand and gravel are carried by stream flow washing the seedlings on the floor. Since they do not affect top canopy, the light flux reaching the floor is not altered. However, it might impact understory vegetation and regeneration forest. On the other hand, a high-intensity typhoon can cause significant tree death or damage by uprooting and snapping, which create small to large canopy gaps in the forest. In fact, Nakashizuka (1987) found that 60-70 % of the discovered gaps were created by the typhoon in one beech forest of Japan. Such large typhoon with precipitation over 300 mm has visited every decade in Chichibu mountains over the last century (Sakio 1997). This heavy rain associated with typhoon result in a debris flow and can trigger other disturbances like landslide and channel movement.

Disturbance in the mountainous region can provide a sudden opportunity for some species. For example, the deposit of gravel and sand offers from mass movement can provide an excellent growing condition for new vegetation, which would not have been possible without the disturbance. For example, species like *Fraxinus platypoda* are well adapted to such disturbances at Chichibu mountain (Sakio 1997). Similarly, Some shade tolerant species like *Cercidiphyuum japonicum* and *Pterocarya rhoifolia* have colonized the gap created by a large landslide which occurred about 80 years ago (Sakio et al. 2002). Thus, such large magnitude disturbances are responsible for changing species composition in the

forest of Chichibu mountains. Smaller gaps do not alter the species composition as they are quickly occupied by advance regenerations or the extension from adjacent trees.

The sub-canopy also has a great impact on gap dynamics (Senecal 2018). The natural forests, like the primary forest of Chichibu, have multi-layer canopy due to rich species diversity and vertical composition of seedlings, saplings and trees of different age (UTCFC 2018). Under the closed canopy where the light barely reaches, most of the sub-canopy species are shade tolerant species. These species are opportunists in the sense that they are waiting for an opportunity to grow into the canopy. As soon as the disturbance strikes, opening the canopy, they grow vigorously taking over the newly created gap. Without such disturbance, they can not establish themselves in the canopy.

2.3 Canopy gap dynamics

According to gap dynamic theory, natural disturbances are certain to occur in any closed forest stand if sufficient time period elapses (Yamamoto 2000). In the absence of major disturbance, forest disturbance dynamics in an old and mature forest is driven by canopy gap dynamics resulting from small-scale disturbances (Vepakomma et al. 2008; McCarthy 2001). Gaps are characterized by their shapes and sizes. Such variation of canopy gaps reflects the pattern and magnitude of mortality or physical damage (Asner et al. 2013). For instance, a forest with many smaller gaps is likely to have high rates of repeated small disturbances resulting tree damage or death (White & Pickett 1985), whereas bigger gaps are due to death of multiple trees caused by the high magnitude of disturbances.

Gaps are characterized by their size, shape, the rate they open and close (Vepakomma et al. 2008b). Gap size is one of the important characteristics affecting recruitment of species into a gap, whereas gap shape reflects the magnitude of disturbance and may reflect the direction and architect of tree fall (De Lima et al. 2012). Gap size is proportional to the intensity of the disturbance. Small gaps result from smaller disturbances whereas bigger gaps are the consequences of larger disturbances. Small gaps reportedly maintain a stable canopy composition, whereas bigger disturbances are required to alter the species

composition (McCarthy 2001). The availability of light, moisture, and nutrient to a newly growing species inside a gap is often dependent on gap-size. This was demonstrated by Chazdon & Fetcher (1984) by comparing daily photosynthetic photo flux density (PPFD) inside gaps of different sizes. Gaps with area 200 m² and 400m² had PPFD of 9 % and 20-35 % respectively, whereas the adjacent understory had a PPFD of 1-2 %. Bigger gaps also affect the light regime of the understory area adjacent to the gap. As the size increases, light can penetrate a greater distance into the understory adjacent to the gap (Canham et al. 1990). This effect was found by Canham et al. (1990) in both temperate and tropical forest. Therefore, the gap size is considered an indicator of environmental heterogeneity and resource sequestration in gaps (McCarthy 2001).

Along with gap size and shape, position and orientation of a gap impacts the light flux and the nutrients availability within a gap and therefore affect the species composition (Oliver&Larson 1996; McCarthy, 2001). The duration and intensity of light depend on many factors like shape, size slope, orientation, the height of the surrounding mature-phase forest and characteristics of post tree fall debris and surviving vegetation (White & Pickett 1985). For example, in the northern hemisphere, the zone of direct sunlight is widest at north because the northern sun is to the south at noon. Thus, north part of gaps is subjected to higher light fluxes than the southern edges. As a result, species of increasing shade tolerance increases as we travel from north to south inside a bigger gap (Coates 1998).

Gaps are the characteristic of forests and can vary according to forest type, age, species and environment. For example, young forests usually have frequent occurring of small gaps due to high mortality through self-thinning, but are rapidly occupied (Kuuluvainen 1993). On the other hand, in the old forest larger trees are receptive to disturbance creating bigger gaps. Typically, in a natural forest, there are many small and few large gaps, and the gap-size frequency can be described by power-law distribution (eq.2) (Fisher et al. 2008; Lobo 2013; White & Pickett 1985). Bigger gaps are fewer but have a bigger contribution in overall gap area proportion in a forest. Gaps proportion in a forest varies according to forest types. Natural and mature forests in Japan have a gap area proportion of 10-20 %

(Nakashizuka 1987) whereas in other forests it can range between 5.8 to 12.6 % (Ott & Juday 2002).

Over time, these gaps are taken by tree individuals. Species which requires a high intensity of light and temperature for germination and growth are found in bigger gaps, whereas, shade tolerant species which can grow in the understory but depends on canopy opening for substantive growth and reproduction occupy small gaps (McCarthy 2001). However, the edge of the gap is usually shadowed by the adjacent trees and therefore shade tolerant species are found in small gaps are also found on the edges of the bigger gaps. For instance, Busing (1994) found that in an old growth cove forest of Appalachian mountains several shade tolerant species showed positive regeneration density response with small (0.01-0.03 ha) gaps, but these gaps were too small for creating light conditions for shade intolerant species. However, in bigger gaps (0.4 ha), there was an increase in regeneration density for shade intolerant species (Bushing 1994).

Small gaps can be a hostile environment for some species to grow due to limited light and competition. Roots of the surrounding site occupy most of the small gap. Although it has canopy opening, direct sunlight may not reach the floor as the sun is never directly overhead except in the tropics (Oliver&Larson 1996). Species which can survive intense root competition and low light might thrive in such small open spaces.

The significance of canopy gaps for growth and regeneration might not be the same between different forest environments (Kuuluvainen 1993). Due to predominantly low sun angles and the narrow vertically extended tree crown in the boreal forests, trees cast long shadow and can affect the radiation condition within a gap for a considerable distance outside a gap. The presence of small gap has very small changes on the light level to the surrounding stand compared to tropic and temperate forest. Therefore, boreal forest canopies may remain more open due to growth factors like nutrients and solar radiation. Compared to boreal forest, temperate deciduous species shows considerable branching flexibility and overall crown shape, which allows them to exploit the nearby gaps rapidly (Kuuluvainen 1993).

Depending on the intensity, severity and extent of a disturbance, it might take several decades before the disturbed land regenerates into a forest stand again. In a case of major disturbances (natural disturbances, clear-cut), it may take a long time to regenerate forest and the species composition might change after disturbances. Based on the theory of stand developmental cycle of Oliver and Larson (1996), forest successional stages can be broadly categorized into four categories: stand initiation stage, stem exclusions stage, understory reinitiating stage and old growth.

In the stand initiation stage, a disturbance gives chance for survivals and new species to occupy the space or gap. Stand initiation stage continues for several years after disturbance and throughout the period new species continue to appear and compete for the available space. Grasses have superficial roots, and this gives grasses a competitive advantage to grow vigorously absorbing the rainwater before other species grow. At the end of the stand initiation phase, a gap or open space is occupied by one or more species. Thus, in the stem exclusion phase, new species do not appear, but rather some of the existing die through intense competition. Death of a tree occurs due to competition for underground and above ground space [Oliver&Larson 1996].

Decades after the stand-replacing disturbance, open space is covered in both above story and understory in the understory reinitiation phase. Along with dominant species, a low stratum of herbs, shrubs and advance regenerations appear on the understory. Hundreds of years after disturbance, a largely disturbed forest-stand turn into an old-growth. At this stage, forest stand contains diverse species, large-old trees with wide spacing, a relatively continuous vertical distribution, standing dead trees and large logs on the forest floor. There is an equilibrium between growth and mortality and the forest has nutrients recycling through decomposition of dead biomass. Throughout this process, forest continuously disturbed by disturbances resulting tree breakage or mortality at different stages of the regeneration process [Oliver&Larson 1996].

2.4 Lidar

LiDAR has been an effective and reliable tool for canopy gap mapping (Vepakomma et al. 2008). LiDAR, also known as airborne laser scanning (ALS), is an active remote sensing technology that determines the distance by accurate measurement of time and speed of laser beam to travel to a target object (Lim et al. 2003). LiDAR was used for profiling and bathymetry at the beginning phase, and with the development of accurate global positioning systems(GPS) and inertial measurement units (IMU), the applications of LiDAR widened into various research fields (Kulawardhana 2011). Since then LiDAR became an important tool in forest research and was applied into different forest ecology studies such as delineating forest stand and understory, canopy gaps, canopy fractional cover, forest maturity, dead biomass mapping, habitat mapping, Leaf Area Index (LAI), forest pigment, forest change detection, disturbance dynamics and other forest researchers (Monnet & Emgr 2012).

Most of the optical sensors can assess only the horizontal distribution, whereas LiDAR remote sensing can provide both horizontal and vertical information of a forest(Lim et al. 2003). Using Multi-echo sensors, it is possible to detect several returns for one pulse including the first and last return, which represent the top of the canopy and the ground surface, respectively (Jones & Vaughan 1010). With a nadir view, the difference between the first and last returns estimates the height of the canopy. Thus, LiDAR directly measures the three-dimensional distribution of forest canopy and sub-canopies which enables accurate estimation of vegetation height, cover and canopy structure (Lefsky et al. 2002).

Conventional remote sensing has been applied in several ecological applications such as gap studies, mapping land cover, estimation aboveground biomass and Leaf Area Index(LAI) (Lefsky et al. 2002). Conventional remote sensing involves either a passive optical system (aerial photographs, Landsat thematic mapper) or active radar system such as RADARSAT. The accuracy and sensitivity of conventional remote sensing in forest applications fall with increases biomass and LAI (Lefsky et al. 2002). More importantly, conventional remote sensing is affected by illumination condition and spectral

inseparability (Vepakomma et al. 2008). The illumination condition from sunlight and the shadow from the neighboring trees might result in different spectral response within a gap with similar height (Koukoulas & Blackburn 2004). Another limitation of conventional remote sensing is its inability to acquire the accurate under-canopy information as a Digital Terrain Model (DTM) (Lisein et al. 2013). Accurate estimation of DTM is crucial for canopy height estimation and gap delineation.

LiDAR method overcomes problems associated with conventional remote sensing by mapping three-dimensional forest structure with high accuracy (Lim et al. 2003). LiDAR uses its one source of electromagnetic radiation and is independent of solar angle and unaffected by spectral reflectance (Koukoulas & Blackburn 2004). ALS data are acquired via the emission of laser pulses from an aerial platform and the emitted pulses record multiple returns as they strike different forest structure (Lisein et al. 2013). These returns represent a three-dimensional point cloud which contains all vertical and horizontal structure of the target. The last return represents the ground level and based on the last return DTM is generated.

Several studies have successfully mapped canopy gaps using LiDAR data (Koukoulas & Blackburn 2004; Vepakomma et al. 2008b; Gaulton & Malthus 2010; Bonnet et al. 2015; St-Onge & Vepakomma 2004; Vehmas et al. 2011b). However, validation of LiDAR detected gaps is important before grasping the technology in forest ecological studies. Some researchers have cross-validated LiDAR detected gaps using aerial photographs or field measurement. In his research, Gaulton & Malthus (2010) obtained an accuracy of 88 % when compared LiDAR (high density: 11.4 returns per m²) detected gaps with field surveyed gaps. However, accuracy dropped to 77 % for low density (1.2 returns per m²) LiDAR. Similarly, St-Onge & Vepakomma (2004) got an accuracy of 96 % when compared LiDAR detected gaps with aerial photographs. Thus, the results from cross-validation and high level of efficiency and accuracy of mapping forest structure make LiDAR a promising cutting-edge tool for gap-dynamics research.

2.4.1 Component of LiDAR system

Basic system components of LiDAR are standard although there might be significant variation in LiDAR sensor. An airborne LiDAR consists of an airborne and ground segment (Shan & Toth 2009).

Airborne segment

- Airborne platform
- LiDAR
- Position and orientation system(POS)

The ground segments

- Global positioning system(GPS) reference stations.
- Processing hardware and software for synchronization and registration which is carried out off-line

Lidar samples line-of-sight slant ranges referenced to the LiDAR coordinate system. Position and origination system (POS) stores GPS data and orientation and phase information of the carrier through inertial measurement unit (IMU) unit. Onboard GPS receiver operating in conjunction with ground GPS provides differential GPS (DGPS). Using DGPS and inertial data, the position of the airborne sensor can be computed with centimeter to decimeter accuracy and stored in GPS-time along with the orientation information of the carries. Scanned data are attributed with the time generated from the received GPS signal, which thus can be synchronized with POS data based on time. After this, each scanned point can be converted into the earth-fixed coordinate system. Today the accuracy of the laser scanner, which is primarily determined by the accuracy of POS, can be better than 10 cm in 3D space [Shan & Toth 2009].

LiDAR used in forest applications is categorized as discrete return and continuous return (Lim et al. 2003). The two systems differ in how they sample vertical and horizontal canopy structure. A vertical sampling of LIDAR refers to the number of range sample recorded for each pulse, whereas the horizontal sampling is determined by the area of

footprint or the number of such footprints. Discrete return system allows few returns to be recorded for each pulse during the flight, whereas full return system records the amount of energy returned to the sensor for a series of equal time interval.

From an ecological perspective, the primary concern in the application of LiDAR is the return from the vegetation canopies (Lefsky et al. 2002). For forest applications, an important characteristic is the ability of small footprint and discrete return sensor to capture multiple returns from different layers of canopy structure (Lim et al. 2003). Thus, the discrete system provides detailed mapping of canopy surface topography and ground (Lefsky et al. 2002).

3 Aim of the study

The purpose of the study is to characterize the canopy gap structure in the Chichibu mountains. Several studies have emphasized the importance of canopy gap for species diversity, understory light regime and species composition. However, there are limited studies on gap size frequency distribution, spatial properties and their differences in different forest types. The topography of Chichibu mountains gives an opportunity to analyze the gaps structure in different aspects and land types such as ridge, upper-slope, middle-slope, lower slope and valley.

The aims of the research are to:

- Analyze the gap characteristics in different forest types and topography
- Analyze the gap size frequency distribution in different forest types
- Analyze the spatial pattern of canopy gaps

4 Methods and materials

4.1 Study area.

The University of Tokyo Chichibu forest (UTCF) is in the cool temperate region spreading over 5812 ha. Our study area covers three classified forests which altogether cover 5124 ha (88 %) of UTCF as shown in figure 1. The elevation of UTCF ranges from 530 m to 1,980 m. The area is surrounded by 2000 m class Chichibu mountains, of which Mt. Kobushi is the highest peak with an altitude of 2,465 m. UTCF receives annual precipitation of 15,14 mm and snowfall less than a half a meter during the winter season. The annual mean temperature is 11.0°C. There are three main rivers, the Arakawa, Fuefukigawa and Chikumagawa. The deep erosion and formation of the V-shaped valley by Arakawa River have led to a very steep slope in the lower portion along the valley. Small streams and water runoff has created several channels throughout the area. The underlying rocks along the forest areas mainly consist of slate, sandstone and shale from the Mesozoic era.

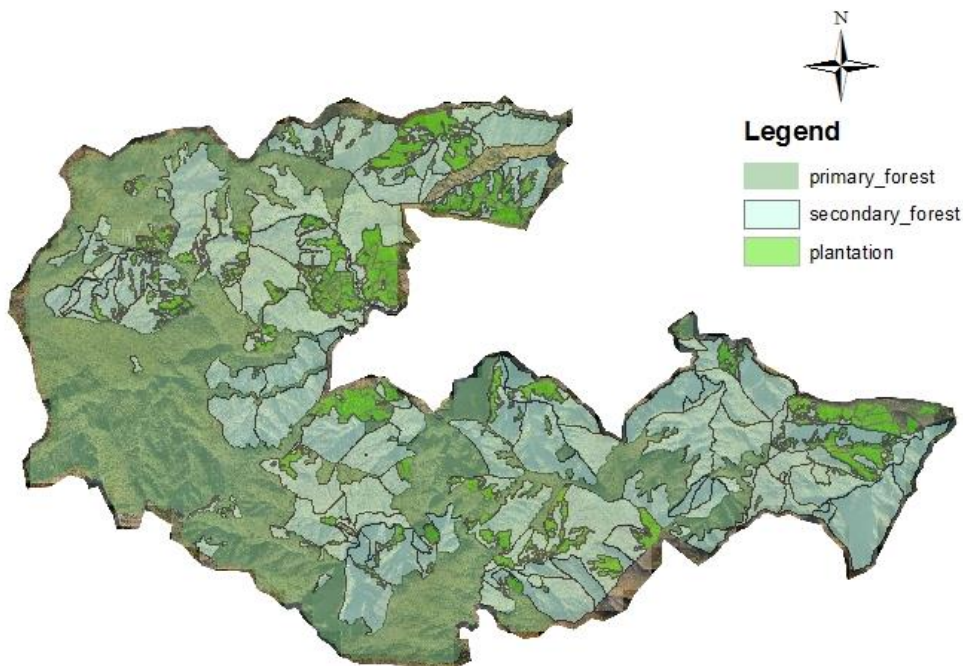


Figure 1. The University of Tokyo Chichibu forest categorized into three different forest areas: Primary, secondary and plantation forest area. Unclassified part of the UTCF, especially on the edge and some inner channel in the north, was excluded in the study.

UTCF consists of natural (86 %) and man-made forest (13 %). The natural forest consists of 37 % of primeval forest (referred to as primary forest in this study) and 63 % of secondary forest and mainly occupy by deciduous hardwood. Secondary forest is the naturally regenerated forest after clear-cut. Plantation forest area is artificially planted forest area which is mostly covered with forests of *Chamaecyparis obtuse* (39 %), *Larix kaempferi* (27 %) and *Cryptomeria japonica* (22 %).

Due to a wide range of elevation, the natural forest has high species diversity. It consists of 260 species and 64 varieties, belonging to 140 genera and 63 families of tree flora.

Montane vegetation occupies the elevation between 600 and 1,600 m. Within this elevation range, forest cover is divided according to the topographic conditions. Species like *Tsuga sieboldii* mixed with *Abies firma* and *Abies homolepis*, occupies the habitats on ridges and *Fagus crenata* and *Fagus japonica*, occupies mesic habitats on middle slopes and *Fraxinus spaethiana* mixed with *Pterocarya rhoifolia*, occupies wet habitats on concave slopes or along valleys. Narrow ridges and rocky places are covered with natural stands dominated by *Chamaecyparis obtusa*, whereas *Tsuga sieboldii* dominates on the driest habitat. The higher altitude above 1,600 m is covered by sub-alpine vegetation like *Thuja standishii*, *Larix kaempferi*, *Pinus pentaphylla*, *Abies veitchii* and *Abies mariesii* mixed with *Picea jezoensis var. hondoensis* and *Betula ermanii* [UTCF, 2018].

4.2 Gap definition

Brokaw (1982) defined a gap as a hole in a canopy extending through all levels down to the height of two meters. In general, the vertical profile of a gap is irregular but is assumed to be vertical. The side of the gap's perimeter is the innermost point reached by foliage at any level. However, gap definition varies according to research application and the methodology used for gap delineation (Vehmas et al. 2011). Most of the gap definitions are based on either a vertical projection of the canopy edge (Brokaw 1982), the extended gap concept (Runkle 1982) or the threshold gap area (Vepakomma et al. 2008). Applying a

threshold canopy height on canopy height model is the most common method of gap delineation.

Focus of this study was on the disturbance-driven dynamics and structure. Therefore, it was important to eliminate gaps created due to interstitial space between tree crowns. Applying the minimum area threshold would reduce such gaps from the gap analysis. Therefore, a gap is defined as a canopy opening due to the death of at least a single tree and with a maximum height of 2 m as in Brokaw (1982). To estimate the threshold area (i.e., corresponding to the size of at least one single tree), a random sampling of 100 crowns was done using aerial photographs in ArcMap. The crown-area distribution ranged from approximately 4m² to 177 m² with the mean of 46 m², and 95 % of the tree crowns were bigger ≥ 10 m². Thus, a gap in this study was defined as an opening in the forest canopy with a height of ≤ 2 m and area ≥ 10 m².

4.2.1 Data

LiDAR data were collected on 26 to 28 October and 8 November 2011 using a RIEGL LMS-Q680i long-range airborne laser scanner (ALS) flown at 500 m altitude on an Aérospatiale AS350B helicopter at 80 km/h. Nominal overlap among flight lines was approximately 50 %, and laser pulse repetition frequency was 100 kHz. The ALS sensor emitted pulses at 60.0 Hz with a field of view of 30.0°, and a footprint of about 25 cm diameter. The average pulse density was 10.96/m².

The total area surveyed was of 53 km². The geo-referencing of ALS point cloud was based on the matching of the GPS time with sensor unique timestamps. Laser returns were combined with the GPS-IMU information to determine the 3-D locations of laser returns. After flight strip adjustment, the horizontal position is transformed into the Japan Plane Rectangular coordinate system IX, and elevation is relative to the Japan datum of leveling.

The LiDAR data points with a considerable number of georeferenced estimates were filtered with noise reduction and classified as ground and non-ground. A digital terrain model (DTM) for the ground surface was fitted to the ground points, producing a raster of 1 m resolution. The remaining points were used to generate a digital surface model (DSM) for the canopy, at 1 × 1 m resolution. The method for fitting the DTM and DSM is a linear interpolation based on a triangular irregular network (TIN) applied to the LiDAR point cloud, where the pixel value is the linear interpolation at the pixel center. A canopy height model (CHM) is then able to be calculated by subtracting the DTM from the DSM. A series of the processing steps were conducted using TerraScan software (Version 011, Terrasolid, Helsinki, Finland). Along with, DTM and DSM, high-resolution aerial pictures were used during analysis.

4.2.2 Gap identification using LiDAR imagery

Gap delineation was done using ArcMap 10. A canopy height model (CHM) was derived from the difference between DSM and DTM. Some of the pixels were found to be negative values as in (Zhang 2008). The negative values may have resulted because of different local points used during interpolation while generating DTM and DSM. All the negative values were set to zero before further analysis.

Pixels were extracted from the CHM using the gap function (eq.1) (Vepakomma et al. 2008). Then the pixels were converted into polygons. Finally, gaps were quantified using threshold area of 10 m².

Gap function (G) at CHM_i(x,y) defined as :

$$G_i = \begin{cases} 1 & \text{if } CHM_i(x, y) \leq h \\ 0 & \text{otherwise} \end{cases} \quad (1)$$

where $h = 2m$

gaps were converted into polygon and applied area threshold ($A = 10 \text{ m}^2$) to quantify gaps according to our definition

4.3 Gap verification

The study area contained rivers and human-made infrastructures such as forest roads, trail, bridges and buildings. To eliminate false gaps, buffer zones were created around river and roads. For rivers, 100 meters of a buffer zone was applied, whereas for highway, forest roads and trails buffer distance of 40 m, 20 m and 10 m was applied, respectively. Using aerial photographs false gaps, created on a rock, roads embankment, and marshland were removed manually

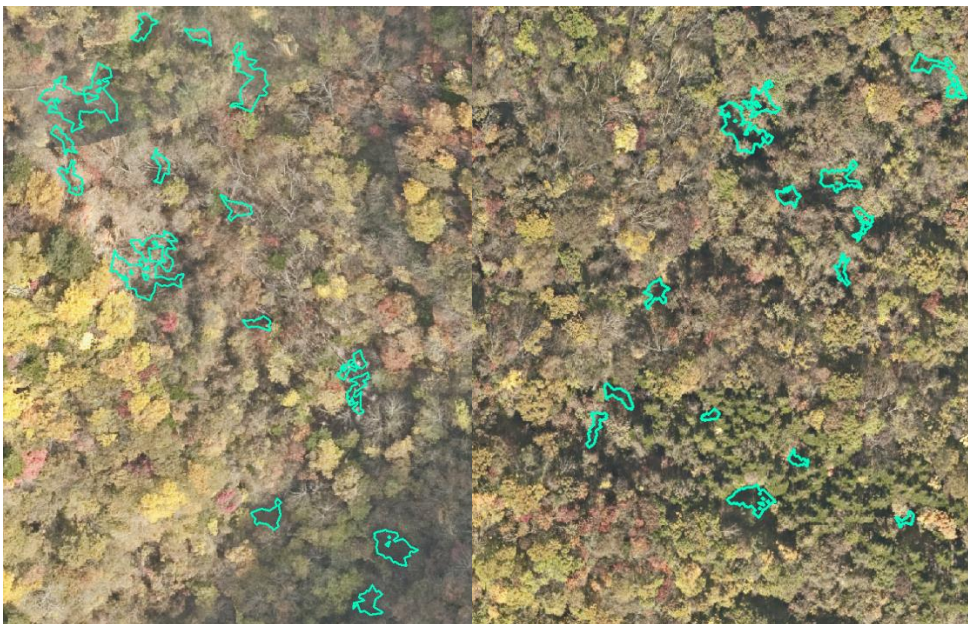


Figure 2. Detected gaps in Primary (left) and secondary (right) forest.

4.3.1 Gap characteristics

Gap characteristics such as area and perimeter were calculated using field calculator in ArcMap. Gaps were classified according to forest type: primary, secondary and plantation. Gaps intersecting the borders of two or more forest types were classified as border gaps and were not included for comparative studies between forest types. However, they are included while studying the gap characteristics of the whole study area. To add aspect and slope attributes to gaps, slope and aspects were generated from DEM. Aspects were classified into North, East, South and West. Gap pixels can have multiple aspects. To overcome the

problem, the majority within a gap was used to define an aspect of each gap. “Zonal analysis” in ArcMap was used to find the majority of the pixels within a gap.

To understand the spatial distribution of gaps, the distance between a gap and its closest neighbor (distance to the nearest gap, DNG) was calculated. The distance was measured from circumference to circumference. The calculated distance gives the estimation whether gaps are closely associated or isolated. This might also explain the compactness of gap distribution. For example, if gaps are closely located or clustered, the distance to the nearest gap would be small. On the other hand, there would be a large distance if gaps are isolated. This finding also could be helpful to explain gap size distribution in different forest types.

Topological position index (TPI), which is derived from the slope raster, is the difference between cell elevation value and the average elevation of neighborhood around that cell (Jenness 2006). TPI is a number between -1 to 1. Positive TPI means the point is higher than the neighbor, whereas a negative value means the point is lower than the neighbor. The analysis requires selecting a scale of neighborhood or a moving window. Each pixel is attributed a TPI value based on elevation-comparison with other pixels within the scale of moving window. However, it was challenging to select the appropriate scale of neighborhood. Using high neighborhood scale resulted in only a few features in the classified raster, whereas selecting small scale resulted in the patchy raster. Finally, (80*80) neighborhood scale resulted in the classified layer containing all six-different land-type features. The resulted raster was used to attribute each gap to the land-type using “majority” tool in ArcMap. The resulting raster was compared to the 3D terrain model (hillshade in ArcMap) to assess the accuracy of the classified raster layer

Land type was classified into five categories according to (Weiss 2001) as mentioned in (Jenness 2006) and are as follow: Valley, lower-slope, flat slope, middle-slope, upper-slope and ridge. TPI and slope raster were used to categorize land-type.

Criteria for land classification (Weiss 2001)

Valley: $TPI \leq -1 SD$

Lower Slope: $-1 SD < TPI \leq -0.5 SD$

Flat Slope: $-0.5 SD < TPI < 0.5 SD$, $Slope \leq 5^\circ$

Middle Slope: $-0.5 SD < TPI < 0.5 SD$, $Slope > 5^\circ$

Upper Slope: $0.5 SD < TPI \leq 1 SD$

Ridge: $TPI > 1 SD$

4.3.2 Semivariance analysis

To understand spatial autocorrelation in gap occurrence, grids (100*100 m²) were generated over the whole area using the fishnet tool in ArcMap. Different grid sizes were visually inspected by placing different sizes of the grid on top of the gap-layer to find the best fitting size. Selecting small grid size resulted in many grids with no gap, which resulted in too many zero-gap fractions. On the other hand, bigger grid size resulted in very few grid cells, which resulted in the loss of information. The chosen grid (100*100) resulted in 41 % of the grids with a gap(s) or partial gap. Finally, value either 0 or 1 is assigned to each grid based on the presence and absence of gap (s). A grid was assigned (0) if it did not contain any gap(s) or a part of a gap, whereas value (1) was assigned to each grid containing a gap(s) or a part of the gap. Finally, forest type was assigned to each grid using respective raster. Grids centroid were used to classify gaps according to forest types. The grid polygon was converted into point feature for semivariance analysis.

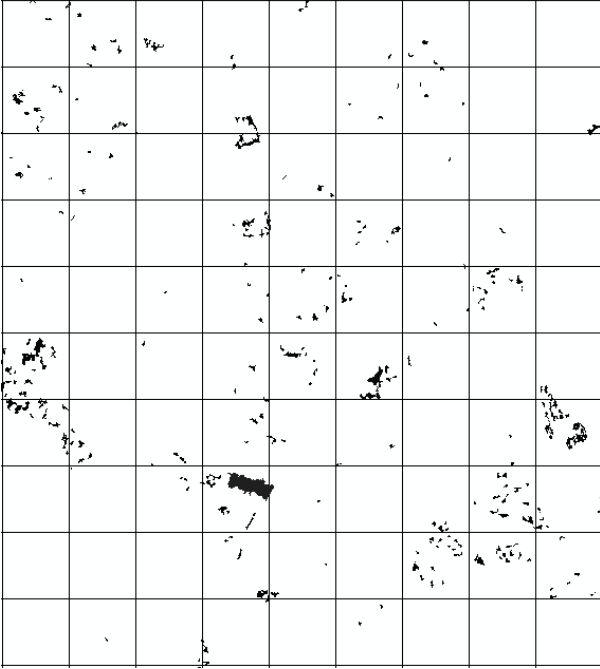


Figure 3. Fishnet (100*100) on top of gap raster while calculating the gap fraction.

4.4 Statistical analysis.

4.4.1 Gap size frequency distribution

There have been several studies to understand the gap size frequency distribution in both temperate and tropical forests. Findings from all such research imply that there are many small gaps and a few bigger gaps in a forest, resulting in a heavy-tailed distribution. Some of the research (Kellner et al. 2011; Lobo 2013; Asner et al. 2013) have used power-law distribution to describe the gap size in different forests. In this study, we try to fit the power-law into gap-size frequency distribution in different forest types. A quantity (x) obeys power-law if it is drawn from a probability distribution (eq.2).

$$p(x) \propto x^{-\alpha} \quad (2) \text{ (Clauset et al. 2009)}$$

Where the exponent (α) is the scaling parameter which typically ranges between 2 to 3.

Gap distribution in primary forest, secondary forest and plantation area was analyzed using power-law package (Gillespie 2015) in statistical software R. Two fit the power-law, two

constants lower cut-off constant (x_{min}) and the scaling parameter (α) were estimated. In most of the empirical phenomena, power-law does not obey for all values of (x), but for the value greater than (x_{min}). Therefore, it is important to estimate the x_{min} accurately to accurately estimate scaling parameter (α). If the x_{min} is too low it will result in biased estimation of the scaling parameter, and if the x_{min} is too high then data smaller than the value will be ignored. x_{min} was estimated using a Kolmogorov-Smirnov statistic (eq.3), which minimize the distance $d(x)$ between the data and the fitted model cumulative distribution function (CDF) as used in Clauset et al. (2009). Then the parameter of the power-law distribution was estimated based on x_{min} .

D(x) is known as the Kolmogorov-Smirnov statistic is given as

$$D(x) = \max_{x \geq x_{min}} |S(x) - P(x)| \quad (3)$$

where S(x) is the CDF of the data for the observation with value at least x_{min} and P(x) is the CDF for power-law model that fits the data in region $x \geq x_{min}$. Mathematically, CDF is defined as:

$$CDF(x) = p(x) = \int_x^{\infty} p(x') dx' = \left(\frac{x}{x_{min}}\right)^{-\alpha+1} \quad (4)$$

Power-law can be fitted to any distribution and therefore it is important to check the validity of the fit. To determine if the distribution follows power-law we tested the goodness of fit as recommended by Clauset et al (2009). Clauset et al (2009) suggested generating $\frac{1}{4} \epsilon^{-2}$ numbers of sample to accurately estimate p-value upto to ϵ decimal values. For accurately estimating p-value upto 2 decimal value we set ($\epsilon = 0.01$). Goodness of fit to power-law was validated based on the hypothesis below:

H0: data are generated from a power-law distribution

H1: data is not generated from a power-law distribution

To check whether a data follows a power-law, we used threshold p-value as Clauset et al (2009). The signification level for p value was used according to Clauset et al (2009). If the

p-value ≥ 0.1 we have no evidence to reject the null hypothesis and we conclude that our distribution follows power-law distribution. If $p \leq 0.1$ then the null hypothesis is rejected, which means our gap size distribution does not follow a power-law distribution. Power-law frequency distribution was tested for all forest types. The scaling parameter (α) obtained was compared to similar research findings. Scaling parameter provides the quantitative measures of gap size distribution and can be a useful parameter useful for comparing between forests (Fisher et al. 2008). Typically, scaling parameter value ranges between 1 and 3 in a forest (Asner et al. 2013). Large scaling parameter ($\alpha > 2$) signifies the forest with dominated by small gaps and indicate high growth and low mortality dynamics. On the other hand, small scaling parameter ($\alpha < 2$) is obtained in a forest dominated by large disturbance resulting in mortality of large canopy (Asner et al. 2013).

4.4.2 Gap aspect and land type

To understand topographical variation in gap characteristics in different aspect and land type, gap characteristics and their distribution in different geographical direction and land-types was investigated. We excluded secondary and plantation forest in this analysis. The silvicultural activities might contribute or mask the topographical effects on gap distribution resulting bias results (Oliver and Larson 1996). Since primary forest is the only forest free from human disturbance, it can truly represent the natural canopy-gap distribution based on topography in the mountains of Chichibu. The gap characteristics (size and DNG) was analyzed based on the topographical features (aspect and land type) of the Chichibu Mountains. Understanding the gap patterns in different lands type and aspect would help to understand the disturbances patterns in UTCM.

4.4.3 Spatial distribution of canopy gaps

According to Tobler (1970), everything is related to everything else, but near things are more related than distant things. This is the foundation of the fundamental concept of spatial dependence and spatial autocorrelation. In our research, the presence of spatial correlation is tested using variogram. Under this theory, gap-grids at proximity would have

small semivariance and semivariance would grow as the distance increase. To test this idea semivariance analysis was done in R.

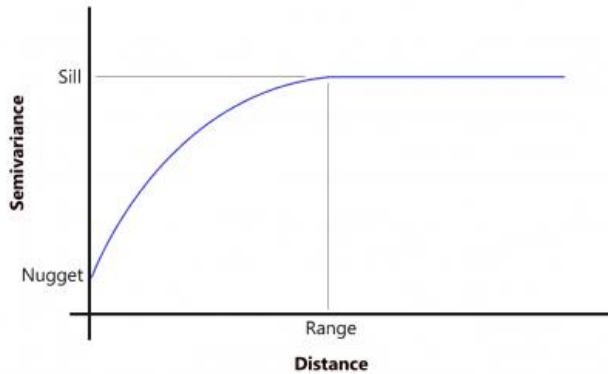


Figure 4. Semivariance model graph. The graph shows three components of variogram: Sill, Range and Nugget. 'Still' is the value at which the model flattens out and the distance at it occurs is 'range'. 'Nugget' is the Y-intercept.

Variogram calculates the distance between two points and stores the distance. Within the points, the variance between the response variable (presence of gap) is estimated. The result which is the semivariance was plotted. The spatial autocorrelation on gap occurrence was investigated using the semivariance graph among different forest types. The components of variogram i.e. nugget, still and range were analyzed for different forest types. Theoretically, at zero distance, semivariance should be equal to 0. However, variograms often have a nugget effect, which is a value (>0) at 0 distance (Esri, 2018). Nugget effect is the random variability caused by measurements or quantification errors (Esri, 2018). The magnitude of spatial correlation decreases with the increasing distance until a distance at which no spatial correlation occurs (Gringarten & Deutsch 2001). The point till which spatial autocorrelation occurs is the range. The semivariance at the range is called the still.

5 Results

5.1 Gap size distribution in UTCF

The geographical extent of the area was 5124 ha before removing buffer areas. The actual study area (SA), after removing buffer zones, was 4450 ha, of which 1678 ha (38 %) was primary forest, 2267 ha (51 %) secondary forest and 505 ha (11 %) was plantation area. In total, 6179 valid gaps were identified, which accounts for the total area of 26 ha and 0.59 % of the total study area. Gap size ranged from 10 m² to 11603 m² with the mean area of 42.07 m². However, the minimum value of the range was fixed by our gap definition. At least half of the gaps in all three forests were less than 19 m². Half of the gaps were in the primary forest, whereas the other half was in secondary forest (38.40 %) and plantation forest area (11.30 %). Gap area in all forest was less than one percent of forest area (SA). The proportion of gap area in primary forest and plantation area were 0.72 % and 0.76 %, respectively. However, the lowest (0.45 %) proportion was found in secondary forest. Mean gap size in the primary forest was 38.71 m², which is the lowest of all three forest-types. Mean gap area in the secondary and plantation forest was 42.85 m² and 55.19 m², respectively.

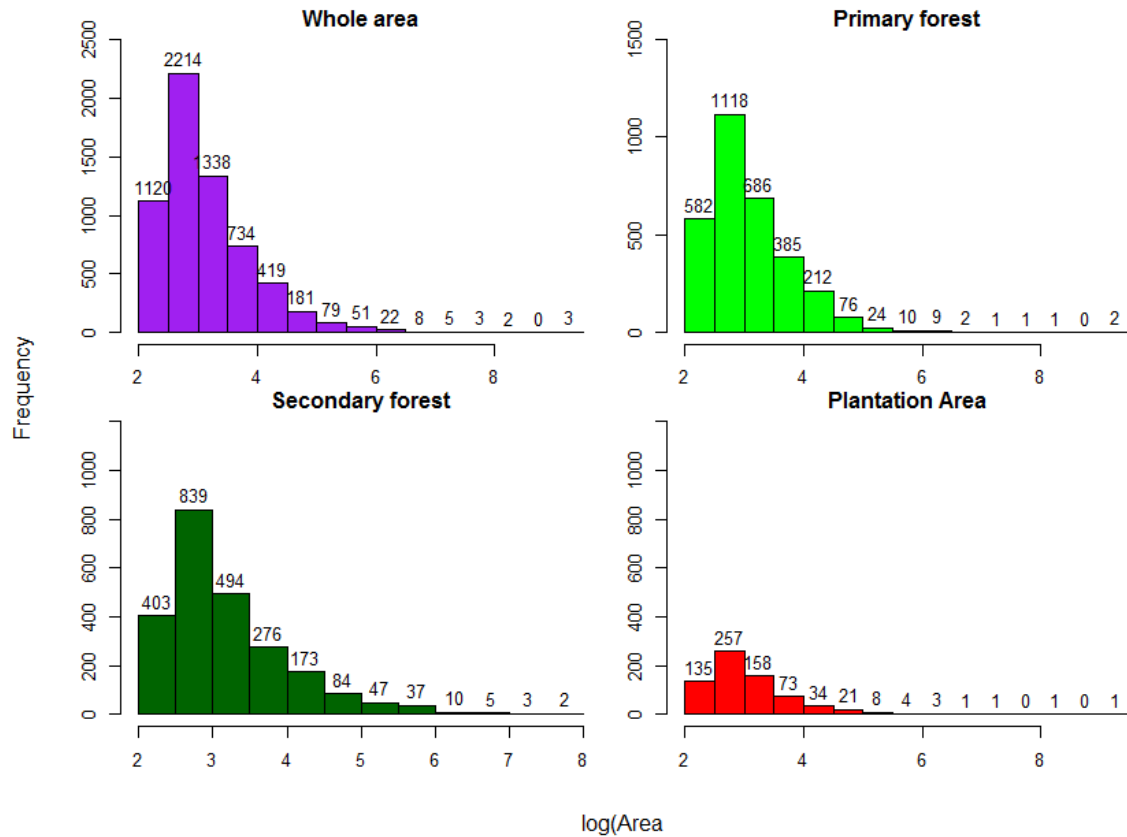


Figure 5. Gap size frequency distribution in different forest types. Gap density (gaps per ha) in different forest-types were primary (1.85 gaps per ha), secondary (1.03 gaps per ha) and plantation (1.15 gaps per ha).

In natural forest (primary and secondary) gap size ranged from 10 to 10440 m². However, most of the larger gaps (>2400 m²) were only in the primary forest. The maximum gap size noted in the primary and secondary forest were 10440 m² and 2377 m², respectively.

Although some of the biggest gaps were present in the primary forest, the average gap size in the primary forest was smaller than in the secondary forest. Half of the gaps in primary forest were smaller than 18.52 m², and 75 % of the gaps were ≤ 31 m². Primary forest had only five gaps larger than 1000 m² which is lower than (6) in the secondary forest.

However, aggregated gap-area due to gaps over 1000 m² was highest in primary forest (22 % of total gap area) than in secondary forest (9 %). In the secondary forest, half of the gaps had an area of less than 19.24 m² and 75 % of the gaps were less than 35.5 m².

Kolmogorov-Smirnov test showed a significant difference ($p < 0.05$) between primary and secondary forest, whereas showed similarity ($p = 0.59$) between primary and plantation forest.

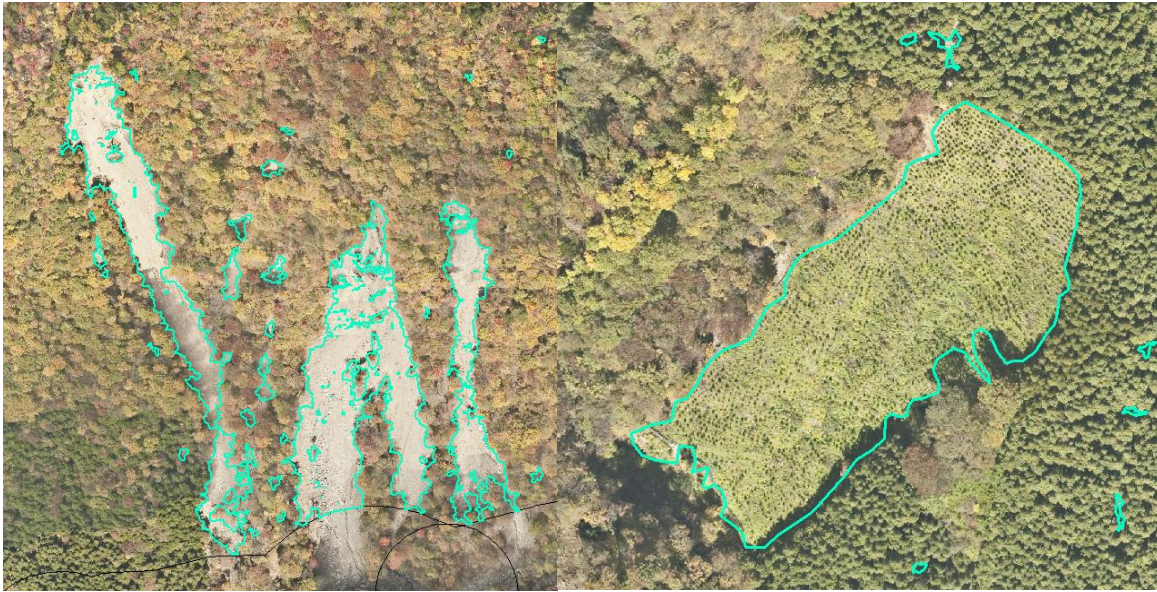


Figure 6. Large gaps created by landslides in the natural forest (left) and large clear-cut patch (gap) in the planted forested area (right) detected by LiDAR and compared with the aerial photograph. The landslide created large gaps were on the south-facing middle slope in the primary forest. The area under the black line is the river buffer zone which was not included in the gap analysis.

In the plantation forest area, gap ranged from 10 m² to 11603 m². Although the biggest gap identified was in the plantation area, it had only three gaps bigger than 1000 m². However almost half of the gap area (43 %) was due to three gaps over 1000 m². Similarly, 39 % of gaps were smaller than 15 m², and 74 % of the gaps were smaller than 30 m².

Altogether, 27 % of the total gap area was due to the 44 gaps which were larger than 400 m². Most of these gaps were located on either valley or middle-slope. Similarly, 20 % of the total gap area was due to 14 gaps were above 1000 m², of which 5 gaps were above 3000 m² taking 14 % of the total gap area. Most of these larger gaps were found in the primary and plantation forest. In the primary forest, some of the bigger gaps were caused by landslides, whereas in plantation forest area, bigger gaps were due to clear-cutting. This was confirmed by visual inspection of aerial photographs (Fig.6).

The mean DNG in a primary forest was 21.63 m, whereas in secondary forest and plantations it was 30.04 m and 25.72 m, respectively. The maximum DNG in the primary and secondary forest was 226 m and 246 m. The greatest DNG was found in the smaller

gaps. The mean DNG was longest in West facing gaps. The mean DNG for different aspects was North 19.74, East 21.53, South 23.41 and West 26.22m. The mean DNG was highest in the ridge (26 m), and lowest (20 m) in the middle slope, and upper slope. The lower slope had the mean DNG of 23m. The overall DNG ranges from 0 to 246 meters.

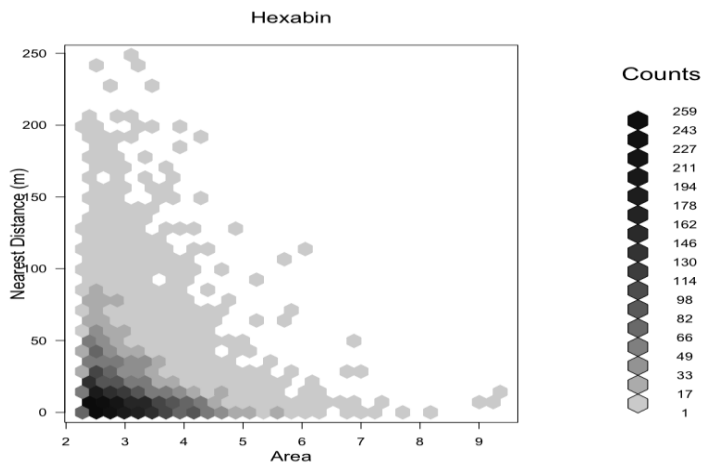


Figure 7. Distance to the nearest gap (DNG) against gap area. DNG ranged between 0-246 (m)

5.2 Canopy gap-size frequency distribution

Canopy gap size frequency distribution in all three forests showed negative skewness (Fig. 8). The distribution was steeper in the primary forest and least in the secondary forest. The frequency of small-size gap was much higher in the primary forest than the secondary and plantation forest. The lowest category of gaps (10-15 m²) were above 1000 only in the primary forest. The distribution showed heavy tail, especially in the primary forest.

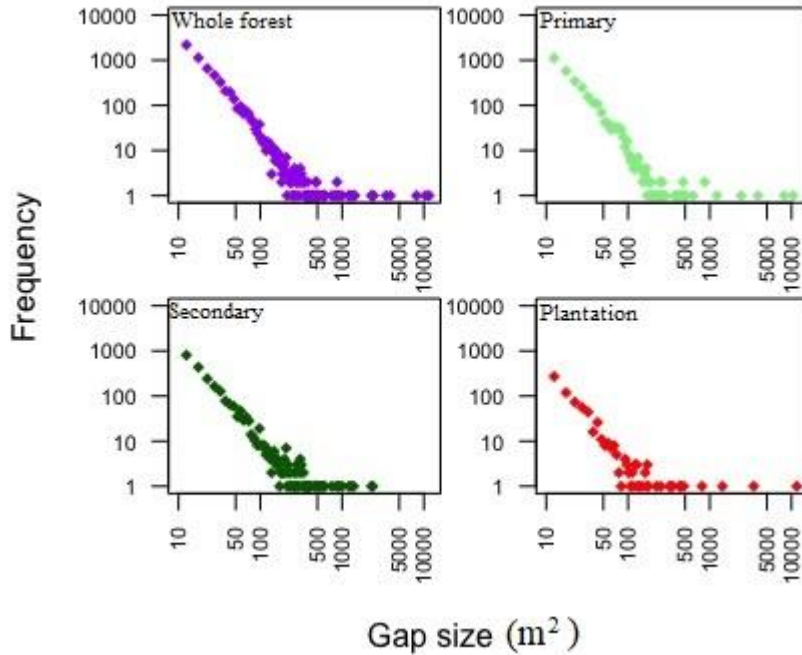


Figure 8. Gap size frequency distribution in different forest types. Gap size data were binned to 5 m² width and plotted against mids

The fitted-line was much steeper in primary forest with $\alpha = 2.56$ ($p = 0.01$). The scaling parameter (α) for the whole forest, secondary and plantation were 2.37 ($p = 0.01$), 2.20 ($p = 0.02$) and 2.27 ($p = 0.12$), respectively.

The larger proportion of tail gaps deviate away from the fitted line in the secondary forest compared to the primary and secondary forest. Less deviated tail gaps were found in the plantation forest area. The estimated minimum value x_{min} varied from 10 to 26. In the plantation area, the x_{min} was 10.33 which was closer to the minimum gap area (10 m²). However, in the primary and secondary forest, x_{min} was greater than 20. In primary the estimated x_{min} was 26.63, and since 67 % of the gaps had area between 10- 26.63 m², significant data was excluded in power-law distribution. In secondary forest x_{min} was 21.48 and with that x_{min} 56 % of gaps were excluded.

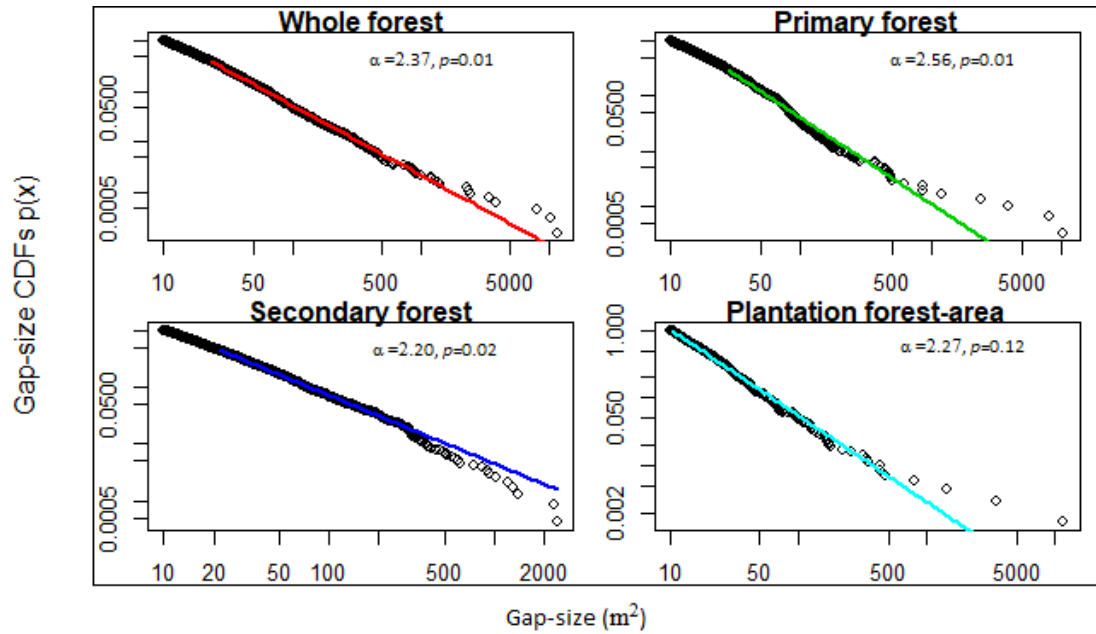


Figure 9. Gap size probability density in different forest types. The trend line represents the fitted power-law distribution. The graph shows the deviation around the tail data in all forests. The distribution, however, followed power-law only on plantation forest.

The goodness of fit test ($p < 0.1$) implied that gap size frequency distribution did not follow a power-law distribution in both primary and secondary forest. However, plantation forest followed power-law distribution ($p = 0.12$). To investigate into this further, we dropped the largest 44 gaps from our study. We had only 44 gaps with area between 400- 116000 m^2 . After dropping those major values, we received significantly increased p -value ($p > 0.1$) in all forests. However, x_{min} value increased significantly. When x_{min} was increased, a significant proportion of data is lost. In primary forest, x_{min} changed from 10 to 69. The goodness of fit test ($p=0.66$) showed that the gap size distribution followed power-law between 69 to 400 m^2 . However, with such a large value of x_{min} , approximately 90 % of the data was eliminated. Out of 2864 number of gaps, only 245 gaps were above 69 m^2 . Similar results were found in secondary and plantation forests.

5.3 Gap, aspect and land type

The study area (SA) consists of ridge (30 %), valley (27 %), middle slope (23 %), upper-slope (11 %), lower slope (9 %) and flat area (<1 %). Almost half (46 %) of gaps were concentrated in the Valley. Another half were distributed in the middle slope (24 %), ridge (15 %), lower slope (8 %) and upper slope (7 %). The highest gap area proportion, which is the percentage of gap area to total area, was found in the valley (1 %), whereas the lowest proportion was in the ridge (0.21 %). The gap proportion in the middle slope was 0.87 %. Lower slope, upper slope and flat area had about a similar gap proportion with 0.29 %, 0.30 % and 0.32 %, respectively.

The highest mean gap size (44 m²) was found in the valley and middle slope as all gaps larger than 454 m² were in valleys or middle slopes. In the valley, gap ranged between 10 to 8000 m² and differ significantly ($p < 0.05$) to other land types. Most of these gaps in valleys (77 %) were facing either North or South. On the other hand, gap size ranged from 10 to 10440 m² in the middle slopes. The higher range of the gap size was due to the presence of the large gaps created by landslides as shown in Figure 6. Lowest mean gap size was found in the lower slope (25 m²) with size class of (10-404 m²). Gaps in the ridge had a mean size of 26 m² and ranged from 10 to 621 m². In the upper slope, gap area ranged from 10 to 454 m², with a mean of 28 m².

Due to the topography of the study area, most of the study area is facing either North or South. Thus, in total, 76 % of the gap were facing North and South. More than 53 % of the gaps in Valley were facing North. The average gap size in the south facing side was highest (62 m²) of all. The largest gap noted in the south slope was 10440 m², which was formed by a landslide. West facing gaps were between 10 and 264 m² with an average gap size of 26 m². In the North, the biggest gap was 1221 m² whereas, in the east, the biggest gap size was 2419 m². The mean gap size in North and East was 29 m² and 35 m², respectively. Gaps in northern slope differed significantly ($p < 0.05$) with gaps on southern slopes but show similarity ($p \Rightarrow 0.25$) with gaps facing east and west. Southern gaps show similarity

($p>0.4$) only to eastern gaps, and western gaps showed similarity ($p=0.2$) only to eastern gaps.

DNG in different land types was distributed between 0 to 246 m. The mean DNG was similar (~20 m) in middle slope, upper slope and valley. Gaps were more distanced in the ridge (25m) and lower slope (23m). The maximum DNG was found in the middle slope which was 226 m. Half of the gaps had closest neighbor gaps within 16 m and third-quarter of the gaps had neighbor gaps within 37 m. Only 52 (1.7 %) gaps (only primary forest considered) had DNG greater than 100 m and were in valley (44 %), middle-slope (21 %), ridge (21 %) and lower-slope (9 %) and upper-slope (5 %).

5.4 Spatial variations on gap formation

The semivariogram analysis showed that the occurrence of a gap has a spatial component in all forest types. The sill was obtained at the range 1300 m in the primary forest. In the secondary forest, the sill was obtained at range 1500 m. The semivariance curve was steeper, up to the distance of 1700 m, in the plantation forest. Nugget effect was seen in all forest types. Nuggets in primary, secondary and plantation forest area were 0.18, 0.20 and 0.19, respectively. Plantation forest had very sharp but wide variation compared to the primary and secondary forest. Semivariance ranged between 0.19-0.28 in plantation forest, whereas it ranged between 0.19-0.24 in primary forest and 0.21-0.25 in secondary forest, respectively.

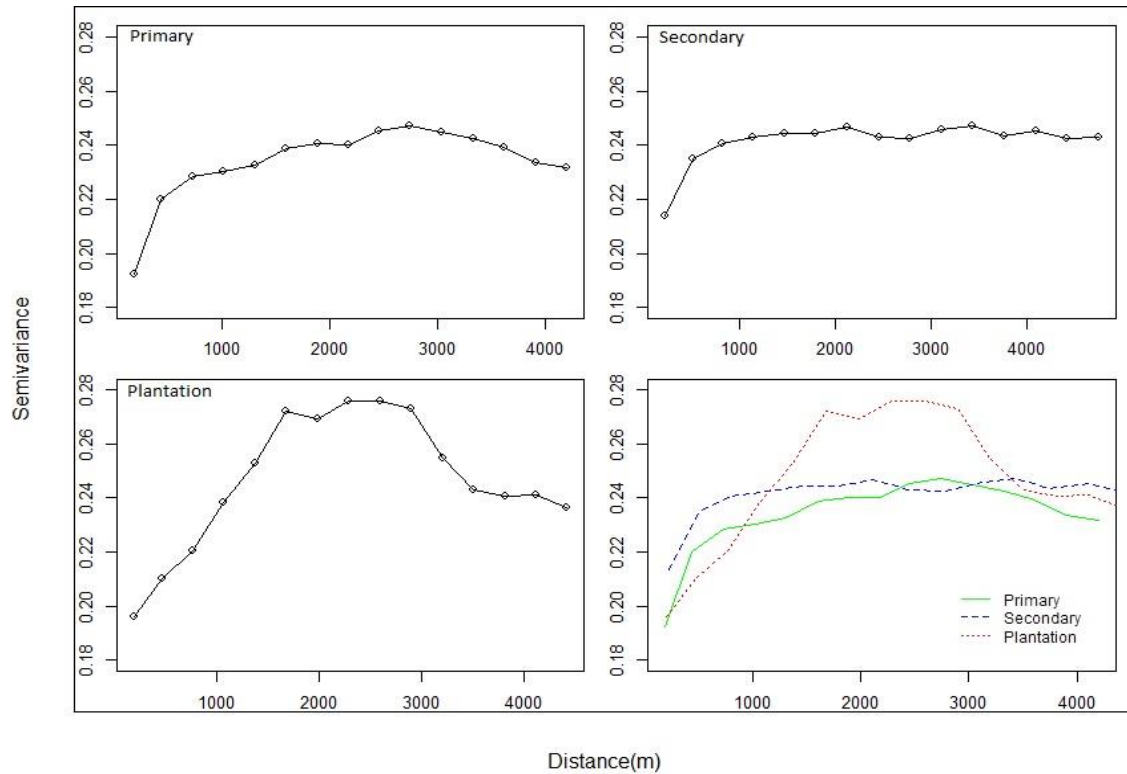


Figure 10. Semivariogram graph showing spatial autocorrelation of gap presence in three different forests. Nugget effect was present in all forests types. Plantation forest had the widest range of semivariance

6 Discussion

6.1 Gap characteristics in different forest types and their ecological impacts on forest development

Overall gap distribution in UTCF showed negative skewness with the majority of smaller gaps and few large gaps. Presence of so many small gaps demonstrates that UTCF is controlled by small-scale disturbances. Gap size was distributed between 10 and 11,000 m², however, there were only a few gaps (< 1 %) larger than 400 m². The upper range of the gap was similar to Yamamoto (1992) where only a few gaps were found above 400 m² in a broadleaved evergreen forest of west Japan. Most (80 %) of those gaps were created by single tree death. However, this study is mainly based on LiDAR and aerial photographs and therefore acquiring information like a number of tree death in a gap is a challenging

task without field visual inspection. Thus, predicting an exact number of dead trees in gaps would not be possible. However, our finding that 75 % of the gaps in all forest types were $\leq 35 \text{ m}^2$ and half of the gaps were under 19 m^2 , reveals that majority of the gaps are created either few mature or multiple young trees.

As a gap in this study refers to an area created by the death of at least a single tree, our threshold gap area value was estimated from a random sampling of 100 tree crowns. The gaps closer to the threshold area (10 m^2) were likely to be created by the death of a single tree or a standing dead tree. However, a single tree crown can have a crown area of 1777 m^2 , which was found through crown sampling, and can create an even larger gap by crushing other trees when it falls by disturbing forces. At the same time, it is important to note that not all the tree death creates a canopy gap. Senécal et al (2018b) found that tree death does not always create canopy gaps in a northern temperate deciduous forest. The gap formation mechanism might depend not only on the top canopy but on the sub-canopy structure. Natural forests have multilayer canopy. Thus, the death of some tree might not always create any gaps but might reduce gaps height which is called canopy height erosion (Senécal et al. 2018).

Advance regenerations are ready to occupy as soon as the gap is open. Sometimes trees die as standing, and this can be a very slow process (Senécal et al. 2018; Zeibig et al. 2005). This gives enough time and gradual increasing light flux, due to the gradual death of foliage and branches, to the understory species to grow. The area occupied by a standing dead tree is less likely to be completely free at any time, whereas uprooting can free the space completely by clearing the vegetation. Therefore, gaps created by standing dead tree can be smaller compared to uprooting. Standing dead tree also do not damage the advance regenerations or other neighbor trees. In such case, the gap might be already taken when dead standing tree ultimately weakens and falls. In fact, standing dead and trunk broken are dominant in the forest of Japan, however uprooting are rare (Yamamoto 2000). Large number of standing dead trees in a forest can be an indicator of absence or rareness of major wind disturbance (Zeibig et al. 2005) because standing dead trees are less resistive to

winds. Standing dead trees might be one contribution factors for the high frequency of smaller gaps in UTCF.

High frequency of smaller gaps might have helped to maintain similar species composition in UTCF. Smaller gaps provide less opportunity for new or foreign species to germinate and occupy a gap, due to limited resource and time (Chazdon & Fetcher 1984). The seedlings which germinate after the gap is already formed have less chance to occupy the newly created place. These small gaps are therefore occupied by regenerations or adjacent growth in very short period. This kind of gap dynamism driven by gap size and species characteristic plays a strong role in species distribution in a temperate forest. For instance, *Dysilium racemosum* and *Fagus crenate* are some of the successful species in the temperate forest of Japan (Yamamoto 2000). They have advance regeneration ready to occupy slow and gradual opening gaps such as gaps created by standing dead tree. On the other hand, shade intolerant species do not regenerate under the closed canopy where light flight is very restricted. This reduces the chance to shade intolerant species to occupy, especially the small and slow-opened gaps. Thus, small gaps help shade tolerance species to maintain their presence in the forest.

Results from several gap studies (Kent et al. 2015; Kellner & Asner 2009; Lobo 2013) revealed that there are commonly few bigger gaps in a forest, but they cover a great proportion of gap area. We found only 44 gaps (less than 1 %) above 400 m². A similar result was found in one temperate forest of the Appalachian mountain (Runkle 1985). Average canopy gap size was 31 m² and proportion of gaps bigger than 400 was approximately 1 %. However, the overall gap area proportion in Chichibu was smaller. In the Chichibu mountain gap area proportion was approximately 0.72 % in primary and 0.45 % in secondary forest. Natural and mature forests in Japan have a gap area proportion of 10-20 % (Nakashizuka, 1987). The smaller gap-area proportion in Chichibu mountain might be due to exclusion of interstitial gaps and other small gaps (<10 m²) due to partial disturbances.

In UTCF, bigger gaps in primary forest were created from landslide. Strong wind can also cause such magnitude of disturbance by uprooting one or multiple trees, however uprooting are rare in forests of Japan (Ohkubo et al. 1996; Yamamoto 1992). Large disturbances occur suddenly, and most of the time, such disturbances kill majority of the vegetation. In such conditions where a gap is suddenly created and vegetation is wiped out, gap is occupied by plants through germination (Oliver&Larson 1996). Bigger gaps allow more sunlight to reach to the gap floor and therefore provide an opportunity for shade tolerant species to establish into the forest (Busing 1994). For example, *Castanopsis cuspidate* and *Betula grossa* cannot grow under a closed canopy, however, they grow and establish themselves into bigger gaps in the temperate forest of Japan (Yamamoto 2000). Thus, bigger gaps help to maintain diversity in the forest.

Gap-size has a profound influence in species composition in a temperate forest of Japan. A finding by Sakio et al. (2002) exemplifies the case. Inside 4.71 ha of study area inside Chichibu mountains, Sakio et al (2002) found that *Cercidiphyuum japonicum* was only found in forest patches of *Pterocarya rhoifolia*. Comparative age study revealed that their age coincided with the major landslide occurred about 90 years ago. The even-aged forest patch with these two species was established on debris caused by the landslide 90 years ago. Forest with these species at the same time and space would not have been possible in the absence of disturbance of that scale. Thus, although there were very few large gaps (<1 %) in UTCF they accounted for 27 % of the total gap area. Therefore, they can have a big impact on forest structure and species composition in UTCF.

Along with the magnitude of disturbance, growth and reproductive characteristics of species play an important role in determining which species will occupy newly created gaps (Oliver&Larson 1996). Because large disturbances are rare and unpredictable, species that flourish in the presence of such event have evolved reproductive characteristics that favor the growth in these sudden and rare chances. For example, *Pterocarya rhoifolia* has rapid growth during seedling and sapling stage, whereas, *Cercidiphyuum japonicum* disperse a huge amount of seeds each year (Sakio et al 2002). On the other hand, some species in UTCF have adapted to both small and large disturbances. For example, *Fraxinus*

Platypods has established as an even-aged stand in larger disturbances, whereas it has successfully colonized small canopy gaps created by tree death (Sakio 1997).

Gap size distribution between primary and secondary differed significantly ($p < 0.05$). Primary forest had frequent small gaps and few large gaps over 10,000 m². These bigger gaps were created mainly due to landslides. Similarly, primary forest had a higher gap-area fraction (0.72 %), highest gap density (1.85 gaps per ha) and smallest mean gap size (38 m²). This implies that most of the disturbances in the primary forest are less intense but frequent. Disturbance history also might have influenced gaps size distribution. A given forest will go through an increasing number of disturbances as it grows older. These disturbances change the chemical, physical and biological characteristics of the forest. Thus, the accumulation of these changes in the forest makes a forest more complex as it grows. These differences also affect the size and the rate at which canopy gaps open and close in forests. Thus, disturbance history in the secondary forest might have changes the complexity of the forest. Similarly, other factors such as topography, species and timber quality might have played some role while making harvesting decisions. Commonly feasibility and expense are crucial in decision making regarding forest harvesting. This might mask or eliminate natural disturbances in secondary forest and created relatively younger forest stand which are more resistive to disturbances (Oliver&Larson 1996).

On the other hand, secondary forest had a larger mean gap size compared to the primary forest. Although secondary forest did not have any gaps over 2400 m², it had a mean gap size of (48 m²) which is larger than the primary forest. However, it had the smallest gap-area proportion (0.45 %), lowest gap density (1.03 gaps per ha) and longest mean-DNG (30m). A forest after large disturbance follows several stand developmental phases as described by Oliver&Larson (1996). In the naturally regenerated forest, high mortality occurs during the stem exclusion stage after that survived species established themselves with height and later growth (Oliver&Larson 1996). Secondary forest in the UTCF might have passed the stem exclusion stage and became more stable forest with greater resistance to disturbances. In the understory reinitiation phase, stand has developed regenerations on the forest floor. Therefore, death of a tree might not even create a gap if quickly occupied

by advance regenerations or growth of trees adjacent to gaps. However, at understory reinitiation stage, trees reach maximum size and death of a mature tree can cause large gaps by crushing tree(s) as it falls. Thus, less gap area fraction and large-average gap size in the secondary forest might have reflected characteristics of a stand at an advance stage of stand development process. On the other hand, primary forest, can have much larger overstory death in an irregular fashion (Oliver&Larson 1996). Thus, primary forest might have high frequency and gap-faction compared to the secondary forest. Secondary forest is a mature forest but comparatively younger than primary forest. It might take several years or centuries to reach the stage of primary forest and thus the gap dynamics differs to primary forest.

Comparative study on gap size between primary and secondary forest has been in a tropical forest of Malaysia (Numata et al. 2006). High frequency of gaps was found in the natural forest compared to the regenerated forest. Similarly, bigger gaps appeared more in primary forest. This was mainly due to lack of presence of large and old trees in the regenerated forest since the regenerated forest was selectively logged in 1950. Similar to the result in Malaysian forests, the regenerated forest of UTCF had fewer gaps compared to the primary forest. The secondary forest at UTCF, however, had the higher mean gap area than primary forest. This might be due to the high frequency of small gaps in the primary forest compared to primary forest.

Gap size distribution showed similarity in primary and plantation forest area ($p=0.59$). This might be explained by gap-size range. In both forest, there were many small gaps and a few large gaps which range from 10 to 11,000 m². Small gaps in the plantation forests might be due to thinning, which creates high frequency of small gaps in a stand or spacing during plantation whereas larger gaps were due to clear-cutting. Although silviculture activities might eliminate or mask natural disturbances (Oliver&Larson 1996), its influence of natural disturbances cannot be totally eliminated in the plantation forest area, however, its severity can be lower than in primary forest. Gaps in the natural forest are profound consequences of the complex interaction between natural disturbances, topography (slope and altitude), forest environment (soil) and species (age, composition) (Oliver&Larson 1996;Gale 2000;

Lobo 2013; De Toledo et al. 2011) . Therefore, disturbance, in the primary forest, can affect the forest regeneration and species composition (Sakio 1997). In contrast, species composition in plantation forest area is controlled through several silviculture manipulations (Oliver&Larson 1996). Therefore, gap size cannot play a substantial role in controlling species composition as in natural forests, however knowing the growth characteristics, response to disturbance and regeneration mechanism of desire and undesired species in a stand, silvicultural activities can be designed and implemented to regenerate forest with desire species (Oliver&Larson 1996).

6.2 Gap size frequency distribution in different forest types

Gap size frequency distribution in the primary and secondary forest did not follow power-law. In the mountainous geography, there are different forms of disturbance such as landslide, typhoon, erosion, wind, streams, and snow and all other disturbing agents. Gaps resulted from different disturbances with their distinct characteristics might create variance in the gap-size frequency distribution. Thus, fitting all these different processes by a single power-law distribution might be difficult. On the other hand, we did not include gaps smaller than 10 m², which is a significant amount of data considering the skewness distribution. However, the gap size frequency distribution in plantation area followed power-law (2.27, $p = 0.12$).

Empirical data rarely fit perfectly to a power-law distribution (Ethan P. White, Brian J. Enquist 2008). In practice, power-law distribution only follows to the tail data. We estimated x_{min} using a Kolmogorov-Smirnov statistic as used in Clauset et al. (2009). Except in plantation forest area, due to the higher value of x_{min} , about 60 % of the gaps were excluded. However, powered-law distribution only followed in the plantation forest area. Removing bigger gaps (>400 m²) in both primary and secondary forest, which were less than one percent of total gaps, allowed power-law fit ($p > 0.1$) in both forest types. However, the estimated minimum value (x_{min}) was high (>60). With this minimum value, we lost about 90 % of the data.

In UTCF, primary forest had had heavy tail gap-size frequency distribution. The heavy tail distribution in the primary forest was due to a few large gaps $>500 \text{ m}^2$. In fact, in the primary forest, there were only 9 gaps $\geq 500 \text{ m}^2$, whereas in the secondary forest had 16 such gaps. This might be one of the reasons for larger scaling parameter (α) or steeper fit, in the primary forest compared to the secondary forest. Kellner & Asner (2009) obtained similar results through simulation of different gap size distributions. Larger scaling parameter was obtained when larger gaps were absent, and the scaling parameter decreased as the larger gaps appeared.

In a similar LiDAR-based study in the tropics, Kellner & Asner (2009) successfully fitted power-law distribution on their gap-size frequency data at different canopy height class, in tropical rain forests. The scaling parameter (α) ranged from 1.594 to 2.802. However, a gap was only defined by threshold height ($\leq 2\text{m}$), and the area threshold was not included. Thus, they had large numbers of gaps (434501 gaps per 500 ha) compared to our case (6500 gaps per 4450 ha). Because of our focus of study, which is gap size distribution created by at least a death of a tree, we set a threshold gap area which might have limited number of interstitial gaps and other gaps from partial disturbances which were smaller than 10 m^2 . Excluding those gaps might also have also contributed to the lack of fit.

Previous studies (Fisher et al. 2008; Asner et al. 2013) have suggested that the exponent of the power-law or the scaling parameter (α) is the quantitative indicator of gap size frequency pattern and can be a useful parameter for comparing gape size distribution between forests. The larger (>2) scaling parameter in UTCF, implies that the forest is dominated by small-scale disturbances (Kellner & Asner 2009). Among all three forest types, the highest value of scaling parameter (2.56) was obtained in the primary forest which had the highest gap frequency (gaps per ha), lowest mean gap size and highest gap area proportion of all forest types. On the other hand, scaling parameter was lowest (2.20) in the secondary forest which had the largest mean gas-size (55 m^2). Thus, the scaling parameter showed a positive correlation with gap frequency or gap density, but negative coloration to mean gap-size.

In their research Kent et al. (2015) tried to explain gap size ($>9\text{m}^2$) distribution in a selectively logged forest by power-law distribution. Gap size distribution did not follow a power-law distribution in both primary and logged forest. Gaps in a logged forest had steeper exponents (1.26-2.51) compared to the primary forest (1.26-1.65). The lower scaling parameter (α) in the logged forest was due to frequent small gaps reaching the floor due to selective logging. In our case, we got the largest exponent (2.56) or steeper fit in the primary forest which had frequent scattered gaps. Plantation forests of UTCF had even forest patches and clear cutting is practiced. Compared to selective logging, clear cutting creates bigger gaps in the plantation area. Thus, the scaling parameter in the plantation area of UTCF was smaller ($\alpha = 2.27$) than the primary forest.

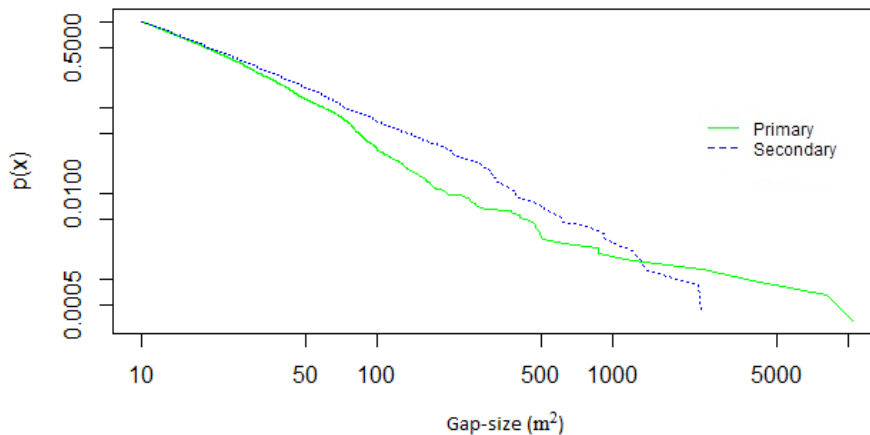


Figure 11. Comparison of probability density $P(x)$ (x = gap size) of different gap size between primary and secondary forest. The graph shows the probability of gaps between 30-1000 m^2 is higher in the secondary forest than primary forest.

Although gap size frequency distribution did not follow power-law it showed variation between primary and secondary forest. Figure 11 shows that the probability of gap decreased rapidly in the primary forest than in secondary forest as the gap-size increases. The probability of gap size distribution at range (30-1000 m^2), as shown in figure 11, was higher in the secondary forest compared to the primary forest. For example, the probability

of gap with 500 m² area in the primary forest was similar to the probability of occurrence of 100 m² gap in the secondary forest. In fact, 26 % of gaps in primary forest were at range (30-1000 m²), where it was 30 % in secondary forest. Therefore, primary forest was dominated by more small-scale disturbance than in the secondary forest.

6.3 Topographical variations in gap characteristics

Disturbance regime in a forest is not solely controlled by disturbance agents, but it is controlled by the interaction between topography, soil type and disturbance history (Lobo 2013). Thus, the interlinkage between disturbance-resulted canopy-gaps and topography is a complex process. Different forests have characteristic geomorphology which determines soil, slope, aspect and elevation patterns (Oliver&Larson 1996). These features influence streamflow patterns, valley shapes and other topographical features. These pattern, shapes and features interact with disturbance cause variation in gap patterns. Thus, canopy gap distribution in a forest is related to local topographic position (Brokaw, 1985), forest types and environment (soil-type).

Very few studies, regarding the interaction between gaps and topography, have been conducted so far. Finding from these studies (Lobo 2013; Gale 2000) have demonstrated the variability of canopy gap characteristics on different topographical land-types. Variation in gap size distribution was also seen in different land-types in UTCF. For example, gap size distribution in valley differed significantly ($p<0.05$) from other land types. Valleys had the highest gap proportion (1 %) of all, whereas ridge has the lowest gap proportion (0.21 %). The variation was also associated with a characteristic feature of disturbing agents. For example, landslides were present on the middle-slopes and therefore average gap-size in middle slope was higher because landslide can create very large gaps. Ridge is less affected by disturbances, whereas slopes, both wind side and leeward, are disturbed frequently by the wind (Oliver&Larson 1996).

Gap formation in a forest is controlled by several factors and therefore one factor cannot be responsible for the whole process. In a study in central Amazonia, (De Toledo et al. 2011) studied the variation in tree mortality predicted by soil and topography. Along with the soil and topography, size of a tree also influences the tree mortality. Topography (Slope and altitude) was associated with 12 % of the spatial variation in tree mortality (De Toledo et al. 2011). However, the effect of topography and soil also varied according to tree size. The relation between tree mortality and the topography and soil was similar in small-sized trees ($1 < dbh < 30\text{cm}$), while large trees showed different (or no) relationships. This result demonstrates the intricacy in gap formation process. More studies are required to unfold the relationship between gap characteristic with different forest aspects.

Majority of our study area in UTCF is facing North or South. Therefore most (76 %) of the gaps were on either north or south. Southern gaps had the largest mean area due to the presence on large landslide created gaps in the southern slopes. Most of the gaps in North and South lied in the valley. Riparian forest in the UTCF lies in the valley region, which is occasionally affected by disturbances like flood and erosion. The rivers Arakawa and its tributaries have created steep V-shaped valley due to severe erosion (UTCf, 2018). Valleys are also affected by the streamflow of rains and snowmelt from the high slope. Thus, valleys are more susceptible to these kinds of disturbances. In UTCF, valley had the highest gap frequency and proportion (1 %). In a study in the mountainous rainforest, Gale (2000) found highest numbers of gaps, defined by threshold height of 5 m, in flat area (plateau) followed by valley, upper slope, middle slope and ridge. In our study, we have a very small portion ($< 1\%$) of the flat area and therefore only three gaps were found in the flat area with gap-area proportion (0.32 %). In contrast to Gale (2000), middle slope in UTCF had higher gap proportion than the higher slope. However, in a tropical old-growth forest, Lobo (2013) found a higher frequency of gaps than in gentle slope than steeper slope. Ridge had comparatively fewer gaps, which was similar to Gale (2000). This might be due to the fact that the impact of wind is less destructive in the ridge but more destructive in the leeward slope (Oliver&Larson 1996). However, since disturbance type and characteristic vary according to climatic zone and therefore it might also create differences in disturbance pattern at different topographic level.

Although different land-type had different gap area proportion, the DNG did not vary greatly. Valley had 1 % of the area as gap however its mean DNG (21 m) was similar to Upper-slope (20m), which had only 0.30 % of gap proportion. Out of 3109 gaps, only 52 (1.7 %) had DNG over 100 m and 75 % of gaps in all land-type had DNG less than 40 m. This implies the majority of the gaps were closely associated with at least a gap. However, DNG only cannot give conclusive evidence about the gap distribution pattern, and more research is needed to fully understand the gap-patterns in different land-types.

Our findings showed variation in gap characteristic between land-types. The large extent of our study area also allowed these sub-categorical gap features to express. The ecological importance of topographical differences in canopy gaps is its effect on species composition and distribution. The variation in species composition can be clearly seen in UTCF. For example, *Fagus crenata* and *Fagus japonica*, occupies middle slopes, where *Fraxinus spaethiana* and *Pterocarya rhoifolia*, occupies wet habitats on concave slopes or along valleys (UTCF, 2018). Some of these variations in species distribution might be the consequences of disturbance regime and topography.

6.4 Spatial variations on gap formation

The semivariogram graph showed spatial dependency of gap-formation up to a distance of 1.3 km and 1.5 km in primary and secondary forest, respectively. Primary and secondary forest showed spherical shape with nugget effect. When disturbance regime is controlled by small-scale disturbances, gap created by the death of trees are spatially well distributed (Kellner et al. 2011). Large disturbances, on the other hand, are randomly distributed (Sotirios & Blackburn 2005) in the forest area. Disturbance, for example, wind, has a spatial component (Zhang 2008). However, the impact of disturbance also depends on forest age and soil (Lobo, 2013). For example, a single windstorm can cause some tree-death in some stand whereas it can completely blow down a whole forest stand. Primary, secondary and plantation forest area in UTCF have different disturbance history, age structure and topography. Therefore, canopy gaps, which is the result of tree mortality, might have different spatial patterns in different forest types.

Disturbances can be localized and isolated events when trees die due to disturbing agents (Oliver&Larson 1996). Disturbances often cover a large area but create a mosaic of small area with a different level of disturbance. Same disturbance can have different impacts on forest depending on the location of occurrence (White & Pickett 1985). After a disturbance, each spatially continuous area with similar soil and climatic conditions might be left with similar structure (Oliver&Larson 1996). The environmental factors (soil and climate) and species composition might be similar over a small area. Thus, intensity and impact of a disturbance can have similar damages within that area than other stand with different conditions.

Plantation forest had very sharp and wide variation compared to the primary and secondary forest. This might be due to the presence of a few scattered clear-cut forest patches along with young forest stands. Even-aged forest management can create more heterogeneity in gap characteristics. For example, 505 ha of plantation forest had several large gaps (>500 m²) along with a large number of smaller gaps. Some area with very young forest, especially before thinning, might have several stands with no gaps, whereas some stands recently thinned might have a high frequency of small gaps. This might have created high spatial variance within plantation forest area.

The nugget effect in all forest types represents micro-scale variation at the beginning of the model due to the measurement error or due to variation in microscale smaller than the sampling resolution (Esri, 2018). For example, in our case, we have a sampling grid of (100*100) m, but the variation in gap-occurrence can exist within the area smaller than the sampling grid. Considering our average gap size in the primary forest (38.71 m²) and average DNG (21.63m) there is likely variation within the grid size.

The complex and diverse topography of the Chichibu mountains has multiple disturbing agents interacting in the forest environment. These disturbances might have a different frequency, return interval, area covered, origin, direction, intensity and consequences on the forest (Oliver&Larson 1996). Thus, although there was a spatial component of such

disturbances, it did not continue to a larger extent. As shown in the gap size distribution, there is a multilevel variation in forest types. For example, gap size distribution varied ($p < 0.05$) between primary and secondary forests, and at the same time, there was also differences ($p < 0.05$) within forest between land-types.

Forest disturbance can show spatial autocorrelation when one disturbance is acting. For example, the disturbance caused by typhoon are not random but have a strong spatial component which is controlled by the field typhoon wind field (Zhang 2008). Similarly, the force of wind is strongest at the stand's edge facing the wind and gradually slows as it travels inside the stand. Thus, the effect of wind on a forest might be spatially correlated in one direction. However, when another disturbance occurs at the same place, the spatial correlation might be changed or lost. Thus, spatial correlation can differ between forests due to geographic features and disturbances characteristics and frequency.

7 Conclusion

The importance of canopy gaps in forest ecology has been widely studied in the temperate and tropical forest (Anderson & Leopold 2002; Canham et al. 1990; Kern et al. 2013; Sapkota & Odén 2009). With modern cutting-edge technology, gap quantification has been easier, precise and efficient. However, due to lack of a universal gap definition, those studies are not straightly comparable. It is very important to understand that different studies use different gap definition with different threshold height and area. Therefore, results should be considered with care.

UTCF was dominant by small-scale disturbances which was shown by skewness distribution pattern in all forest types. There were few larger gaps but accounted for the significant proportion of total gap area. Gap size frequency distribution in the primary and secondary forest did not obey power-law distribution ($p < 0.05$), but it showed a clear distinction in gap size distribution. Forest is a complex system and there may be so many factors affecting the occurrence of gaps and one factor may not explain the whole phenomena. Therefore, gap-size distribution in the UTCF showed variation at different

forest types and topography. Our findings of gap-size distribution in different land-type somehow demonstrate the interaction between disturbances, topography and forest environment in UTCF. However, to fully understand the relationship between gaps and topography, more studies are required.

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