The Miyawaki method – Data & concepts

Multiple Miyawaki forests projects have been documented across the world since 1980. This document aims at gathering and highlighting scientific data through the compilation of existing Miyawaki forests studies. It also covers the benefits associated to urban forests, and tree exchanges.

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1. Miyawaki forest key-numbers

Multistratal quasi-natural forest – Miyawaki method

Planting density: 2 to 7 trees per m²

Green surface area: 30 times more than a meadow

Survival rate (Natural Selection): 15 to 90%

Growth rate: 1.5 m/year [rainforest], 1 m/year [temperate forest], 0.3 m/year [Mediterranean forest]

Growth stabilization: from 15-20 years [temperate zone], 30-40 years [tropical zone]

Final average size: 20 m [upper layer.], 4m [lower layer]

Density after stabilization: 0.5 to 2.5 trees per m²

Biodiversity (fauna): 18 times more (mean of different species)

2. Photographic survey

Yokohama Campus, Japan

1979 – 40 cm

20 yrs

1999 – 15 m

Hirohata Works, Nippon Steel Corp., Hyogo Prefecture, Japan

±1980 - Ø

10 yrs

±1990 - ±10m

Nara prefecture, Kashihara highway, Japan

1982 – 30 cm

16 yrs

1998 – 15 m

Eidai, Brazil

1992 – 40 cm

10 yrs

1999 – 10 m

Kitakami school, Japan

1 yr

2011 – 30 cm

2012 – 1.5 m

Barvaux school, Belgium

1 yr

2018 – 1 m

2019 - 2 m

Ormeignies, Belgium

3 yrs

2016 - 30 cm

2019 - 3.5 m

3. Concepts

A Miyawaki forest is an opportunity to take part in **ecosystem restoration** (1). Indeed, the method takes into account **ecological successions** (2), and allows to immediately plant an advanced forest through the choice of the most adapted **plant communities** (3). It is called the **Potential Natural Vegetation** (4). **Cooperation** between trees (5) enhances quick development and great resilience.

(1) Natural restoration : *"an intentional activity that initiates or accelerates recovery of an ecosystem with respect to its health, integrity and sustainability (Aronson et al. 2002)"* (Schirone et al., 2011)

(2) Ecological succession: *"In a natural forest cycle, as Clements (1916) described, annual plants on barren land are succeeded by perennial grass, sun-tolerant shrubs, light demanding, fast-growing pioneer trees, and finally natural forests; each step may require decades, and the climax vegetation could be formed after two centuries or more (Connell and Slatyer 1977). Currently, most forest reforestation programs adopt a scheme of planting one or more early successional species; after successful establishment, they are gradually replaced by intermediate species (either naturally or by planting), until late successional species arise. This pattern tries to simulate natural processes of ecological succession, from pioneer species to climax vegetation. However, it requires several silvicutural practices and normally takes a long time." (Schirone et al., 2011) "It was said that it would take 150-200 years in Japan to reach the final indegenous natural forests by secondary progressive succession and 300-500 years in Southeast Asia. It is proved here that multistratal quasi-natural forests can be built in 15-20 years in Japan and 40-50 years in Southeast Asia by ecological reforestation based on the system of natural forests."* (Miyawaki, 1999)

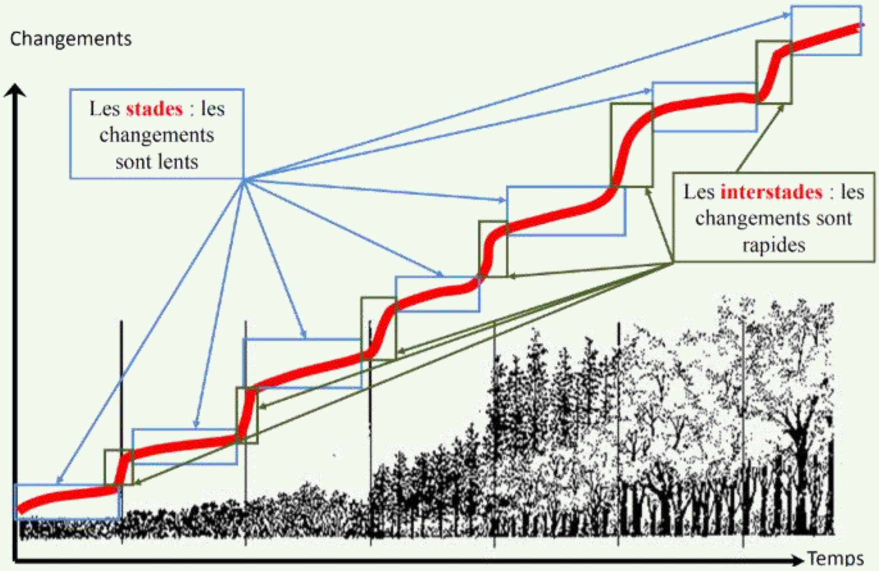


Figure 1 – Ecological successions, (Marie, 2010)

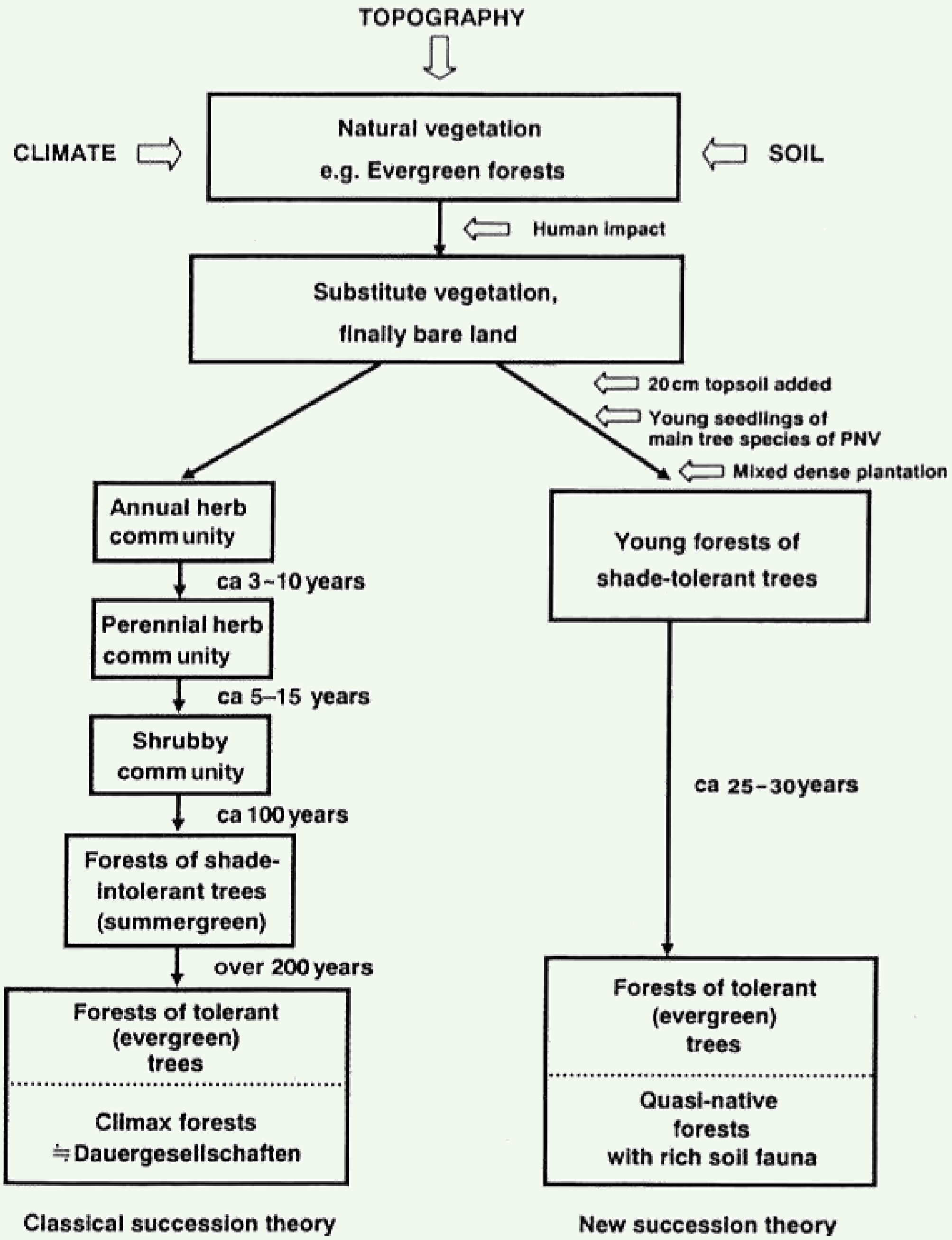


Figure 2 – Comparison between the classical theory and the new one (Miyawaki, 2004)

(3) Plant community: *“We decide local community units by tablework comparing releves and grouping similar species combinations. Then we compare them with community units investigated and systematized in other parts of the world and see the species combinations. When we see species combinations, we find high-fidelity species for particular communities. These species are called character species. We decide phytosociological units based on the character species. We compare phytosociological units widely from natural forests to secondary communities, and decide "associations", basic units of a plant community system, which can be applied to worldwide vegetation science. Likewise, we group the units into alliances, orders and classes by species combinations. In this way the hierarchical vegetation community system is decided.”* (Miyawaki, 1999)

(4) Potential Natural Vegetation (PNV): *"Potential vegetation is a concept of vegetation science, developed in Europe by Tuxen (1956). It does not imply an ecological climax, in the sense of Clements (1916) or a climax as a steady-state, in current American ecological terminology. Potential vegetation is an abstract concept of a vegetation made up of the plant species present in remnants of the plant cover, without human influence. The vegetation scientist studies patches of natural vegetation and, through understanding the relations of species to each other and the physical conditions of the site, reconstructs the potential patterns. The potential patterns give the ecological engineer an endpoint or a design goal to guide reconstruction."* (Miyawaki, 1993)

(5) Cooperation: *"Numerous studies indicate that the abundance, fitness, zonation, and perhaps even local existence of species are not simply due to abiotic conditions and competition, but are highly affected by direct positive interactions within the plant community and complex indirect positive interactions with consumers and mutualists. Perhaps our conceptual models of community organization should incorporate the idea of the abiotic environment as a template on which the effects of competitors, consumers, mutualists, and facilitators on community structure and diversity vary in intensity and importance. The ubiquity of positive interactions indicates that some plant communities may be "real entities" (Van der Maarel 1996), albeit not necessarily with tidy, discrete boundaries." (Callaway, 1997) "Low plant density has been traditionally retained as appropriate in arid and semiarid environments in order to avoid competition for water resources between plants (Caramalli 1973; Bernetti 1995), but it is now evident that cooperative processes, e.g., mutual shading, prevail over competitive processes (Callaway 1997)."* (Schirone et al., 2011)

4. Miyawaki forest growth data

A. Multiple protective forest projects in Japan

Many reports written by Miyawaki provide averaged key values for micro-forests development in Japan:

- ***''By natural selection, the trees grow about 10 meters tall in 10 years, and 20 meters tall in 20 years."*** (Miyawaki, 2014)
- *"In about three years the trees grow 2 to 3 meters high, and the crown covering the forest floor comes to keep the sunlight from coming in."* (Miyawaki, 1999)
- *""Though it was said to be difficult to restore native forests in the area because of dry air in summer and overgrazing, we have found that native forests can be restored if we take sufficient care for the first several years after planting."* (Miyawaki, 1999)
- *"It was said that it would take 150-200 years in Japan to reach the final indigenous natural forests by secondary progressive succession*

and 300-500 years in Southeast Asia. It is proved here that multistratal quasi-natural forests can be built in 15-20 years in Japan and 40-50 years in Southeast Asia by ecological reforestation based on the system of natural forests." (Miyawaki, 1999)

- *"Field surveys have told us it is not climate conditions but soil conditions that matter. […] In this way we have succeeded in restoring quasinatural forests in 15–20 years in every region of Japan."* (Miyawaki, 1999)
- *"On the average one person planted 20 seedlings in 1 h. The results of these ecological plantations based on a vegetation-scientific scenario are quite good. Seedlings that were only 30– 50 cm high when planted grew to 7 m high after 10 years, higher than 10 m after 15 years, and form so called antidisaster environment protection forests. […] Dense, mixed planting of 30–50 species of the potential natural vegetation is in accordance with the system of natural forests, and enables a multilayer forest to grow after 15–20 years by the peculiarity of planted species. At some planting sites, however, even after ecological dense, mixed planting, adequate natural selection is not seen until 10–15 years after planting and some tall trees have thin stems compared to their height. This problem will be solved in time."* (Miyawaki, 2004)
- *"Among 550 locations of our planting throughout Japan we don't see a single failure. We succeeded in restoration of native forests from in cold-temperate zone to in tropical forest zone."* (Miyawaki, 1999)
- *"The green surface of a multi-stratal forest of the potential natural vegetation is about thirty times as large as that of a mono-stratal lawn, which needs periodical maintenance. As for absorbing and accumulating CO2 multi-stratal native forests have a much larger capacity than do lawns."* (Miyawaki, 1999)

Figure 3 - Miyawaki forest in Kimitsu, May 2015 *("Google Maps," n.d.)* – The forest is probably part of the 1973 project, hence it would be 47 year-old.

B. Rainforest restoration project in Brazil

Miyawaki's project for Mitsubishi ("Brazilian Project in Tropical Forest Regeneration," n.d.) makes reforestation trials on two locations : Belem, and Breves a secondary site. Belem site does not develop as expected and does not satisfies Miyawaki and his team despite some results. On the other side, Breves site yields excellent results. The following extracts (Miyawaki and Abe, n.d.) (Miyawaki, 1998) summarize the project's data and conclusions :

> *"Fast-growing species like Balsa; Ochroma pyramidale and Boleira; Joannesia princeps, were 6 m high in 1994, 2 years after planting; 10 m high in 1996, 4 years after planting; and 15 m high in 1998, 6 years after planting. DBH measured up to 20–30 cm.* ***The trees had grown magnificently, and the physiognomy was a quasinatural forest****. However, in the field investigation of 2000 and 2001, we found that most of them had fallen down although they had not experienced very strong wind." | "In the Belem forest, fast-growing pioneer species developed shallow horizontal roots before soil conditions changed to those of mature sites. The stems of these species broke and fell down in the somewhat strong winds. As a result, the broken pioneer stems killed many individuals of the PNV species, which waited in the lower layer." | "The fallen trees prevented the growth of Virola spp. and the other main component species of the potential natural vegetation in the forest. Unfortunately, biodiversity there cannot be said to be adequate (Miyawaki & Abe 2002). For comparison studies we had planted potted seedlings of 14 species only from the potential natural vegetation, including Virola spp., on Breves Island, Brazil.* ***They have grown steadily and reached 8–10 m to form a quasi-natural forest in 10 years****. We saw great differences in growth between the two sites, Belém and Breves (Miyawaki & Abe in press)." | "In the Breves forest, unplanted species such as Cecropia spp., Vismia cayannensis, Synphonia globulifera, Bertholletia excelsa, Diplotropis purpuria were also recorded. These species might have invaded from surrounding forests." | "The Breves forest grew well for 9 years, because of planting mainly Virola surinamensis, which composed the mature Varzea forest (Prance 1989; Worbes et al. 1992).* ***In the future the Breves forest is expected to change to be more natural by self-thinning and invasion of native trees.*** *From this study, we concluded that, for tropical forest restoration surely in the longterm,* ***seedlings of species from the mature potential natural vegetation should mainly be used, if the number of species is not sufficient, and that planting pioneer species like pulpwood trees, which grow so fast, may be avoided*** *unless other reasons suggest their utilization." | "As a result, it can be said that restoration of diverse quasi-natural forests in a shorter period is attained from dense, mixed planting of main and companion tree species from the potential natural vegetation, following the system of natural forests with much care for soil conditions. It takes 15– 20 years in Japan and 30–40 years in the Torrid Zone."*

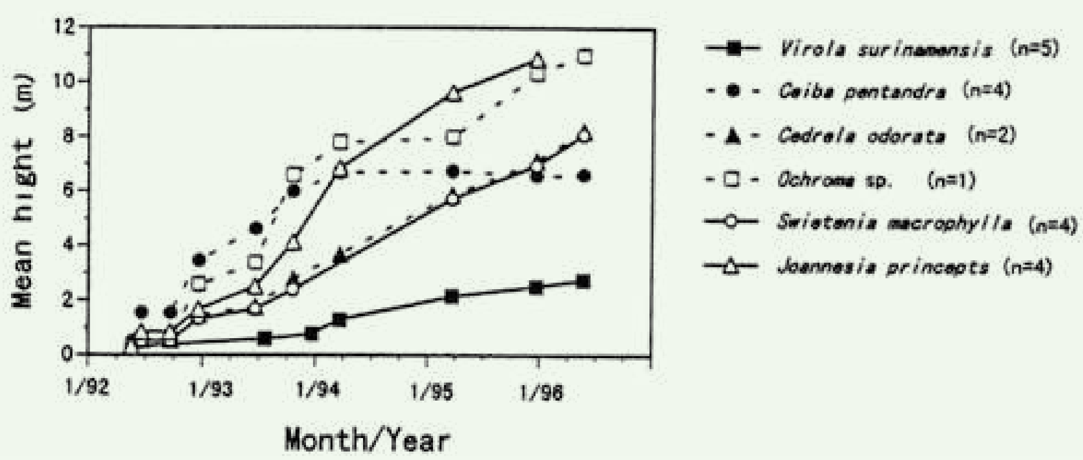


Figure 4 – Growth rate of the main trees species, Belem / Brazil

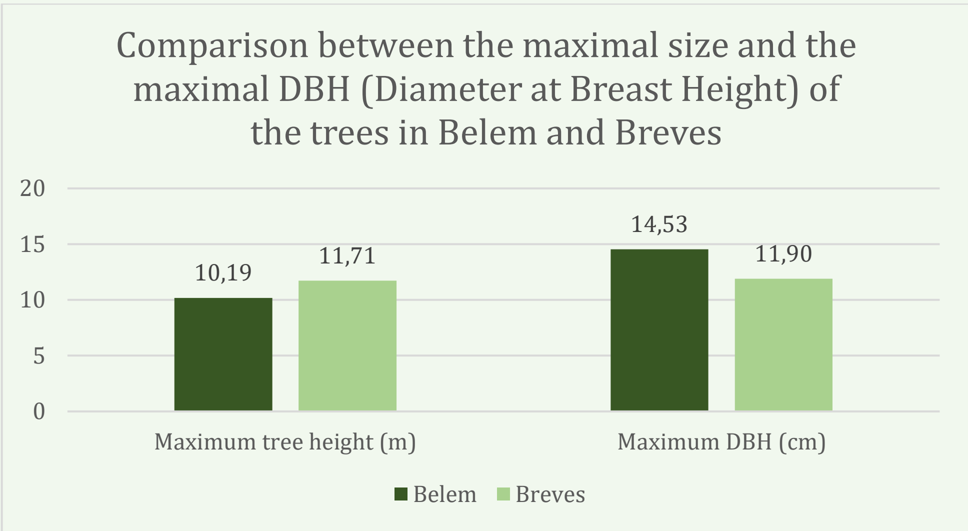


Figure 5 - Charts made from table 4, *(Miyawaki and Abe, n.d.)*

C. Rainforest restoration project in Malaysia

Frequently, tropical rainforests are damaged and it is difficult to regenerate them: *"Since 1978 we have been researching in the tropical rainforest zone of Malaysia, Thailand and Indonesia. The study results show that natural forests were completely destroyed in many areas because of slash-and burn farming, felling trees and oil palm farming. Slash-and-burn farming over a large area has destroyed every tree within a forest and it takes quite a long time to see a forest naturally restored. Sometimes it is nearly impossible."* (Miyawaki, 2004)

However, the Miyawaki method is an interesting tool to speed up forest restoration. Miyawaki's team does an attempt in Bintulu as early as 1990, Miyawaki gives details about the forest development (Miyawaki, 2011) :

- 1990-2011: *"From 1990 to 2011, 350,000 seedlings from 126 tree species were planted at four different areas and surrounding the nursery. Meanwhile, 100 research plots* *were established and growth performances of planted seedlings were recorded twice a year."*

- 2000: *"**15 tree species started flowering and fruiting in the plots established in 1991 to 1993**. Some of the young seedlings have reached **4.5 meters in height**. Seeds of these tree species were collected and used for subsequent replanting."*
- 2011: *"With time, the number of surviving plant species decreased because of natural selection. Instead, surviving trees grew tall and thick, and form a splendid quasi-natural multi-layered forest. Planted trees at Phase One area [1991] are about 15 m high."*

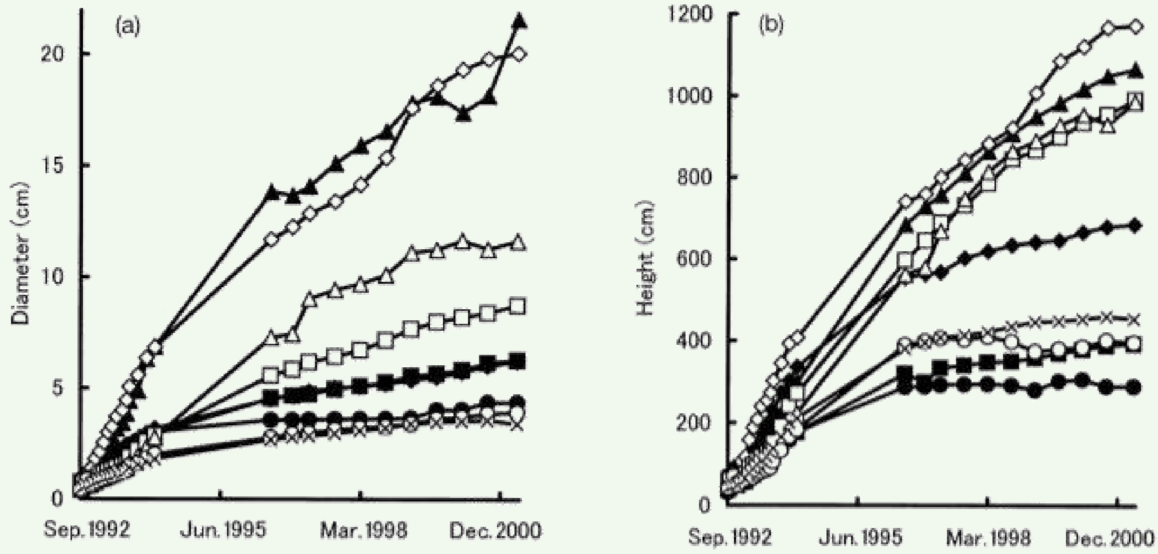


Figure 6 - Growth behavior of (a) tree height and (b) diameter of planted seedlings at Bintulu reforestation site, Sarawak, Malaysia, based on vegetation surveys. (⬩) Baccaurea lanceolate (4) ; (■) Baccaurea macrocarpa (12) ; (▲) Dracontomelon dao (20) ; (●) Eurycoma longifolia (10) ; (◊) Sandoricum koetjape (20) ; (□) Shorea dasyphylla (92) ; (∆) Shorea leprosula (59) ; (○) Shorea mecistopteryx (77) ; (×) Shorea ovata (170). The numbers in parenthesis are those of investigated trees. *(Miyawaki, 2004)*

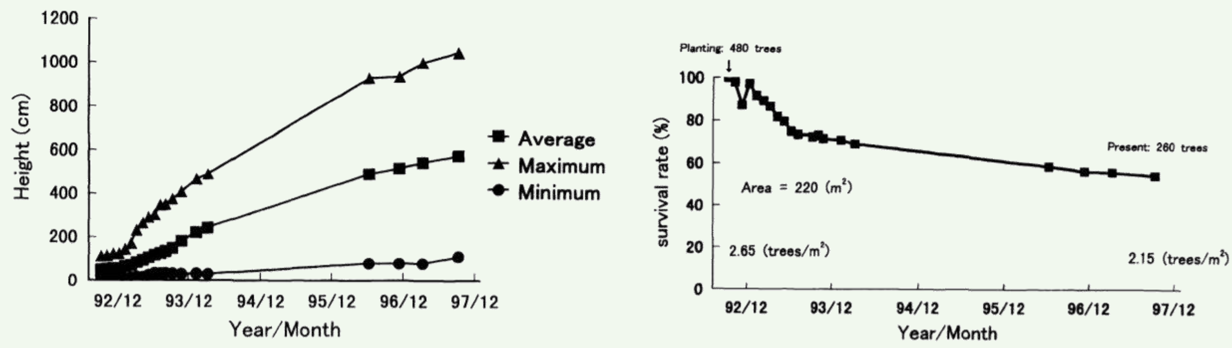


Figure 7 – Growth curve in height on PQ 203 in Bintulu, Sarawak, Malaysia (left) ; Survival rate passage time on PQ 203 in Bintulu, Sarawak, Malaysia (right). *(Miyawaki, 1999)*

One could wonder to what extent a Miyawaki forest grows faster than a naturally regenerated forest. A study about young trees' growth in Gabonese tropical forest windthrows (Hladik and Blanc, n.d.) provides data from which rainforest usual growth rate can be estimated. **On average, trees grow at a pace of 20 cm/year over the five first years. Whereas Miyawaki tropical forests rather grow at a pace of 110 cm/year.**

D. An impossible task yet a success in some arid area in Sicilia

The following figures are extracted from the report about the first Miyawaki forest attempts in dry climate (Schirone et al., 2011), on two sites: A and B. Reforestation in such places is complicated and often fails. Thus, the method has been adapted. The results turned out to be very encouraging. The price of this success? A high mortality rate, hence an intense natural selection. In this way, very dense and resilient forests were obtained after 12 years. A high mortality rate is not something negative: it simply indicates that the most adapted trees have been selected.

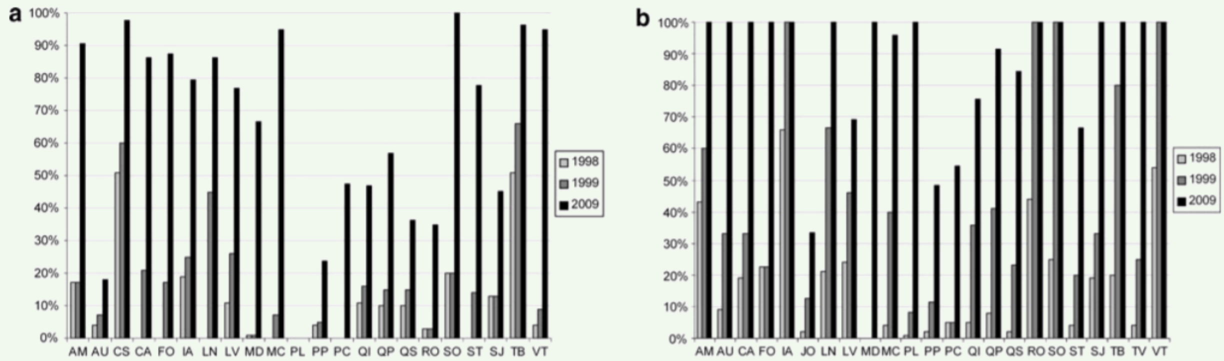


Figure 8 – Mortality rates in experimental fields. Percentage measured during three surveys for each species on site A (a); result on site B (b). X-axis labels refer to the species acronyms, *(Schirone et al., 2011)*

Sites A and B (Miyawaki Forests A and B) were compared to parts of traditionally reforested sites with forests around 15 years old (Control Forests A and B). It seems that the Miyawaki method in arid zone guarantees a greater density for trees of identical size to those obtained with conventional reforestation techniques: *''Although mean height of species common to all study areas does not differ significantly, plant density on site A is around four times higher than on [Control forest A] and five times on [Control forest B], whereas on site B, maritime pine densities are 3 and 4.5 times higher than on traditional reforested plots were observed."* (Schirone et al., 2011)

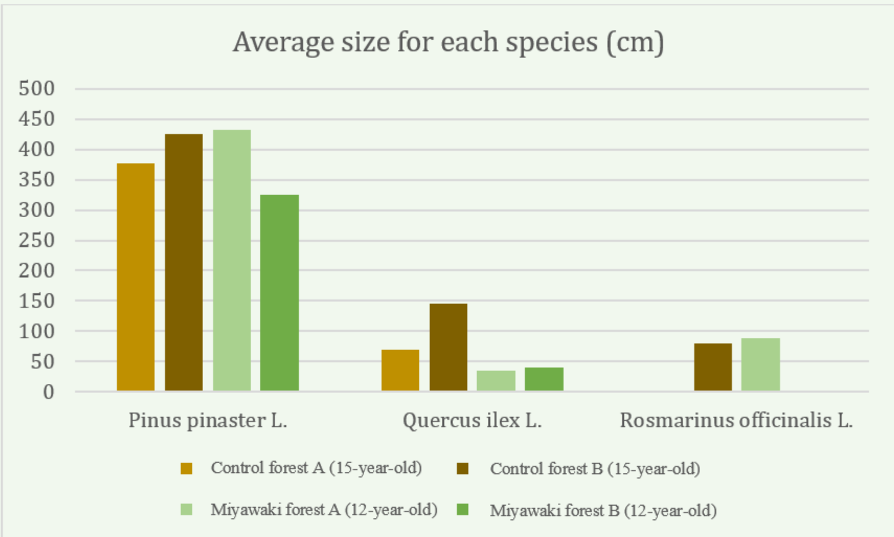


Figure 9 – Chart made from table 5, *(Schirone et al., 2011)*

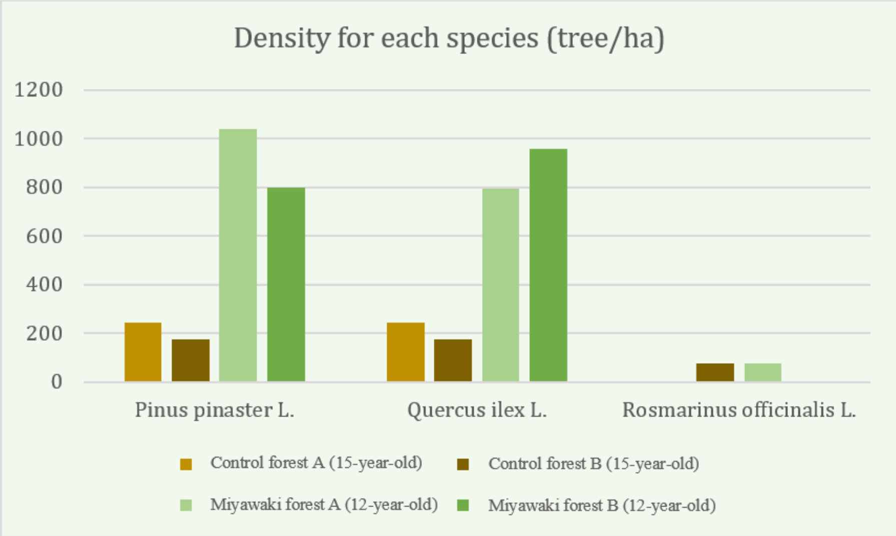


Figure 10 – Chart made from table 5, *(Schirone et al., 2011)*

The report provides a favorable conclusion to the use of Miyawaki method and sums up the changes to be done:

"The Miyawaki method could offer a quicker and more effective reforestation approach in the Mediterranean environment, adopting naturalistic theoretical principles not previously tested in Mediterranean Europe, which has the additional challenge of a seasonal climate characterized by summer aridity compounded in several cases by winter cold, and also by thin soils. Here we provide a comparison between the Miyawaki method and two other reforestation methods (gradoni and holes) traditionally applied in Mediterranean countries. The results showed a more rapid development of trees on the Miyawaki plots, in particular, early-successional species. The benefits over previous methods are remarkable and comparable with those obtained by Miyawaki in Asia and South America. At the same time, some of the changes made in this study to better fit the method to the Mediterranean environment seem to be particularly useful. First, we used tillage to improve soil water storage over the winter and reduce water stress during the summer. Summer aridity implies the soil would be able to stock winter rainfalls in order to allow the plants avoiding water stress of the next season. This outcome has been achieved using tillage; such action is necessary and should be enough, even if it would be possible to get a better performance by adding compost or local soil. Mulching with green material does not seem effective (Navarro-Cerrillo et al. 2009), whereas mulching with dry material has been useful. Moreover, avoiding clearing all bush is opportune for the Mediterranean environment, in contrast with some studies." (Schirone et al., 2011)

E. Biodiversity project in Netherlands

In Zaanstad in the Netherlands, two Miyawaki micro-forests were created in 2015. In 2017, a study (Alterra - Animal ecology et al., 2018) was carried out over a full year in order to compare the biodiversity in these forests (in green below) with the one from surrounding woods (in brown below).

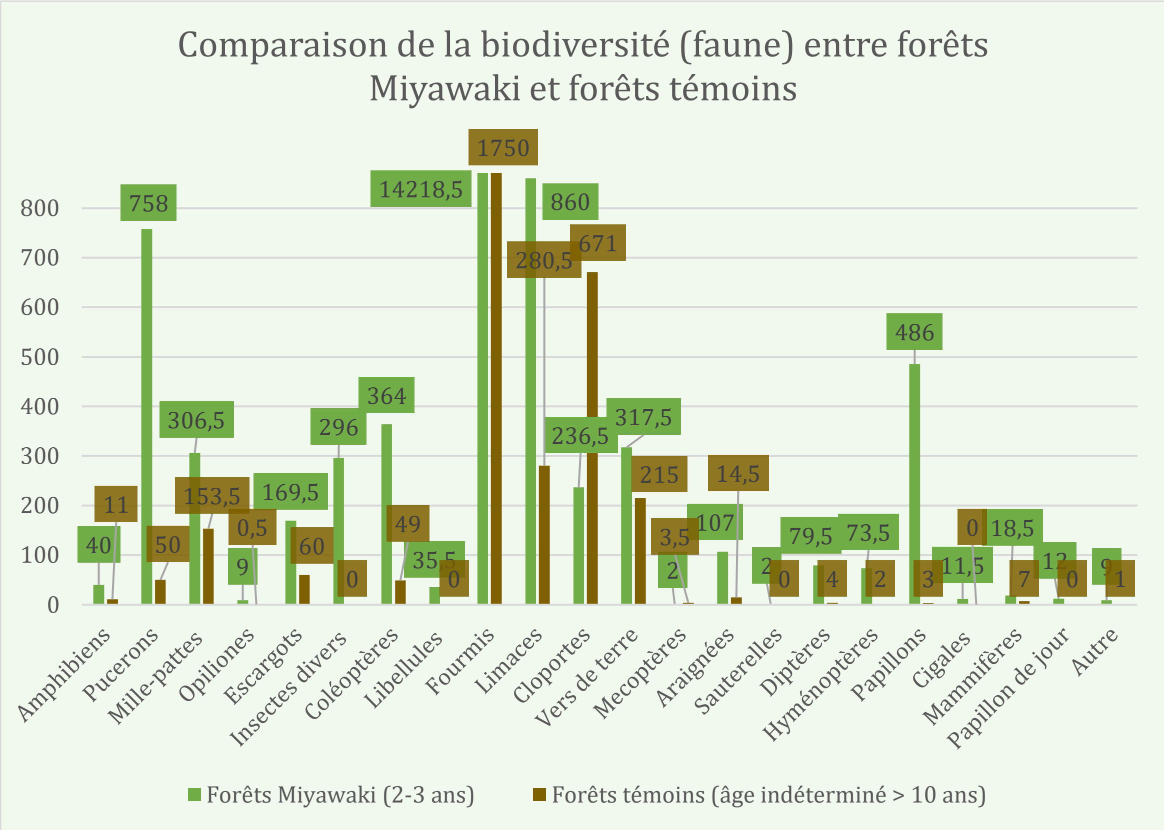


Figure 11 – Chart made from the report *(Alterra - Animal ecology et al., 2018)*

The results are clear: the Miyawaki micro-forests, although very recent, are much richer in biodiversity, from 2 to 162 times more, on average 18 times more.

5. Comparisons between climates

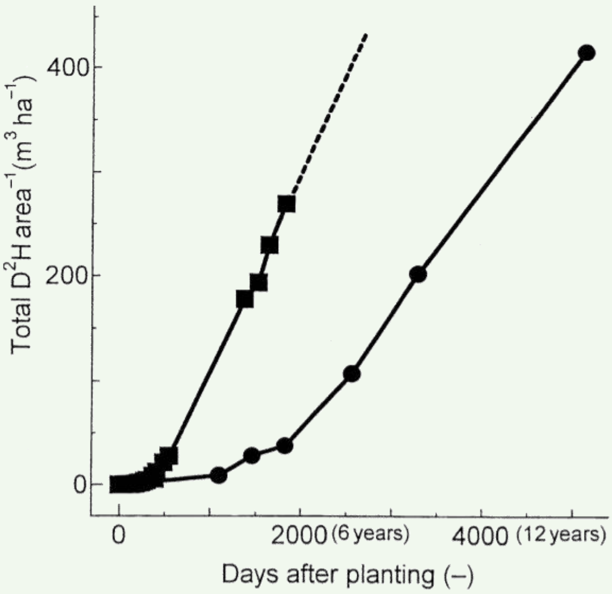
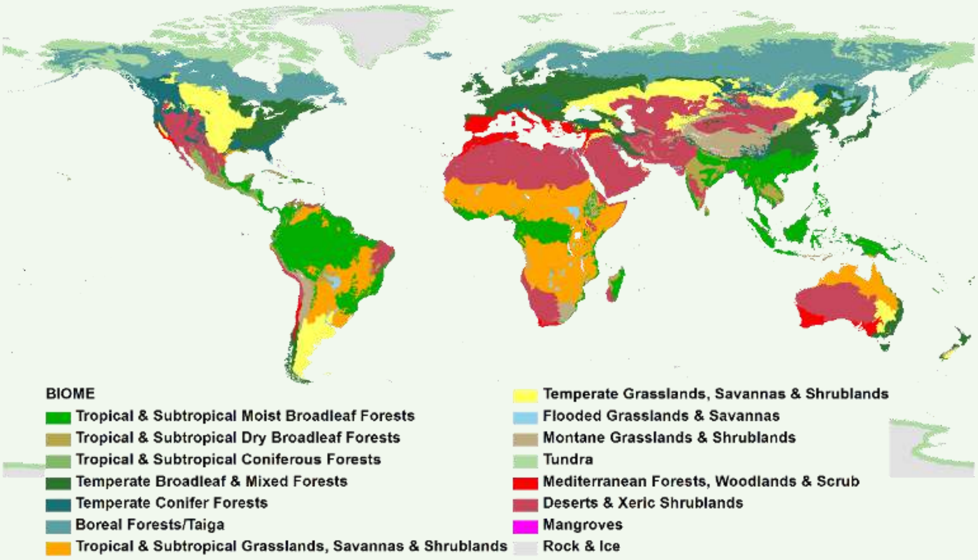


Figure 12 – Volume indicator « D²H » at a tropical rainforest zone in Malaysia and a laurel forest in Japan. (■) Bintulu/Borneo (27.3 t ha-1.y) ; (●) Ohgishima/Tokyo Bay (16.6 t ha-1.y). *(Miyawaki, 1999)*

If we simply observe the volume of vegetation formed in a tropical Miyawaki forest and a temperate Miyawaki forest in Japan, it appears that the Miyawaki forest in the temperate zone grows more slowly. But the difference is not immense: in 3 to 6 years depending on the stage of growth, the temperate forest overtakes the tropical forest. For two very different climates, the development gaps are therefore rather small. Miyawaki reports on the prevalence of the soil and not the climate in the development of the forest: *''Field surveys have told us it is not climate conditions but soil conditions that matter."* (Miyawaki, 1999)

In addition, the observation of a biomes map indicates that similar types of forests grow in Japan and in Europe:



From: Olson et al. (2001)Terrestrial ecoregions of the world: New map of life on earth. Bioscience 51:933-938

➔ **We can therefore assume that the development of Miyawaki forests in Europe is on average similar to that recorded in Japan.**

6. Micro-forest benefits

Even if the benefits delivered by the Miyawaki forests as such have not all been the subject of studies, it is nevertheless possible to rely on studies of urban forests in general. Miyawaki forests' particularities will be taken into account.

Urban forest benefits

Temperature reduction : -2℃ minimum, locally

Air quality improvment, pollution clustering : absorbtion of 15% microparticules, leaves and bark intercept dust.

Noise reduction : -10 dB for a mature Miyawaki forest

Health and well-being : reduction of stress, anxiety, solitude, cardio-vascular et respiratory diseases.

Biodiversity balance : biodiversity is on average 18 times higher, pest concentration can be lower, the forest ensures transfers and biodiversity increase in urban context.

Soils stability : the entanglement of roots forms a matrix-pillar system that retains soils

CO2 sequestration : stock = 60 kgC/m2 forest cover, flux = 0.5 kgC/m2 forest cover/ year. 100 m² of Miyawaki forest long-term compensates one year of a european person's carbon emissions.

Real estate prices : properties with tree cover can see their price increase by a few thousands of euros

A. Temperature reduction

The study (Long et al., 2019) focuses on the temperature difference between trees according to their location : isolated decorative trees (landscape), urban forests edge trees (edge) and trees within the urban forests (interior).

Figure 13 – The different studied locations are marked with a star. (Long et al., 2019)

The surveys are carried out at the canopy level, there is a significant difference in temperature between the isolated trees and the forest trees, up to 2 ℃ less in the forest.

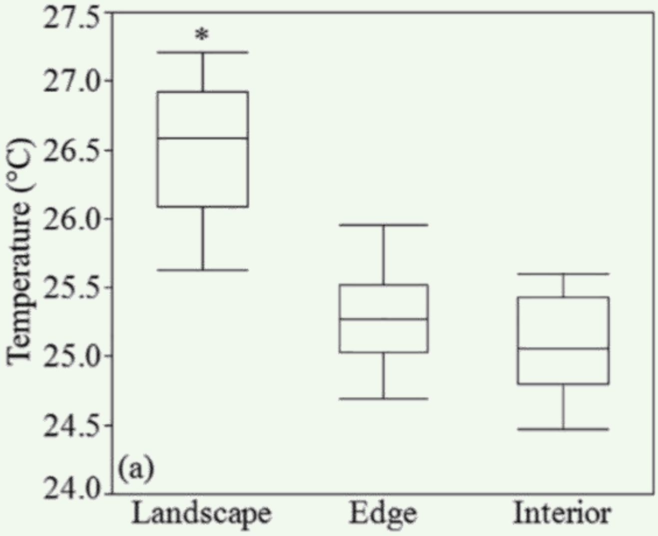


Figure 14 The effects of tree location on canopy temperature illustrated using boxplots to demonstrate the range of values obtained. The median of the data range is marked by the line which divides each box. Boxes represent the interquartile range and upper and lower whiskers represent data outside the middle 50% of observations. Asterisks indicate significant differences from Tukey HSD tests. The average canopy temperature of urban landscape trees (n=16)was significantly greater than it was for trees growing at urban forest fragment edge(n=16) or interior(n=16). (Long et al., 2019)

As for whether urban forests create micro-climates, in other words, if nearby people can benefit from this additional freshness; the following study (Howe et al., 2017) shows that they do. The study used a network of 10 identical weather stations and high-resolution land cover and land use data in Knoxville, Tennessee, to analyze the microclimates of a mid-sized city with a temperate climate.

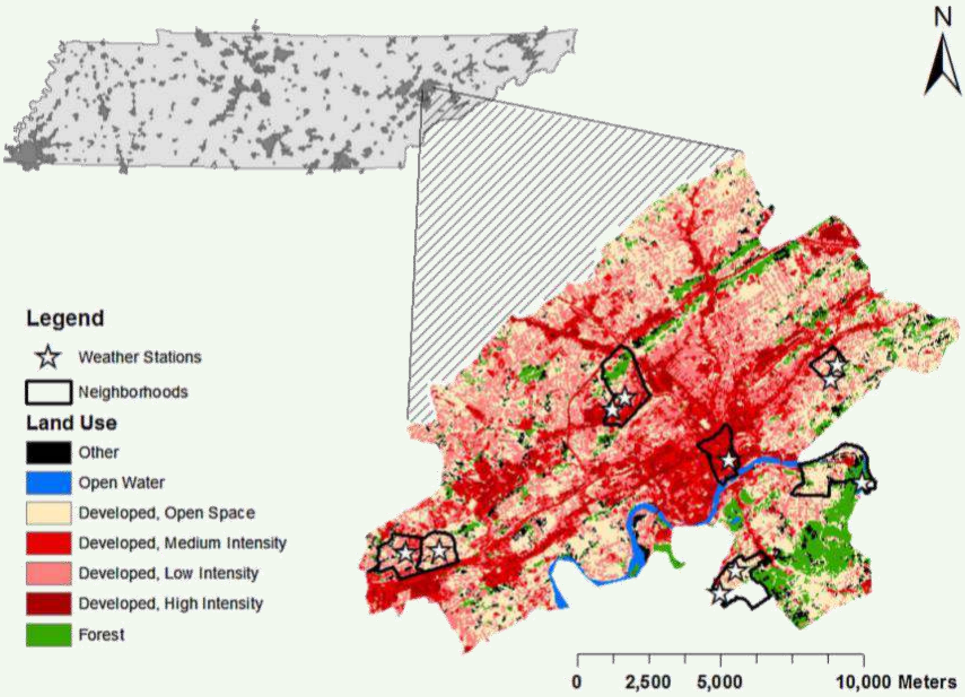


Figure 15 - Location of monitoring stations, national land use data 2011

The challenge is clearly described: *''Increasingly extreme heat waves are frequent in city centers, and their increase is very likely given climate change. […] The heat island is a widely documented phenomenon, due to urbanization. It is characterized by locally higher temperatures in a city than in the other surrounding spaces, day and night. […] Thus, it is urgent to determine how to live in urban environments sustainably and in line with public and ecological health.''* I *''These data can be used as support for the development of plans aimed at strengthening resilience extreme heat in urban environments, taking into account the influence of forest cover.''*

In the following table, two values are important for the analysis. The p value shows that the results are statistically significant when $p < 0.05$. When this is the case the values appear in bold. It is also interesting to consider the value of the coefficient of determination R^2. The closer its value is to 1, the more the trees have an impact on temperature. The minus sign has been added to specify the nature of the correlation: when it is present, it means that the trees tend to lower the temperature.

SSC	Statistic	Correlating Variables	R^2	p
Dry Moderate	Tmax	50 m Impervious	**0.746**	**0.01**
		100 m Tree	−**0.76**	**0.01**
	Tmin	100 m Impervious	**0.73**	**0.02**
		500 m Tree	−**0.89**	< **0.01**
	DTR	–	–	–
Moist Moderate	Tmax	Distance from Downtown	−0.57	0.08
	Tmin	100 m Impervious	**0.93**	< **0.01**
		500 m Tree	−**0.90**	< **0.01**
	DTR	–	–	–
Moist Tropical	Tmax	100 m Tree	−0.59	0.07
	Tmin	100 m Impervious	**0.89**	< **0.01**
		500 m Tree	−**0.88**	< **0.01**
	DTR	–	–	–

Figure 16 - Correlation results for summer when data are analyzed by CCN. Bold numbers indicate $p < 0.05$

The study reaches the following conclusions: *''The intra-neighborhood results suggest that there is a significant temperature variability within a single neighborhood as a function of the density of the tree cover immediately surrounding a given weather station. Neighborhood-wide land use (especially the percent forest cover at 500 m radius) had the highest correlation with the minimum daily temperature (Tmin) during the summer season.''* In other words, there are really differences in temperature from one neighborhood to another and this is linked to the density of the tree cover. **On a 500 m radius, a wooded neighborhood has a lower minimum temperature than the other districts in summer: the temperature is better there at night than elsewhere.**

"When the amount of forest cover increases, Tmin decreases. This trend continued when temperature data were analyzed by season and by air mass (SSC)." **Regardless the weather conditions, trees induce lower temperatures.**

B. Air quality improvement, containment of pollution

Air quality in western (North American) cities has been assessed using models based on environmental databases and simulations (eg i-Tree) : *''Despite the limitations, there are several advantages to the modeling estimates, which include the use of best available tree, weather, population and pollution data, modeling of tree effects on hourly pollution concentrations and modeling of pollution effects on human health.'' (Nowak et al., 2014)*

The capacity of urban forests covers to reduce pollution over a year has been calculated by pollutant type (CO, NO2, O3, PM2.5, SO2). The health and economic benefits are also examined.

The conclusions (Nowak et al., 2018) are the following :

- *'The total amount of pollution removal in the 86 cities in 2010 was 16,500 t (range: 7500 t to 21,100 t), with a human health value of $227.2 million (range: $52.5 million to $402.6 million).''*
- *''Maximum annual air quality improvement among the cities averaged around 0.01 percent for CO, 2 percent for NO2, 3 percent for SO2, 4 percent for O3 and 15 percent for PM2.5.''*
- *''The greatest effect of urban trees on ozone, sulfur dioxide, and nitrogen dioxide is during the day time of the in-leaf season when trees are transpiring water. Particulate matter removal occurs both day and night and throughout the year as particles are intercepted by leaf and bark surfaces. Carbon monoxide removal also occurs both day and night of the in-leaf season, but at much lower rates than for the other pollutants.''*
- *''Ozone studies that integrate temperature, deposition and emission effects of trees are revealing that urban trees can reduce ozone concentrations.''*
- *''Under stable atmospheric conditions (limited mixing), pollution removal by trees could lead to a greater reduction in pollution concentrations at the ground level. Large stands of trees can also reduce pollutant concentrations in the interior of the stand due to increased distance from emission sources and increased dry deposition (e.g., Dasch, 1987; Cavanagh et al., 2009).''*
- *''Forest canopies can limit the mixing of upper air with ground-level air, leading to significant below-canopy air quality improvements.''*

The study also mentions a few negative effects:

- *''However, where there are numerous pollutant sources below the canopy (e.g., automobiles), the forest canopy could have the inverse effect by minimizing the dispersion of the pollutants away at ground level.''*
- *''Air pollution removal is only one aspect of how urban trees affect air quality. Trees reduce air temperatures, which can lead to reduced emissions from various anthropogenic sources (e.g., Cardelino and Chameides, 1990). Trees around buildings alter building energy use (e.g., Heisler,1986) and consequent emissions from power*

plants.Trees reduce wind speeds, lowering mixing heights and can therefore increase pollution concentrations (e.g., Nowak et al., 2006a). Trees also emit pollen, which affects allergies (e.g., Ogren, 2000), and volatile organic compounds (VOCs) that are precursor chemicals to O3 and PM2.5 formation (e.g., Chameides et al., 1988; Hodan and Barnard, 2004).''

The study sums up the **conditions to avoid** to enhance trees' positive effect on air quality:

''At the local scale, pollution concentrations can be increased if trees: a) trap the pollutants beneath tree canopies near emission sources b) limit dispersion by reducing wind speeds, and/or c) lower mixing heights by reducing wind speeds (Nowak et al., 2006a). These local scale interactions are important for determining the net effect of trees on air quality and human health.''

C. Noise reduction

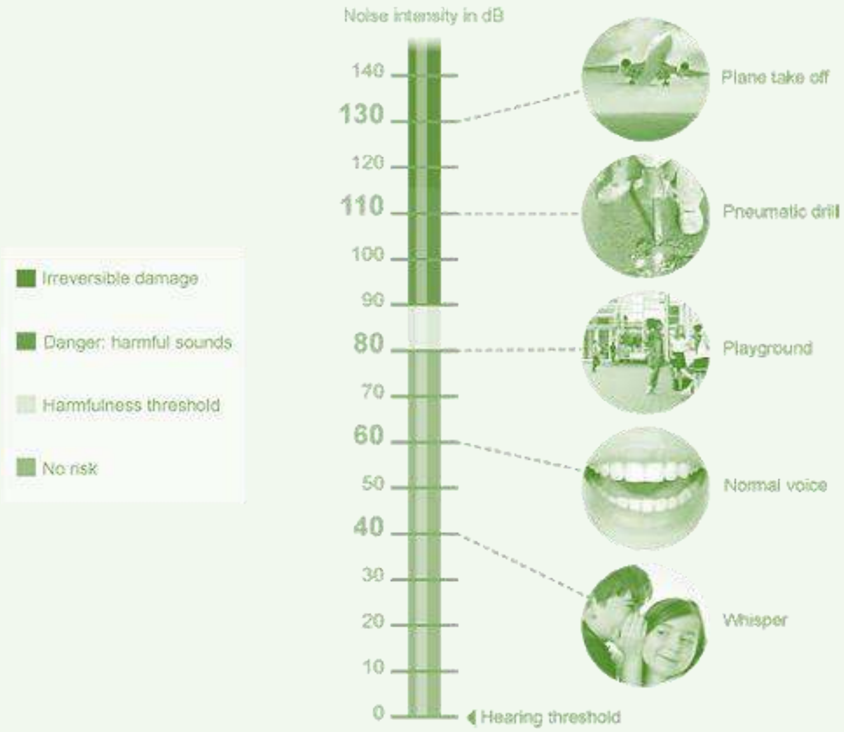


Figure 17 - Scale of auditory decibels and associated soundscape. A difference of 10 dB (A) allows to change the sound environment

Traditional noise barriers allow a noise reduction of ten decibels A. This corresponds to the difference that human beings perceive between the noise of a highway (70 dB) and a normal voice (60 dB). Some studies focus in increasing the performance of noise barriers by adding vegetation. It appears that a noise barrier with approximately 30 cm of vegetation on each of its faces reduces the sound by an additional 3 dBA. Vegetation can also be used directly as a noise barrier, in the form of an urban forest. The study (Ow and Ghosh, 2017) analyses the noise reduction resulting from urban forests along highways. It takes into account the porosity of the soil, the presence of plant cover, its density, its thickness, as well as the thickness of the trunks. The results show a reduction in noise of the order of **10 dB** in the most favorable cases, that is to say a medium to high density, a 20-meter-thick forest and 20-centimeter-thick trunks. It is also mentioned that the best cost / benefit balance is obtained with a 5-meter-thick forest. The study also reports the results of other studies, for example, indicating a reduction of 12 dBA by a 20-meter-thick urban forest. Performance is even better if the noise barrier forest is located less than 15 meters away from the road. Ultimately, **a Miyawaki forest is one of the favorable combinations** with its medium to high density. By the age of 15 the trunks can reach 20 cm thickness and can therefore place the forest in optimal conditions to reduce noise pollution. **Thus, an anti-noise forest continues to improve its performance from year to year as it develops. It represents an alternative to noise barriers or an inexpensive and aesthetically appreciated addition.**

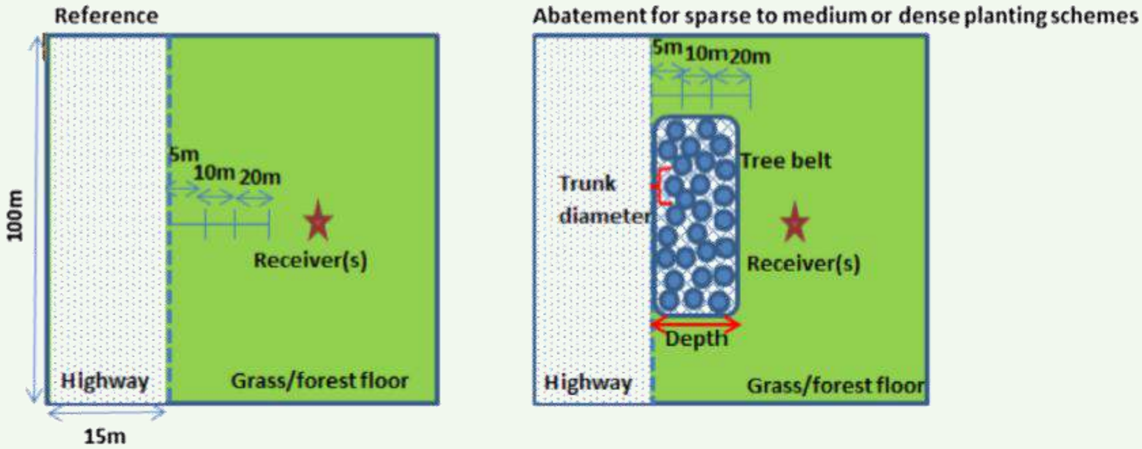


Figure 18 - Examples of reference and abatement experimental set ups for numerical predictions.

D. Health and well-being

The study (Donovan et al., 2013) reports on the consequences of the loss of 100 million trees in the United States because of the emerald ash borer. Data collected between 1990 and 2007 lead to the following conclusions: *"There has been an increase in mortality from cardiovascular and lower respiratory diseases in the counties infested with the emerald ash borer. The magnitude of this effect was greater as the infestation progressed and in counties with median household incomes above the average. In the 15 states in the study area, emerald cherry [loss] was associated with 6,113 additional deaths related to lower respiratory tract disease and 15,080 cardiovascular deaths. […] This finding is added to the growing evidence that the natural environment has major benefits for public health."*

The effects of a green setting (for example, an urban forest) on well-being are observed by studying the level of anxiety, stress, and depression. Among others:

• A study carried out in an underprivileged district shows a **drop in the level of stress hormone (cortisol)**: *''Results indicate significant relationships between self-reported stress (p <0.001), diurnal patterns of cortisol secretion (p <0.05), **and quantity of green space in the living environment**. Regression analysis indicates percentage of green space in the living environment is a significant (p <0.05) and independent predictor of the circadian cortisol cycle, in addition to self-reported physical activity (p*

<0.02). […] We conclude that salivary cortisol measurement offers considerable potential for exploring relationships between wellbeing and green spaces (…).'' (Ward Thompson et al., 2012)

• A recent study concluded on the importance of green spaces for mental health: "*The present study suggests a potential protective role of green spaces on mental health (depression and anxiety) in adults. Results also indicate that these associations are partly mediated by air pollution and in a lesser extent noise, whereas physical activity and social support seem to play a minor role. Also, we did not find evidences that the observed benefits are particular for certain subgroups of the society*." (Gascon et al., 2018)

• There are studies on the combined effects of sport and exposure to green areas. The study (Han, 2017) documents the well-being of students who have been running or walking in 40% wooded areas (natural environment). Control experiments are carried out in a city environment (built environment). In terms of increased well-being, sport accounts for 9.2% of the variance and nature accounts for 17.9%. **The combined effect of moderate physical activity and trees contributes for 58% of the total increase in well-being. There is therefore a synergy.**

Figure 19 - Photos illustrating visible greenness rate on the paths taken by the studied subjects, (Han, 2017)

Finally, urban forests also benefit people through the social events they generate, such as planting days. These events are environmental civism, defined as follows in the report (Townsend, 2006) : *''Collective voluntary actions carried out to promote the sustainability of ecosystems.''* Volunteers, including those from the Trust for nature foundation, were followed.

This series of studies (1, 2, 3, 4) systematically shows the presence of physical, mental, and social benefits.

World Health Organization element of health		Study 1	Study 2	Study 3	Study 4
Category	Specific benefit				
Physical	Increased physical activity→cardio-vascular benefits and improved weight control	✓	✓	✓	✓
	Respiratory benefits from opportunity to breathe 'fresh air'	✓	✓	✓	
Mental	Mental/spiritual wellbeing from shared fun with others	✓	✓	✓	✓
	Mental relaxation from bush land environment	✓	✓	✓	✓
	Reduced stress resulting from knowledge of support from other members	✓	✓		
Social	Sense of belonging and connectedness through membership of group	✓	✓	✓	✓
	Widening of the social circle of children and families through membership	✓	✓	✓	✓
	Opportunity for all people (young and old) to contribute and to enjoy the park	✓	✓	✓	

Figure 20 – Benefits of environmental civism for health, (Townsend, 2006)

Variable	TfN volunteer mean ($n = 51$)	Control group mean ($n = 51$)	Significance
General health (1 = v. healthy – 5 = v. unhealthy)	1.7	1.9	$p = <.028$
Annual doctor visits (1 = <1; 5 = >10)	2	2.9	$p = <.013$
Feel safe in area (1 = always; 5 = never)	1	1.3	$p = <.000$
Utilize life skills (1 = always; 5 = never)	1.4	1.8	$p = <.001$
Sense of belonging to community (1 = high; 5 = low)	1.4	1.7	$p = <.010$

Figure 21 - Differences in means on key variables in the study of volunteers for the Trust for Nature (TfN), (Townsend, 2006)

E. Biodiversity balance

A. Miyawaki (Miyawaki and Box, 2006) expresses the completeness of an ecosystem and its ability to regenerate from fragments: *''The variety of species in a biological community is called biodiversity, a term that emcompasses both the number of species (species richness) and some aspects of the relative abundance of the different species. A more comprehensive concept of biological diversity is that of* ***biological complexity****, which includes diversity not only in entities but also in the many functional relationships just suggested. No one creature monopolizes the available space and energy; rather, these ressources are shared. Thus, within the biological community, the habitats of the member populations are segrated, horizontaly and verticaly, according to each group's mode of life. For example, a forest consists of an overstorey tree layer, a ground layer of herbaceous plants, possibly a layer of mosses or lichens directly on the ground, and certainly an underground system of roots.* ***All these components, above and below ground, divide the living space three-dimensionlly and coexist*** *while competing with one another. To a certain extent,* ***a biological community can restore a destroyed portion of itself by re-forming its living environment anew*** *or by relocating itself.''*

The study (Sullivan et al., 2009) reports on this phenomenon by which the urban forest gains in biodiversity and subsequently serves as a reservoir and relay of biodiversity : *''Site colonization by native species was particularly high at sites ≤ 100 m from existing native vegetation, suggesting that* ***even small patches of native vegetation in urban landscapes will be valuable as seed sources for accelerating native plant establishment*** *at nearby receptive sites.''*

The previously cited study (4.E) conducted in the Netherlands on the Miyawaki forests of Zaanstad shows **an average biodiversity 18 times higher** in the two Miyawaki forests studied than in a conventional forest. Even though these Miyawaki forests (in green below) are very young, and the control forests (in brown below) are much older.

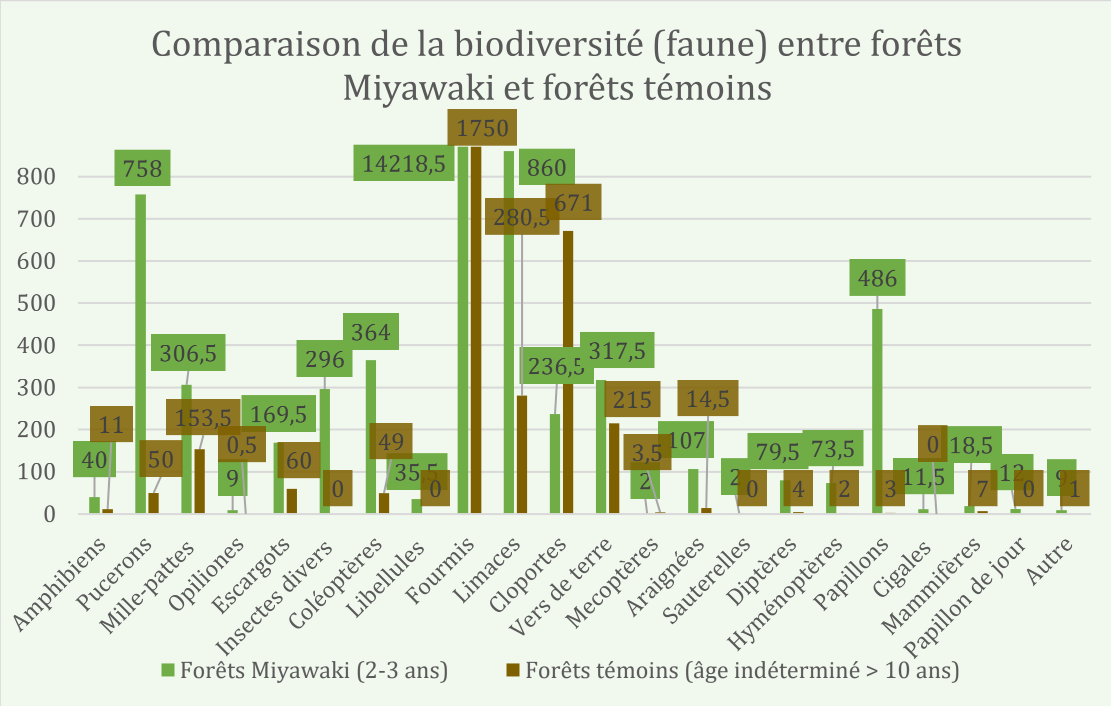


Figure 22 – Chart made from data from the report *(Alterra - Animal ecology et al., 2018)*

Furthermore, another study (Long et al., 2019) shows another advantage. In some cases, trees in the form of an urban forest host fewer invasive and parasitic species than single trees. Three positions were tested: isolated as decorative trees (landscape), on the edge of an urban forest (edge) and within an urban forest (interior). The following statement relates to a parasitic wasp of the hymenoter family.

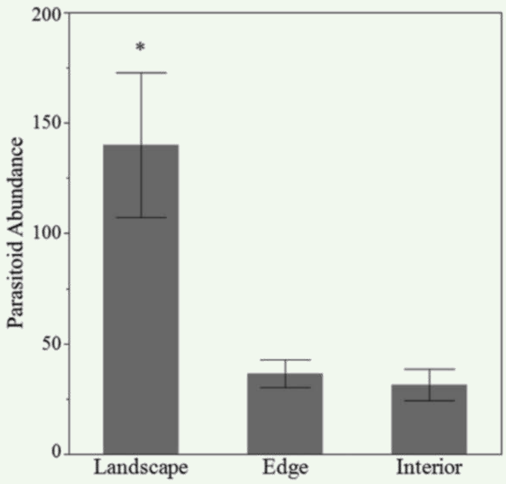


Figure 23 - Effect of tree position on parasitoid wasp abundance. The total number of parasitoid hymenopterans captured on sticky cards from three families (Aphelinidae, Encyrtidae, and Signophoridae) were more numerous in landscape trees (n=13) than either forest fragment edge (n=12) or interior trees (n=11). Post hoc nonparametric multiple comparisons from Steel-Dwass all pairs test. Asterisks indicate significant differences (P<0.05). Error bars represent +/-1 standard error of the mean. (Long et al., 2019)

F. Soils stability and natural disaster prevention

In his study (Miyawaki, 2014), Miyawaki observes native trees after the 2011 tsunami (photos below). He concluded on the protective role of native trees. The well-rooted trees served as protection, and their roots retained part of the soil (b) This is not the case for non-native conifers originally planted for protection (c), their weak rooting failed to resist and the trunks swept away by the tsunami created even more damage.

Figure 24 – (a) General view after the 2011 tsunami (b) A native tree and its root system that enabled it to resist and maintain the soil (c) Protective conifers that did not fulfill the intended function (Miyawaki, 2014)

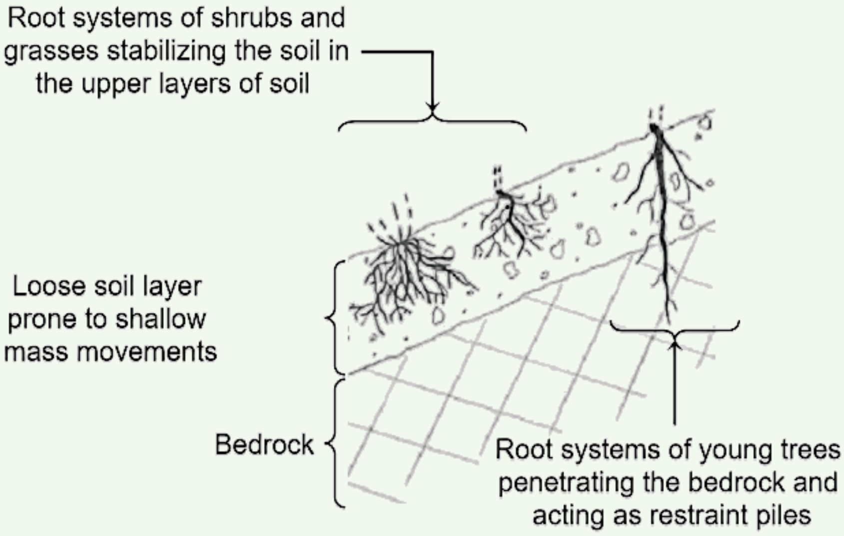


Figure 25 - Schematic representation of the combined effects of trees, shrubs and herbaceous species in their early stages of development on the stabilization of surface slopes

According to (Burylo et al., 2011) fine roots are proportionally more resistant to tensile forces due to their elasticity. Large diameter roots can withstand higher absolute forces but are more rigid and brittle. Diversified vegetation forms a complementary matrix-pillar system, by entangling the horizontal and pivot root systems. The study concludes on the interest of taking vegetation into account in the study of soil stability: *''Combined with the knowledge on vegetation dynamics, ecological site properties and species resistance to erosion, these results can help in evaluating land vulnerabilty to erosion and the efficiency of restoration actions in eroded marly lands.''* (Burylo et al., 2011)

G. CO2 balance sheet

Forests are the second largest carbon stock on Earth after the oceans. For a given area in France, forests absorb each year 15 times more carbon than meadows. The recent report (“La séquestration de carbone par les écosystèmes en France,” 2019) **of EFESE (French Assessment of Ecosystems and Ecosystem Services) on carbon sequestration indicates the following figures:**

Table 1 – National carbon sequestration data

Metropolitan French forests (biomass + soil)	EFESE 2019 values	Units
Surface	17 158 000	ha
Carbon stock	10 263 000 000	tCO2eq
Sequestration flow	87 000 000	tCO2eq/an

The following terms are defined as such:

- **The current carbon stock in situ**: this is the average amount of carbon contained in the compartment [in this case the forest ecosystem] considered as observed today (in tCO2eq / ha).

- **The current sequestration flow**: it is the average annual carbon sequestration flow in the compartment [in this case the forest ecosystem] considered, as it is currently observed (in tCO2eq / ha / year).

These data take into account the role of forest soil in carbon retention.

It can be noted that these average values bring together those of different types of forest ecosystems: *”Thus, in the continental biogeographical region, carbon stocks in deciduous closed forest are among the highest, of the order of 730 tCO2eq / ha whereas those in the Mediterranean biogeographical region, notably made up of low-productivity holm oak coppices, have much lower carbon stocks, of the order of 500 tCO2eq / ha.”* (“La séquestration de carbone par les écosystèmes en France,” 2019)

The values of the EFESE flows were compared with the values of a similar Inra survey, and with the values of the UTCATF national inventory (Land use, land use change and forestry) that did not take into account the impact of the soil. Aside from assumption differences, values are close for each category.

MtCO2eq/year (M=million)	Total flow	Dead wood and soils flow	Biomass flow	Land use change flow
EFESE	86.8	21.8	65	0
Inra (2017) for 2013	88	17.6 (dead wood 10.3 ; soils 7.3)	70.4 (broadleaves 56 ; conifers 14.4)	
UTCATF	62	0	55	7

Figure 26 - Comparisons of major data on carbon sequestration flows in a forest environment (“La séquestration de carbone par les écosystèmes en France,” 2019)

The following table displays the results of calculations for a Miyawaki forest of medium age, with an area of 100 m², soil sequestration included:

Table 2 – Carbon sequestration data applied to a 100 m² Miyawaki forest

100 m² Miyawaki forest	Values calculated from EFESE 2019 values	Units
Surface	100	m²
Carbon stock	5980	kgCO2eq
Sequestration flow	50,7	kgCO2eq / year

According to these data, **the biomass and soil of a Miyawaki forest of 100 m2 and of average age (a few decades)** therefore represents **a stock of 5980 kg of CO2 equivalent, i.e. two thirds of annual carbon emissions of a European person** (average: 8400 kg of CO2 equivalent / person / year in the EU), or even the total annual carbon emissions of a Swedish. ("Empreinte carbone − Indicateurs de richesse nationale | Insee," n.d.). **In other words, a European with very reasonable emissions can hope in the long term to offset one year of carbon emissions per 100 m² lot of planted Miyawaki forest.**

After stabilization, **the micro-forest sequesters 50.7 kg of additional CO2 equivalent each year, the equivalent of the carbon emissions of a European over more than two days.**

These calculations readily overlap with a figure regularly cited by the ONF (Office National des Forêts): a 5 m³ tree can store 5 tonnes of carbon. However, a Miyawaki forest represents, according to estimates, around 400 m³ / ha of tree biomass after about fifteen years. Which is 4 m³ per 100 m², so a stock of 4 tonnes of CO2 equivalent (a lower figure because the soil action is not taken into account).

The study from (Nowak and Greenfield, 2010) et (Nowak et al., 2013) is also very popular but does not incorporate the storage of forest soils either. Annual sequestration is estimated from the total carbon accumulated during tree growth, subtracted from the estimated amount of carbon lost during decomposition of dead trees. The average annual value of total carbon accumulated as a stock by urban forests in the United States is 7.69 kgC / m2 of forest cover (standard error (SE) = 1.36 kgC / m2). Estimates of annual sequestration (flow) vary according to the length of the growing seasons, the average value is 0.226 kgC / m2 / year (SE = 0.045 kgC / m2 / year). Values range from 0.430 kgC / m2 / year (Hawaii) to 0.135 kgC / m2 / year (Wyoming).

H. Impact on real estate prices

A study (Escobedo et al., 2015) conducted in Florida screens the impact of different vegetation types on real estate prices : "*Results, on average, indicate trade-offs in that more trees with greater Leaf Area Indices (LAIs) [Individual LAI is the amount of one-sided leaf surface area (m2) over ground unit area (m2) and is often used as a proxy for the amount of tree crown density and overall tree health] add to property value, while biomass and tree–shrub cover have a neutral effect, and replacing tree with grass cover has lower value.* ***On average, property value increased by $1586 per tree and $9348 per one-unit [400 m2] increase in LAI****, while increasing maintained grass from 25% to 75% decreased home value by $271." (Escobedo et al., 2015)*

Hence, the presence of a tree cover in the properties increases their price by several thousand euros.

In Europe, climate change is increasing the average temperatures in certain areas, especially during summer. The results put forward by this study of subtropical Florida may then be relevant in a European context.

7. Tree exchanges

Recent report (Fournier and Moulia, 2018) takes stock of current knowledge regarding tree communication: *''**The messages sent are, for example, electric signals transmitted inside the plant, or chemical substances diffused to other parts of the plant**. The most spectacular are the alert messages: for example, when a leaf is attacked by a caterpillar, a molecule, the systemin, is transported by the sap, and quickly warns the other leaves which can set up defense reactions, for example by producing substances toxic to the animal. These chemical messages are also volatile substances released into the air, which warn other plants or attract caterpillar predators. If we consider that communication is the emission of a signal followed by its reception inducing a change of attitude, we can speak of plant communication.''*

Trees can also transfer water to each other, through their roots or connecting fungi networks: *''We found up to 21.6% of the water in a seedling could be supplied by HR from a source tree. The average value was substantially lower, only 1.8% after two weeks and 4.9% after three weeks. This is an approximate estimate […] but it does highlight the potential importance of HR for seedlings surrounding residual trees.''* (Schoonmaker et al., 2007) **It can be estimated that hydraulic redistribution is usually low, but it can reach up to 20% when stress occurs.**

Also, there are some **carbon (C) transfers.** Carbon is an essential element for green plant storage and energy: *''We showed that mycorrhizal networks exist in tundra, and facilitate belowground transfer of C among Betula nana individuals, but not between or within the other tundra species examined. **Total C transfer among conspecific B. nana pairs was 10.7 ± 2.4% of photosynthesis, with the majority of C transferred through rhizomes or root grafts (5.2 ± 5.3%) and mycorrhizal network pathways (4.1 ± 3.3%)** and very little through soil pathways (1.4 ± 0.35%).''* I *''Below-ground C transfer was of sufficient magnitude to potentially alter plant interactions in Arctic tundra, increasing the competitive ability and mono-dominance of B. nana. C transfer was significantly positively related to ambient temperatures, suggesting that it may act as a positive feedback to ecosystem change as climate warms.''* (Deslippe and Simard, 2011) While a laboratory experiment, similar observations have been recorded for different species (diagram below).

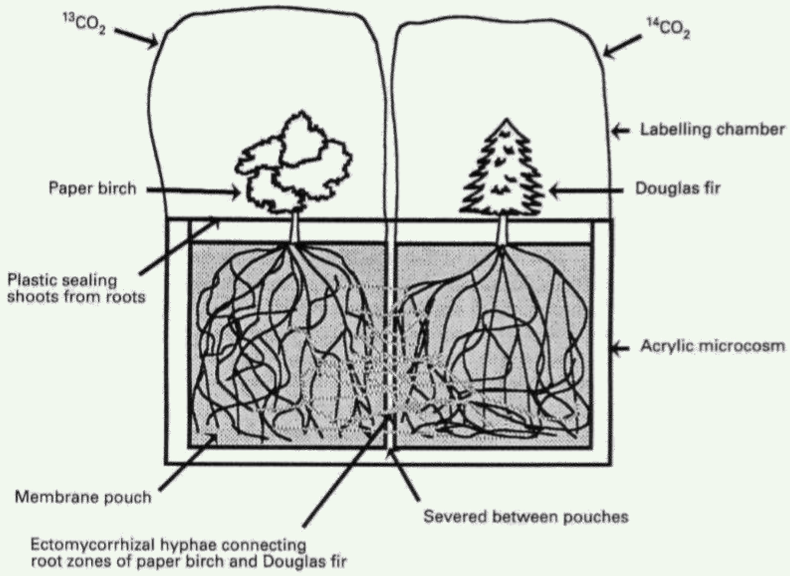


Figure 27 - Microscosms and labeling chambers. The gas (carbon dioxide) marked by two different isotopes is injected into each room (one type per room). Carbon progression is recorded, leading to the observation of carbon transfers between the two species via mycorrhizal networks.(Simard et al., 1997)

As mentioned above, mushrooms are connected to trees in the form of mycorrhizal networks, themselves connected to each other, thus connecting the trees together. The mushrooms serve as root extension. **The oldest trees often have very developed mycorrhizal networks, allowing them to be strongly connected to the trees of the forest, they are called central trees or mother trees.** The study (Beiler et al., 2015) is interested in the complexity of these networks, illustrating the concept of central tree by surveying the DBH (diameter) of trees correlated to their age, and their degree of connection (node degree). **Within the same species, the more mature the tree, the higher its degree of connection to others.**

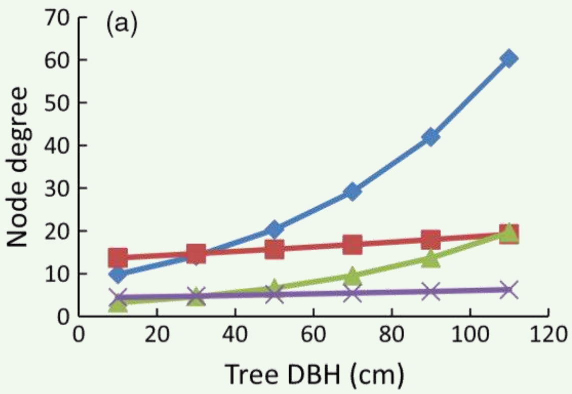


Figure 28 - Large mature trees acted as hubs with a significantly higher node degree than smaller trees. The colors correspond to different types of soil and fungi, we observe an increase in all cases even if subtle for two cases.(Beiler et al., 2015)

The following study illustrates forest tree networks with schemes:

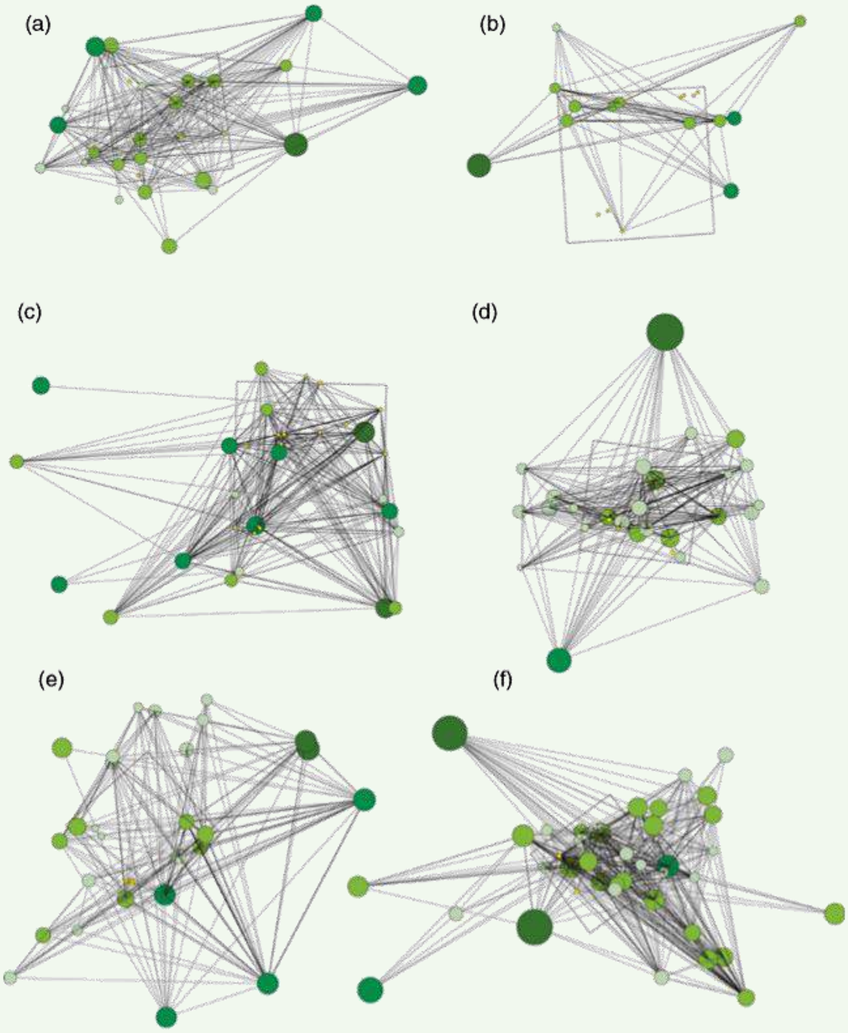


Figure 29 - Network models depicting the socio-spatial topology of tree-mycorrhizal fungus interaction networks in 100 m plots with xeric (a-c) or mesic (d-f) soil moisture regimes (squares show plot boundaries, models shown at different scales). Nodes (circles) are Psuedotsuga menziesii trees, sized relative to tree diameter and darkening in colour with increasing age class, and links represent the number of Rhizopogon spp. genotypes shared between trees (shown by line heaviness). (Beiler et al., 2015)

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