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Review

Research History of Forest Gap as Small-Scale Disturbances in Forest Ecosystems

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Abstract: Forest gaps, which are formed by small-scale disturbances that often occur in forest communities, are the most dominant form of disturbance in many types of forests around the world and play an essential role in the dynamics of forest regeneration, plant diversity conservation, nutrient cycling, and forest succession. Forest gaps are one of the vital directions in forest research. Dynamic disturbance and vegetation regeneration are important elements of forest gap research. The research on forest gaps has a history spanning over 70 years, but there is a lack of a systematic overview of the process. Therefore, this review outlines the spatial changes in the whole process of forest gap development by systematically analyzing the occurrence, basic characteristics, micro-environmental changes, and the effects of forest gap disturbance processes on understory animals, plants, soil microorganisms, and forest regeneration and succession. The results contribute to a better understanding of forest gaps and their impacts on forest regeneration and management. Based on this, we remapped the forest gap process during forest succession. We suggest directions and recommendations for improvements in response to the dilemmas and challenges facing the future of forest gaps.

Keywords: forest gap; disturbance; micro-habitats; succession; biodiversity

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1. Introduction

Forest gaps were proposed by the British ecologist Alex S. Watt in 1947 during an exploration of the patterns and dynamics in forests and patterns and processes in the plant community. He suggested that a fourth phase, the forest gap phase, excluded from other phases, should be added to the existing three successional phases (Bare, Oxalis, Rubus) [1,2]. They were defined as the canopy gaps created by the fall or decay of one or several large trees in the forest crown layers under natural mortality or external disturbances that can generate localized succession within the forest gaps, namely, the theory of gap-phase regeneration. The theory became the basis for the research on forest dynamics [3,4]. As research continued, Runkle, an American forest ecologist, divided the concept of forest gaps into two parts after studying mature forests in eastern North America [5]: (1) canopy gap, the area or space of land directly under the canopy gap (i.e., forest gap in the narrow sense); (2) expanded gap, the area or space of land surrounded by the trunks of the trees surrounding the open space, includes the area or space enclosed by the canopy gap and the edge of the base of the trunks of the surrounding trees (i.e., forest gaps in the broad sense). Since then, the definition of forest gaps has not changed, and researchers have begun researching forest gaps in different regions. Due to the different ways of their formation, light gaps [6], treefall gaps [7], fire gaps [8], hurricane gaps [9], canopy openness [10], and canopy opening [11] also appear in the studies as similar terms to replace forest gaps without standardization. Even the definition already exists. There are two expressions in the Chinese article, but the translations are consistent in English.

Forest gap research is an important part of forest regeneration, even if it is a relatively niche research direction. Currently, research on forest gaps is still traditional, and the conclusions are one-sided and dispersed, lacking long-term monitoring of the same site and comparison between different study areas, which is not conducive to the long-term development of forest gap research. Reviews of forest gap research are too old, and each review had its focus and lacked a comprehensive and systematic analysis of forest gap research. We review the research results of the previous researchers and systematically sort out the whole process, from the causes of forest gaps to the changes brought by the occurrence of forest succession on a larger scale. On this basis, we point out the direction of future research to provide a better reference for forest gap researchers.

2. How/Why Forest Gaps Are Formed

Various modes and levels of disturbance produce different forest structures and directly contribute to the variation in forest space and gap size [12]. There are many ways of causing disturbances; selective logging is one of the primary disturbances consciously enacted and managed by humans. Moreover, prescribed fire is treated as an effective forest management tool to reduce fire risk and promote a sustainable age structure [8,13]. There are various forms of disturbances in nature. In addition to the small fluctuations caused by the death of old trees over a while, there are other notable gaps caused by wind (including hurricanes, typhoons, and storms in different forms), burning, lightning, avalanches, intermittent flooding, bark beetles, epidemics, animals, and so on (Table 1). Wind is the most common disturbance source in nature and the most dominant disturbance factor in tropical and European forest ecosystems, with more significant impacts on basins than highland landscapes [14,15]. Other forms of disturbance occur more often in some specific regions, e.g., forest lightning occurs more frequently in the tropics [16], alpine snow cover occurs only in high-elevation areas and cold zones [17], watershed flooding frequently occurs alongside summer streams [18], tropical rhizobium tends to happen where there is no wind damage, etc. [19].

Table 1. Research related to disturbance forms in forest gaps.

Formation of Forest Gaps	Disturbance Forms	Reference
Artificial disturbance	Selective logging	Valverde-Barrantes, O.J. (2022) [10] Trindade, A.D. (2021) [20] VanderMolen, M.S. (2021) [21] Moreau, G. (2022) [22]
Natural disturbance	Hurricane	Greenberg, C.H. (2021) [9] Xi, W.M. (2019) [23]
	Typhoon	Yang, H. (2017) [24] Chao, K.J. (2022) [25]
	Windstorms	Dietz, L. (2020, 2022) [26,27] Bonanomi, G. (2018) [28]
	Ice-storm	Arii, K (2007) [29] Aarssen, L.W. (2004) Lafon, C.W. (2004) [30]
	Sleet windthrow	Ravnjak, B. (2022) [31] Fukui, D. (2011) [32]
	Wind	Kramer, K. (2014) [33] Berg, E.C. (2019) [34]
	Burning	Izbicki, B.J. (2020) [8] Molina, J.R. (2022) [35] de Almeida, BN (2020) [36]
	Lightning	Gora, E.M. (2021) [16] Amir, A.A. (2012) [19]

Table 1. *Cont.*

Formation of Forest Gaps	Disturbance Forms	Reference
	Snow-covered	Bouchard, B. (2022) [17] Mitamura, M. (2009) [37]
	Intermittent flooding	Keram, A. (2019, 2021) [18,38] Zhu, C.Y. (2017) [39]
	Microburst	Rader, A.M. (2020) [40]
	Bark beetle	Worrall, J.J. (2005) [41] Orman, O. (2018) [42]
	Epidemics	Nagel, T.A. (2015) [43] Navarro-Cerrillo, R.M. (2014) [44]
	Animals (black bears)	Takahashi, K. (2013) [45]

Forest gaps are formed primarily by trunk breakage or uprooting; small-scale disturbances are most common, and most gaps are caused by a single dead tree [46] while larger gaps occur more commonly in floodplains and storm areas [47]. The large size of forest gaps is due mainly to a chain reaction of falling trees causing the death of neighboring trees or the trees growing so tall that a large gap is created when they fall [48,49]. During forest management, the area of forest gaps created by logging is even more significant [50]. Disturbance intensity is not proportional to forest gap size, and the size distribution is skewed towards the medium size [51,52].

The occurrence of forest gaps is not only directly related to climate change but also to latitude [53], soil geology [39], and pests and diseases [54]. At the spatial scale, forest gaps show aggregation but are random at the temporal scale. The spatial and temporal distribution pattern of forest gaps influences the structure and species composition of the forest [55].

3. Basic Characteristics and Measurement of Forest Gaps

The creation of forest gaps is accompanied by many of its characteristics. Many endemic terms have arisen around these studies, including gap maker, gap age, gap border trees, gap size, gap shape, gap density, gap openness, and gap disturbance rate [56,57]. Gap makers are dead or downed trees that create forest gaps and are the cause of forest gap formation [58], with coarse woody debris from the gap makers providing a refuge for the growth of surrounding seedlings [59]. Another related concept to gap-forming wood is gap age, which is the number of years since the gap maker was formed to the time of the survey, that is, the maximum age of the trees in the forest gap [24]. It can be calculated using the theory of gap dynamics. Still, the results are usually younger than the actual age, and studies of gap dynamics have contributed significantly to our understanding of the role of small-scale disturbances in forest ecosystems [60]. It can effectively reduce the bias in gap age using annual ring widths in combination with carbon isotopes to estimate the gap age [61].

Gap border trees are standing trees that the gap makers do not damage. The closed space that gap border trees form together is the forest gap, and the canopy inclination may appear during the growth of border trees due to the release of space [62]. Gap size is related to the tree height of the area and expressed as the ratio of the radius of the forest gap to the mean of the height of the border trees [63]. Gap sizes reported in the literature range from 4 m^2 to 2 ha, a range that needs to be more specific and makes it challenging to compare forest gaps in different study areas comprehensively. For the upper and lower limits of forest gap size, Zhu et al. (2015) indicated that the lower limit of gap size is determined only by the location and the height of border trees surrounding the gap, which should be applicable worldwide, while the upper limit needs to be judged according to the local sunshine duration [64]. There is no optimal size range in the succession of forest gaps [65]. A gap shape presents irregularities and is difficult to describe using a specific geometry, especially since ellipses should no longer be used as a standard gap shape [66]. Using hemispherical photographs to estimate the size and shape of forest gaps is one method that is commonly used [67]. The gap area is the planar area of the forest gap size and is an important standard to measure the size. The distribution of forest gap area is normally distributed in one research area [68], and the variation is large when using different methods to measure the area of forest gaps [63]. With the advancement of science and technology, deep learning techniques are used to remotely track forest canopy gaps and provide more possibilities for measurement [69].

Forest gaps are not static. Small gaps close within a few years [51], and more gaps expand over time due to the mortality of border trees and the coalescence of gaps. Forest gap closure decreases, root disease, and wind are important agents of forest gap expansion [41]. The forest gap will persist and even expand, the duration being a result of the spatial succession of gap-filling concerning the replenishment and successional pathways of species until they are filled with the vertical inward growth of trees from lower strata [70,71].

The methods of investigating forest gaps include the strip spline, the canopy cover census, and aerial photography. The strip spline method is the most suitable for preliminary investigations of forest gaps in the field through the comparison of different methods [72]. Technology changes the tools of surveys and makes them more diverse, from film cameras to the use of aerial photographs combined with a variety of methods to the combination of high-resolution impact and UAV LiDAR [73–75], as well as fisheye cameras, ground-based LiDAR, aerial detection, remote sensing technology, and many other products and technologies of different periods; they play an important role in the process of forest gaps surveys [76–78]. Although it is more susceptible to weather than traditionally used technology, modern smartphones have also begun to be used in forest surveys, and how to choose tools is relevant to the purpose of the study [79]. Research funding is an aspect that should be addressed.

To have a better understanding and prediction of forest gap disturbance, Botkin established the first forest gap model, JABOWA, in 1972 with the forest growth theory [80], based on which FORET, FORTHITE, LINKAGES, FORSKA, ZELIG, SORTIE, and other models emerged successively; all these models are similar in their basic principles and structures, and all of them simulate the dynamics of the landscape with the renewal of a limited number of trees in the sample plot (Table 2). Therefore, almost all forest gap models are applicable only in some particular regions and are difficult to apply on a large scale. ForClim can only achieve localized accuracy with site-specific parameters [81]. FAREAST can explain the interrelationships between individuals and plants and individuals and the environment better [82]. SORTIE better describes the interactions between forest gaps by using the dynamics of forest gaps [83]. SIBBORK is a model for spatially explicit gaps in boreal forests [84]. Due to the differences in forest growth history and environments across the study areas, it was impossible to develop the most representative algorithms. Hence, developers of forest gap models have focused more on developing simulation tools to improve the understanding of forest succession than on predicting growth and yield accurately [85]. Species diversity is an important feature in forest gap modeling and can directly influence model results [86].

Table 2. Information on important forest gap models [87].

Name of the Model	Year of the Model	Author of the Model	Main Views
JABOWA	1972	Botkin et al.	The first forest gap model
FORET	1977	Shugart and West	First time considering sprout tillers update
FORTHITE	1982	Aber and Melillo	First time considering nutrient cycling and litter decomposition
LINKAGES	1986	Pastor and Post	The first comprehensive model that includes the whole soil process
FORSKA	1987	Leemans and Prentice	First time designing the 3D geometry of a forest canopy
ZELIG	1988	Smith and Urban	The first forest gap model considering the spatial relationships of the samples
SORTIE	1993	Pacala et al.	The first spatial model

4. Microenvironmental Changes within Forest Gaps

In forests, natural and artificial disturbances are the main drivers of abrupt changes in environmental conditions (including solar radiation) [88]. Removal of tree canopies changes the dynamics of the microclimate [89]. The size of forest gaps is decisive for the spatial and temporal distribution of the microclimate in addition to the height and density of the forest stand [90], elevation [91], slope direction, and slope gradient [92,93], which affect the microclimate. The combination and interaction of the microclimate and soil parameters in forest gaps at medium scales creates optimal conditions for understory regeneration and favors border tree productivity [94]. Each forest gap has its environment, with the greatest variation in light environment when the gap is created. Light will beam down along the border trees as the canopy opens, creating a strong drive for growth and morphology for the border trees. At the same time, the border trees also create barriers to light penetration, resulting in asymmetry of light and differences in micro-pointing [95]. The changes in light, in general, provide conditions for the growth of the seedlings. Canopy conditions affect seedling distribution, indicating that light conditions play a crucial role in seedling growth [42]. Suitable light levels promote plant photosynthesis and growth in large forest gaps or the central part of forest gaps, where localized light is the primary driver of plant growth [96], increasing the efficiency of light energy utilization by seedlings, and sudden increases in light do not cause pressure on seedling growth [6,97].

Gap maker collapses drastically change the understory environment [98]. Whether the trunk is broken to form mounds or uprooted to produce small pits, the microtopography near the roots is the most directly affected area; the spatial correlation between forest gaps and the pits and mounds suggests that the micro-succession of fallen trees is related to the dynamics of forest gaps [99]. Falling trees prevent transpiration from plants, making some of the soil water content higher, and increasing light also accelerates the evaporation of surface soil moisture [100], sometimes with the presence of heavy fog limiting light and providing moisture to the soil surface. Soil temperature varies with moisture dynamics [101], the PH distribution is also influenced by moisture [102], and forest gaps provide a conduit for moisture cycling outward in the understory [103].

Coarse woody debris decomposition within forest gaps is influenced by a variety of environmental factors such as solar radiation, moisture, and temperature [104]; downed woody debris (DWD) produces microbial communities that contribute to biodiversity enhancement [105]; light and soil moisture content can increase soil microbial diversity [106,107]. Environmental factors such as microclimate, microtopography, and soil temperature and moisture are drivers of microbial community change and have a large impact on altering surface apoplastic decomposition and soil nutrient cycling [108,109]. The process of litter decomposition releases elements such as carbon (C), nitrogen (N), and phosphorus (P) [110]; lignin, cellulose [111], phenolic compounds [112], etc.; and different metal elements such as Cu^{2+}, Zn^{2+}, Ca^{2+}, K^{+}, Na^{+}, Mg^{2+}, etc. [113–115], which accelerate the decomposition of litter and fibrous roots by forest gaps [116]. Forest gaps accelerate cellulose and lignin degradation during log decomposition by increasing cellulose mass loss and slowing lignin enrichment [117]. Decomposition rates are influenced by growing season [118], forest gap size [119], soil temperature [120], and soil moisture content [121]. Coarse woody debris removal does not significantly change soil physical properties but accelerates the leaching process of decomposed nutrients to the deeper soil [20]; water, as the main medium, plays an important role in the leakage of dissolved substances [122]; light has a greater impact on nutrient distribution [123]; average annual precipitation and temperature have a significant effect on nutrient storage and cycling, and the canopy at the edge of the forest gap also plays a filtering role in nutrient cycling from precipitation [115,124]. Both soil physical properties and stoichiometric properties improve over time [125], with water and nutrient availability only becoming better characterized after several decades [126]. Gap size and the location within gaps are key factors influencing changes in tree microenvironments, accelerating nutrient cycling between decaying logs and epiphytes, and are key features influencing stand renewal [127,128].

5. Effects of Forest Gap Disturbance on Plants

The formation of forest gaps provides essential habitats for vegetation survival and accelerates the renewal of dominant species in the understory but does not significantly affect the understory plant community outside of physical canopy openings [23,31,58]. Seed rain is a graphic description of the dispersal of plant propagates, which is a key link in the natural regeneration of plants, the vast majority of which is spread by wind and is greatly affected by the season. Forest gaps provide space for seed dispersal and have a significant effect on the spatial distribution pattern of seed rain density and the soil seed bank [129]. Rodents mostly spread seeds in the understory and scrub [127]. The soil seed bank has a limited potential for renewal [130]. The trade-off between seed size and number is necessary to maintain renewal within the forest gap [131], while the environmental factors affecting seed germination are mainly light [132], temperature [133], and humidity [134]. Medium-sized forest gaps provide the optimum environment for seed germination [135].

Seedling establishment within forest gaps is complex due to the interaction of biotic and abiotic changes [136]. Although the role of forest gaps is not evident for some tree species, forest gaps provide for seedling survival and growth [137]. The relative density of seedlings varies with forest gap size [138]. The species composition and regeneration structure within a particular forest gap were similar, being a random dispersal and replenishment of surrounding species [139]. Seedling survival was significantly higher in the forest gaps than in the understory, and species were differentially affected by gap size, location within the gaps, microenvironment, and forest type [128,140]. An increase in photosynthetically active radiation improves seedlings' physiological and ecological indicators by increasing the chlorophyll content of the leaves [38,141] and, at the same time, increasing the resource grabbing by species regeneration [142] since species grow best at the edge of the forest gaps, which is a preferred regeneration ecological niche within the forest [143].

Forest gaps provide space for the radial growth of border trees but simultaneously increase the asymmetry and risk of fracture of the canopy [144,145]. Lianas are strong competitors for tree regeneration and are major builders of ecological niches [146], preventing trees from regenerating in gaps, thus creating a high-light environment that favors the continued proliferation of lianas and inhibits tree regeneration and diversity [147]. Biodiversity in forest gaps is associated with resource heterogeneity and species diversity in the shrub and herbaceous layers, which are more sensitive to changes in soil nutrients [148,149]. In maintaining biodiversity, the appropriate selection of tree species and matching them to the size of the gap and its location can improve the spatial utilization rate of forest gaps [150]. Seedlings and seed banks of the shade-tolerant species, on the other hand, play a major role in forest gap closure [151].

6. Effects of Forest Gap Disturbance on Animals

The formation of forest gaps significantly alters habitat structure and the distribution and abundance of diaspora, with small rodents and birds using gaps as important feeding areas and accelerating seed dispersal, as well as using gaps as important habitats and ranges [152,153]. Forest vegetation structure has a significant influence on bird habitat selection [154]. Forest gap disturbance creates bird diversity and richness in the range; bird richness also significantly increases with larger gaps [155,156]. Rodents have a higher risk of predation in larger forest gaps, so predation behavior is regulated by the size of forest gaps [157], while frequent rodent activity is also an important factor in high seedling mortality [158]. Hoofed animals (especially deer) are more prevalent in forests and visit for longer and more frequently in forest gaps [159], and the feeding characteristics largely influence species renewal and species diversity in forest gaps [160,161]. Overconsumption hinders natural regeneration, and adequately controlling hoofed species in forest gaps facilitates plant regeneration [21,162]. Habitat modification that opens up the canopy will likely result in an increase in these widespread species and a decline in understory species with restricted distributions. The increased range of habitat also attracts different animals to visit, such as tortoises [163], snakes [164], tree frogs [165], flying squirrels [166], bats [167,168], and different species of insects [32,169], butterflies [98], bees [170], etc. Correspondingly, the herbivory of these animals is higher in forest gaps than in the understory [171]. Of course, some animals prefer the understory to the forest gaps, such as orangutans [172].

7. Effects of Forest Gap Disturbance on Soil Fauna and Microorganisms

Soil macrofauna contributes significantly to soil amelioration, with higher populations in forest gaps such as earthworms [173], spiders [174], and ants [175]; large forest gaps increase the abundance and community diversity of soil fauna [176]. The rainy season attracts more arthropods to the site [177], but at the same time, provides more predation opportunities for birds overhead [178]. Soil nematodes, as indicators for monitoring multifunctional changes due to soil thinning [179], have a significant impact on functional diversity in detrital food webs, whose changes in community structure have a profound effect on forest soil biogeochemical processes [180]. Forest gap size, location within gaps, and their interactions alter the soil microenvironment and soil nutrients, with humus providing higher soil nutrient availability for medium-sized forest gaps and an effective microenvironment for soil microorganisms [181,182]. Larger forest gaps provide more favorable habitats for the diversity of above-ground plant communities and below-ground soil microbial communities, and above-ground plant community diversity is an important environmental factor influencing the composition and diversity of soil microbial communities [183]. Increased coarse woody debris within forest gaps promotes litter decomposition and elevates fungal species [184]; soil enzyme activity is highest in small forest gaps, germinants, and established seedlings found as much on moss as humus and decaying wood [185].

8. Effects of Forest Gap Disturbance on Regeneration

Spatial variation creates horizontal and vertical microenvironmental heterogeneity within forest gaps, increases forest functional diversity and functional identity [186], and has a significant impact on forest structure and composition, helping to maintain rich species diversity [187]. The gap partitioning hypothesis suggests that resource heterogeneity allows ecological niche redistribution for stable forests [188], with regenerating tree species regenerating and spreading along the gap environment gradient according to varying resource demands [189]. In some relatively barren habitats, where the plasticity intensity and light range width of the tree species are most important [190], individual trees have genetically determined growth strategies; fast-growing genotypes are more common in light-rich environments [191], and vegetation in forest gaps has a greater competitive advantage with higher light and water availability [192]. However, community assemblages are controlled by local ecology (limited ecological niches). The most common canopy mortality is also filled in by the renewal of that species or by lateral canopy expansion [193,194], which does not contribute to floristic change in the community as a whole [195]. It is only in large tree forests that forest gap dynamics may take longer to re-establish naturally [196].

Forest gap size is an important factor influencing the composition of naturally regenerating tree species [197]. Forest gap disturbance reduces competition and facilitates resource utilization, thereby enhancing the efficiency of ecological niche complementarity through species richness, stand density, and tree diameter at breast height (DTH) diversity [198]. Of course, there are many factors influencing understory regeneration, which are only facilitated by characteristic conditions [199]. In addition to forest gap size and age, other ecological attributes, such as microenvironmental variables and shade tolerance, affect species diversity and regeneration to varying degrees [200]. The animal communities in the forest gaps act as filters for the establishment, creating a complex mosaic of conditions and enhancing species diversity [201].

The processes of understory species regeneration due to natural and anthropogenic disturbances are not the same [202], and contemporary forests are more homogenized than historical ones due to continuous anthropogenic interventions, and the ability to provide a diverse microclimate for the understory and to withstand a variety of disturbances has been lost [203]. The anthropogenic creation of forest gaps and their continuous monitoring is necessary. The relationship between microenvironmental changes after the creation of forest gaps and the regeneration response proves that this process accelerates the adaptation of forest vegetation to global climate change [143,204], as well as increasing the resistance and resilience of trees and forests to global change by promoting the development of root systems [205]. Retention of coarse woody debris and feces and elimination of low-value tree species during forest gap management may mitigate the decomposition process, helping to accelerate secondary forest restoration and increase forest carbon storage capacity [22,206].

9. Effects of Forest Gap Disturbance on Forest Succession

When forest vegetation is relatively consolidated and infertile, destroying the understory and restarting succession can lead away from forest stagnation and towards a path of higher diversity [207]. The formation of forest gaps provides opportunities not only for native pioneer species in the early stages of succession but also for climatic peak species to develop toward canopy dominance in the later stages of succession, with the successional process providing opportunities for the development of more natural forests [208]. Natural regeneration is delayed by changes in the forest microclimate and nutrient cycling [204], providing an important mechanism for the regeneration of bryophytes and canopy species that dominate the early successional stages of secondary forests [209]. Resource heterogeneity helps to maintain diversity in the understory community by allowing more typical early-successional community species to coexist with late-successional community species, and the functional traits of intermediate and shade-tolerant species are likely to shift less than those of pioneer trees under moderate drought conditions [210], as long as the forest light environment is maintained [211]. Light availability and other climate factors combine to influence species ranges at sensitive scales, and in general, climate is a major predictor of adult tree distributions. In contrast, climate and soil are important predictors of seedling distribution, and saplings have the potential to monitor the early stages of tree migration [212]. Zhu J., who summarized nearly 50 years of secondary forests in Northeast China, indicated that natural forest gaps can promote the renewal of late-successional species in secondary forests, after which the species within the gaps stabilize [213].

The combined effects of natural and artificial disturbances can effectively promote vegetation coexistence, create suitable forest gaps, and utilize forest gap micro-habitats to accelerate the process of restoring vegetation succession [214]. The dynamics of forest gaps in each study area are comparable, with large forest gaps taking 30–40 years to close and small forest gaps taking at least ten years [215]. In contrast, the effects of human activities on forest successional processes are universal, and anthropogenic control of competition within forests can lead to better renewal of vegetation and accelerate the closure of forest gaps, even in protected areas [11,216].

10. Conclusions and Recommendations

Forest gaps are important components of the dynamic development of forest ecosystems. This review provides a systematic review of studies on forest gaps, the occurrence of forest gaps, key concepts, research methods, and various changes in and under forest gaps, a schematic diagram of the forest gap succession process (Figure 1), and clarification of the development route for forest gap research. At the same time, some issues still need continued attention and improvement.

1. The concept of forest gaps has yet to be standardized. Forest gaps occur for various and complicated reasons; researchers always define them using the occurrence reasons, which makes the research on forest gaps too fragmented. Whether and how to standardize the concept of forest gaps is important for global research on forest gaps.
2. With the advances in science and technology, many new methods have been used in forest gap research, but there needs to be a uniform specification. The same or similar principles of research methods help the horizontal comparative analysis of the research. Forest gap models are diversified, with their focus and minor scope

of application. Multi-dimensional and multi-parameter forest gap models must be established to improve the accuracy of model prediction so that the model can be applied more widely.

3. Current research needs coherence among forest gaps, and the focus of research varies from one area to another, lacking comparison of different types of areas and long-term multi-directional monitoring of a single area, which makes it difficult to break out of the current situation. In China, forest gaps are mainly researched in the secondary forests of Northeast China and the alpine forests of Southwest China. While some progress has been made, there still needs to be more understanding of the role of forest gaps in the forest succession process and new forests at the end of the succession.
4. The renewal succession process of forest gaps provides a reference for different types of forest ecosystem services. Forest managers can enhance ecosystem services by controlling the renewal of forest gaps, promoting the aesthetic services of forest landscapes, and strengthening the coordinated development of the economy, society, management, and ecology [217,218].

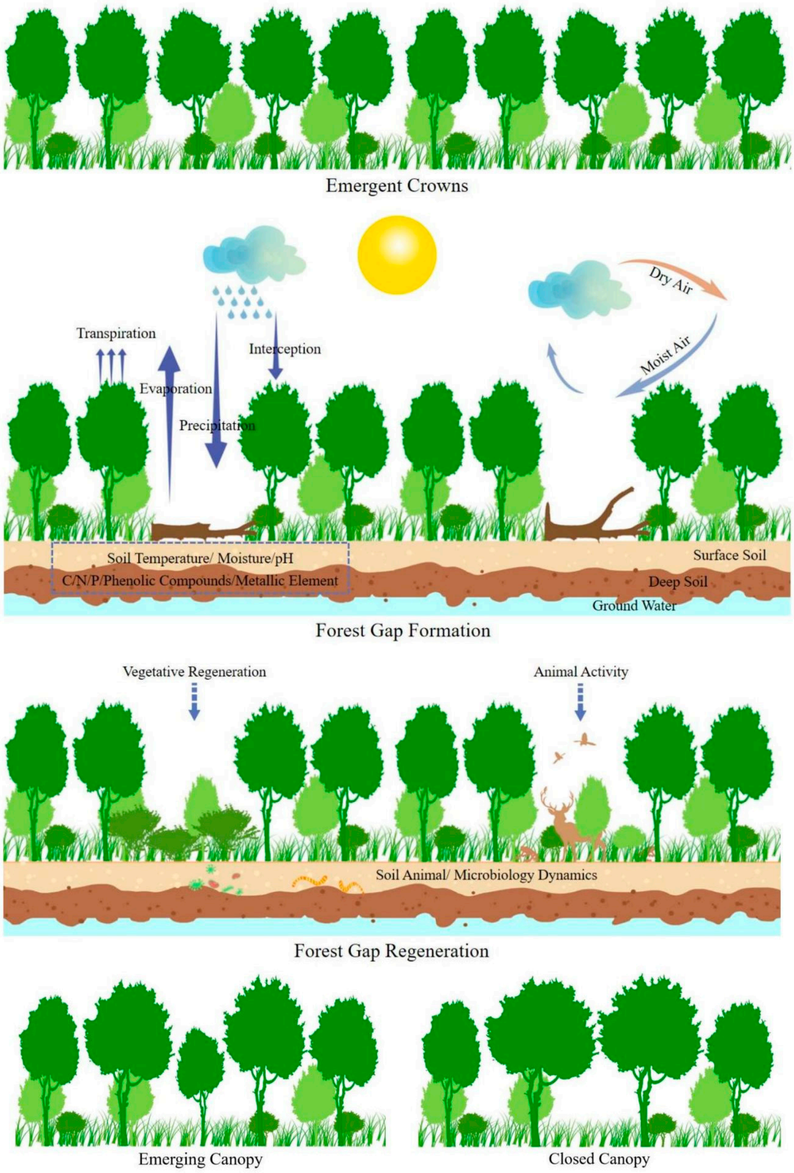

Figure 1. Schematic diagram of the forest gap succession process.

Author Contributions: A.T. designed the article framework, completed the data collection and visualization, and edited the original manuscript. Ü.H. supervised the research, designed the research framework, reviewed the manuscript, and approved the final draft. W.F. designed and completed the schematic diagram of the forest gap succession process. S.S. and S.C. were engaged in data visualization. J.L. reviewed the manuscript with critical comments and linguistic proofreading. All authors have read and agreed to the published version of the manuscript.

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