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LECCIÓN MAGISTRAL DE HANS PRETZSCH

Integrative ecosystem management through the diversification of structure and tree species

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Contents

1 Increasing requirements regarding the functions and services of ecosystems. Criteria for sustainable ecosystem management
2 Diversification of structure and species
3 Reorientation of forest science towards more diverse systems. From measurement to modelling and silvicultural prescriptions
4 Revealing mechanisms of competition, competition reduction, and facilitation
5 Cross-sectoral perspectives. There is only one biodiversity, one carbon, one health, one sustainability
6 Acknowledgements
7 References
8 Picture credits
9 Affiliation

Abstract

The history of systematic forest science is wood-centered, dominated by monospecific stands, and the homogenization of forests. Recently, demands on the forest have become very extensive and multi-criteria. The agricultural and urban greening sectors are facing similar challenges such as promoting biodiversity, increasing carbon stock, improving social services like landscape esthetics, human recreation, and health.
In the first part will be shown that diversification of forest structure and species mixing can improve many ecosystem functions and services including productivity. In this way diversification paves the way to integrative forest ecosystem management.
Second, will be stressed the need for information for establishment, planning, and steering of more complex forest stands. I address the need for long-term experiments to acquire knowledge of structure and growth dynamics of mixed-species stands. I will emphasize and prove the need for statistical models for scenario analyses and planning, and further show the need for simplified silvicultural prescriptions for feasible operational implementation and teaching and training tools such as marteloscopes.
Third, is shown that the size ratio of humans and trees makes forests an ideal system to analyze and model tree-tree interactions such as competition, competition reduction, and facilitation. Forest scientists can enter forests and measure individual trees, their size, position, inclination, distances and also their interactions with other trees, including

competition and facilitation nearly without disturbances, without artifacts. Thus, recent studies found that structural diversity can improve productivity and is even a better predictor of forest productivity than tree species diversity. Mixed species stands can be more heterogeneous, and their canopies by 10-30 % more densely packed, than monocultures. Competition reduction and facilitation can increase mixed species stand productivity by up to 50 %.

As perspective I underline that there is no isolated forestry biodiversity, agriculture biodiversity, urban biodiversity. There is no isolated forestry health, agricultural health, or urban health. There is only one biodiversity, one carbon cycle, one health, and also only one sustainability. This suggests a cross-sectoral diversification. Recognizing the "One Biodiversity, One Carbon, One Health" paradigm and re-opening the borders between the established sectors to work towards common research, teaching, training, and planning is a great, innovative, cross-sectoral perspective.

Estimado Rector Magnífico,
Estimados miembros del Consejo Rector de la Universidad de Valladolid,
Estimado Laudatário,
Señoras y Señores,

...como todos ustedes bien saben, la ciencia es trabajo, trabajo y más trabajo.
Y de pronto, uno recibe una condecoración. Es un gran honor para mí y una gran motivación estar aquí hoy. Me siento muy orgulloso, ¡Muchas gracias!

Desde hace tres años, durante unas semanas en primavera y en otoño, trabajo con el grupo del catedrático Felipe Bravo en el Campus de Palencia.
En la Universidad Técnica de Múnich trabajo como en un grande y pesado petrolero.
Sin embargo, cuando vengo aquí, me siento como en una lancha rápida y ligera.
Aquí siempre encuentro una atmósfera innovadora e inspiradora.

Doy las gracias a los hermanos Andrés y Felipe Bravo Oviedo y a Miren del Río.
Ellos iniciaron esta cooperación a través de su red internacional.
Doy las gracias también a mi esposa Martina Mehring por su comprensión, quien a veces también me acompaña y está hoy aquí conmigo.

Estar tan a gusto aquí, no es solo por la pasión académica y la cooperación.
Es también debido a la personalidad de las gentes, los austeros paisajes, la ancestral historia… ...y ahora, mi tardío amor por España, y por Castilla, recibe además este especial reconocimiento

Los alemanes tienen fama de que les encantan los premios, las medallas y las condecoraciones.
En Alemania existen más de tres mil quinientas (3500) condecoraciones.
Pues, como buen alemán, me alegra enormemente la gran distinción que hoy recibo de esta universidad.

Me alegro, de forma personal, pero también por mi campo, las ciencias forestales.
La ciencia forestal es: el sector primario, las botas de goma, somos habitualmente los "underdogs" en el mundo científico moderno…. igual que las ciencias agrarias.
… y aquí y hoy, donde se condecora a la Política, la Economía, la Literatura, la Historia…
... como científico forestal me siento profundamente honrado y agradecido.

Discúlpenme, por favor, mi reducido español es suficiente para sobrevivir en el campo, en el bosque o el día a día en el campus de la Universidad.
No lo es tanto para una presentación científica. Por ello, continúo en inglés.

1 Increasing requirements regarding the functions and services of ecosystems. Criteria for sustainable ecosystem management

The history of systematic forest science is dominated by monospecific stands and the homogenization of forests (Yaffee 1999). The main reason is that inventory, planning, forest utilization, and processing of wood products from homogenized, domesticated ecosystems seems easier compared with heterogeneous forests (von Gadow et al. 2016). Even the concept of sustainability has been developed primarily for sustainable wood supply (von Carlowitz 1713) and is now extended to a broader set of ecosystem services and functions and to nearly all fields of existence (Lüttge 2024).

Many of today's forest scientists were socialized in monocultures. Figure 1 shows a Norway spruce monocultures established for wood production after World War II far beyond the natural range of this species. In this stand the speaker is at the age of 2 playing with two of his older brothers.

Figure 1: Typical Norway spruce monocultures established for wood production after World War II far beyond the natural range of this species. The PhD candidate of today was socialized by and in monocultures. Here he is at the age of 2 playing with two of his older brothers in summer 1959.

So, in the past the wood production was the main goal of forest management, and it certainly still plays an important role. But nowadays we expect much, much more from forests then in the past. These multi-criteria expectations and objectives of forest management are well reflected by the six criteria of MCPFE (2006) shown in Figure 2.

- Maintenance of the forest area and stock (forest area, carbon stock, standing volume…)
- Health and vitality (tree mortality, crown defoliation, deposition…)
- Forest growth, yield, wood production (annual growth, annual cut, assortment yield…)
- Biological diversity (landscape fragmentation, deadwood, species richness…)
- Protective functions (climate smartness, area for water protection, protection against erosion…)
- Socio-economic functions (financial yield, number of employees, esthetic and recreational value…)

Figure 2: For integrative management the European states agreed on the 6 criteria (MCPFE 2006, Helsinki-Geneva-Warsaw process) and selected indicators in brackets.

The forest monocultures of the past centuries hardly match these criteria of sustainable forest management and the six respective criteria (Figure 2). After World War II deforestation, urgent need of building material, lack of suitable seeds or plants for other species than spruce and pine, resulted in the establishment of extensive unnatural monocultures. Such monocultures reduce biodiversity, forest health and vitality, but also carbon storage. Frequently calamities caused by fire, drought, storm, snow, late frost or bark beetle damage especially artifical monospecific stands (Griess et al. 2012, Knoke et al. 2008). One well knows these reports from all over the world, acid rain in Central Europe and Scandinavia, storm damages in France, Switzerland, Germany, bark beetle and mountain pine beetle in Europe and North America, drought damages in nearly all over the globe (Figure 3).
Many monocultures as products of the green revolution in agriculture and horticulture also do not match the modern criteria of sustainable management in agriculture. Reduced biodiversity, loads of pesticides, antibiotics, and water quality reduced by nitrate are a topic. Maybe, such moncultures fullfil the economical objective of an individual enterprise. But they often neglect the goals of national, political economy for a country or a continent. The same applies to many monocultures in horticulture where a risk distribution might reduce damages by virus or bacteria (Paut et al. 2019).

Figure 3: Monocultures, especially when cultivated beyond the natural range of the respective species, proved to be more susceptible to among other acid rain, storm, bark beetle calamities, and drought.

Although in the past there was often hardly any alternative, presently the existing monocultures get strongly criticized. Those disadvantages of monocultures brought the whole green sector into disrepute and under suspicion of ignoring sustainability, although the paradigm of sustainable management originated from there (von Carlowitz 1713).

Following Rousseau (1762) it is debated that nature without human interference may do best (Rousseau 1762) and huge proportions of the landscape may be entirely protected (EEA 2023).

2 Diversification of structure and species

Recently there is a tendency to replace monocultures by mixed species systems (Figure 4) that show advantages such as higher C-storage, resilience against drought, or biodiversity and can even overyield monocultures (Locatelli et al. 2015). Monocultures are certainly easier in terms of establishment, planning, utilization, technology; however, diversified, mixed systems pave the way to integrating various ecosystem services including acceptance by the public (Huuskonen et al. 2021).

Figure 4: Transition from mono-specific to mixed species stands (from left to right). Presently more diverse forest stands are on the rise in science and forest practice.

What is meant by diversification in this context: The classical age class system of monocultures (Figure 5a) may be further developed towards uneven-aged monocultures (Figure 5b). Uneven-aged mixed stands may result in selection forests which are very stable, productive, and beautiful (Figure 5c). Here the trees are no longer growing in cohorts of different ages, but all ages are combined in the same stand. In the figures trees of different ages are represented by different symbol sizes. Figures 5, b-c visualizes diversification of structure or tree species within a stand.

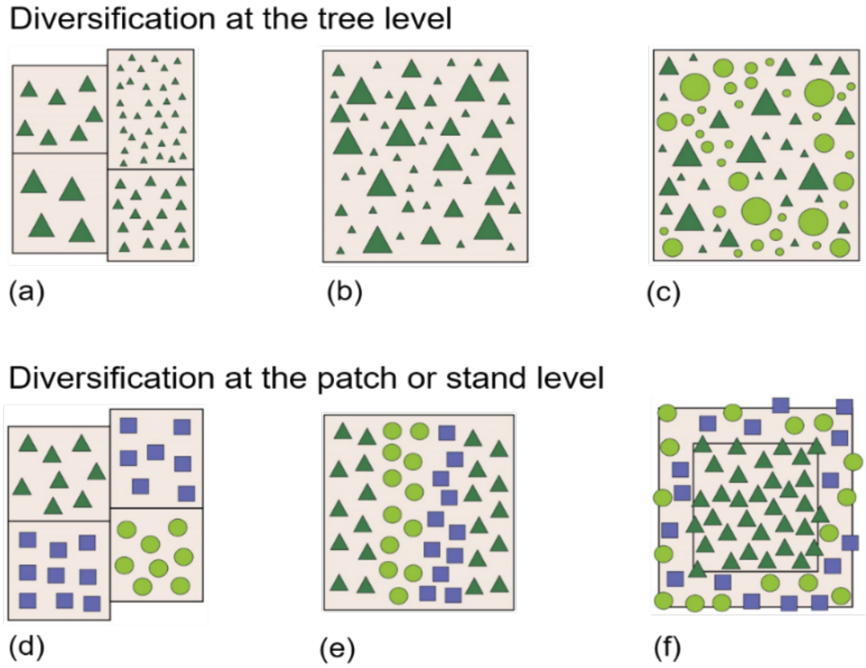


Figure 5: Diversification can be achieved at the (b-c) tree level within a stand or (d-f) at the stand, strip, or framing level (according to del Rio et al. 2016 and Jactel et al. 2017).
Another promising option is the diversification at the stand, patch, strip or framing level. A mixed pattern of monospecific areas no matter whether in squares, stripes, patches can diversify, create barriers against insect attacks, positive interactions in terms of matter cycle, biodiversity, esthetic and risk reduction (Zhai et al. 2022, Jactel et al 2018). Examples are combinations of squares, strips, framings (Figure 5, d-f). In all cases interactions between trees of different sizes or species come into play, at tree, patch, or stand level.
Similar tendencies of mixing are in progress in agriculture, e.g. nitrogen fixing tree species are mixed with non-nitrogen fixing ones to harness facilitation and reduce fertilization, called new green revolution by Martin-Guay et al. (2018).

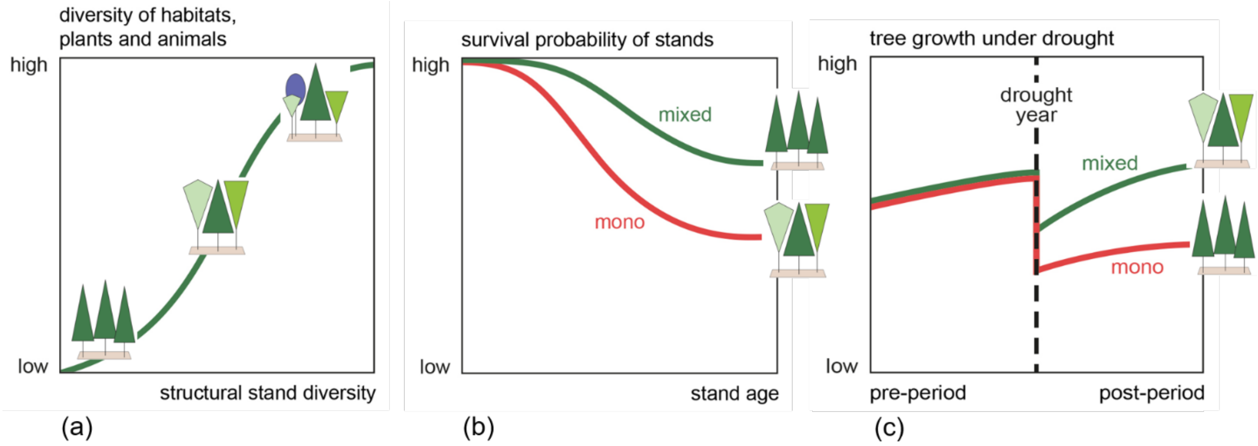


Figure 6: Diversification of structure and species can significantly increase (a) biodiversity, (b) survival probability of stands when affected by storms, pathogens, and (c) drought resistance (according to Begon et al. 1998, Paul et al. 2019, and Pretzsch et al. 2013).

Interestingly, diversity of structure and species promote most of the six criteria demanded by modern forest management. Figure 6 shows three examples. Many works show that structural diversity has mostly a positive effect on plant and animal biodiversity (Begon et al. 1998, Dieler et al. 2017) as shown schematically in Figure 6a. And the biodiversity can stabilize ecosystem functioning and integrity. Species diversity by tree species mixing can reduce the risk of storm damages (Paul et al. 2019) as shown in Figure 6b for mixed stands of Norway spruce and European beech. Figure 6c shows that resilience against drought stress can be improved by tree species mixing, due to spatial or temporal complementarity of resource use (del Rio et al. 2017, 2022, Pardos et al. 2021), hydraulic lift (Pretzsch et al. 2013, Hafner et al. 2017), or shading (Grote et al. 2016, Pretzsch et al. 2018, 2022).

Many recent studies show that species diversification can even increase the growth in terms of stand productivity, i.e. *the* classical forest ecosystem service (Jactel et al. 2018, Pretzsch and Schütze 2009, Kelty 1992). Due to a lack of multi-species experiments the mixing effects were mainly shown for two-species mixture in even-aged stands.
The productivity of the mixed stand of different mixing proportions often exceeds the weighted mean of the two mono-cultures, which is called overyielding (Figure 7a). Overyielding was found to be 10-30 % (Pretzsch 2016) in common mixtures and up to 50 % in mixtures with atmospheric nitrogen fixing tree species (Forrester et al. 2006). This means an increase without fertilization, tending, or continuous thinning. It is essential to realize this potential of tree species mixing. The overyielding can be harnessed just by knowledge-based design: by establishing the right species ensemble.

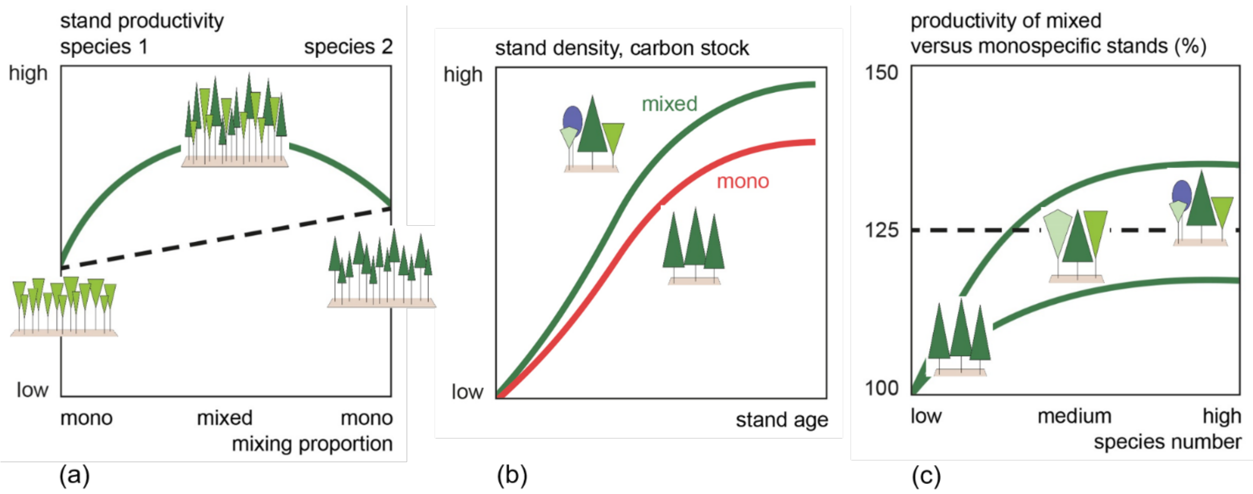


Figure 7: Tree species mixing can cause overyielding in (a) two-species stands, (b) higher carbon stocks, (c) even higher overyielding in multi-species stands (according to Forrester and Pretzsch 2015, Pretzsch and Biber 2016, Liang et al. 2016)

Overyielding is partly based on a higher tree packing density in mixed compared to monospecific stands (Pretzsch and Biber 2016). Due to complementarity in space and resource use, more trees can survive and grow in mixed compared to monospecific stands (Pretzsch 2014). The maximum stand density can be higher. This also means a higher carbon-storage capacity of mixed stands compared with monospecific stands especially in older ages (Kobler et al. 2024, Hulvey et al. 2013) as shown in Figure 7b. Strong crop tree thinning, for example, can certainly reduce the density in a way that the mixing effect in terms of density increase is “thinned away”. But mixed stands have the potential to have higher stocks of volume or carbon. Long-term tree species mixing experiments with more than 2 species are very rare (Bravo-Oviedo et al. 2018). Several research institutions now start to establish such experiments; but it needs some survey time until the first results will be available. As a substitute forest inventory data are presently used for getting insights into the effect of multi-species mixtures. A study by Liang et al. (2016) based on worldwide national forest inventories showed an asymptotic increase of stand productivity with increasing tree species number (Figure 7c). With increasing species number, the effect of niche complementarity if another species is added decreases. The redundancy of species functions and traits increases and also the marginal benefit in terms of stand productivity (Marquard et al. 2009, Hooper 2004).

Diversity of structure and species’ promoted many ecosystem services and functions: biodiversity, drought resilience, forest health. But it also can improve classical aims such as productivity and carbon sequestration. Diversification by spatial or temporal combination of different plant species or farm animals at the stand or landscape level can be a strong tool of integrating various ecosystem services including nature conservation and production (Harvey et al. 2008). In this way diversity paves the way to integrative forest ecosystem management. This means integration of multiple forest functions and services on large areas and not segregation, which would mean conservation, national parks here versus high intensive wood production plantations there (Figure 8).

(a)

(b)

Figure 8: Concept of Integration versus Segregation. (a) Integrative forest ecosystem management. (b) Segregation of unmanaged and managed forests.

Segregation would mean that large proportions of the landscape may be entirely protected while others may be managed intensively (Pittelkow et al. 2015, Bollmann and Braunisch 2013, Milad et al. 2011). An alternative to this segregation is the integration of both nature conservation and food or wood production (Ma and Zhuge 2024, Boncina 2011). Certainly, the integration by diversification can also have disadvantages, such as the need for more sophisticated and expensive planning tools, or wood quality reduction due to more heterogeneous structure, or challenges for forest utilization and product transport in diverse forests.
However, in densely populated areas in Europe where people use the agricultural and forest areas for both livelihood and recreation, humans are an important part of the system, and the option of segregation and set-aside is questionable. In such areas ecosystem services such as recreation value, esthetics, biodiversity, food and wood production are rather required on larger areas, and integration of sustainable management and conservation, forestry and agriculture have a high potential of reconciling various needs and stakeholders (Aggestam et al. 2020).

Interim summary 1: Demands on the forest have become very extensive and multi-criteria. Diversification of structure and species mixing can improve many ecosystem functions and services including stand productivity. In this way diversification paves the way to integrative forest ecosystem management.

3 Reorientation of forest science towards more diverse systems. From measurement to modelling and silvicultural prescriptions

To date, the majority of methods and tools in forest science have been developed for homogeneously structured monospecific stands. This applies to models, simulators, and silvicultural prescriptions as well as demonstration plots and model forests (Bravo et al. 2019, Pretzsch et al. 2017). However, these methods and tools require adaptation to more diverse stands. This is because mixed species stands do not act like the weighted mean of monocultures. Instead, they exhibit synergistic and multiplicative effects regarding ecosystem functions and services.
Long-term experiments in mixed stands are scarce. Thus, recent studies have frequently relied on inventory data or temporal triplets along ecological gradients to acquire information. However, inventory plots cannot reveal defined thinning effects (Figure 9a); and triplets along gradients often represent only medium stand ages (Figure 9b). Therefore, in the long term, only experimental plots that address experimental factors such as site condition, species combination, stand density, and mixing pattern can help us fill existing knowledge gaps (Figure 9c). Figure 9c shows an innovative experimental setup for promising tree species combinations that has now been established across various Central European countries.

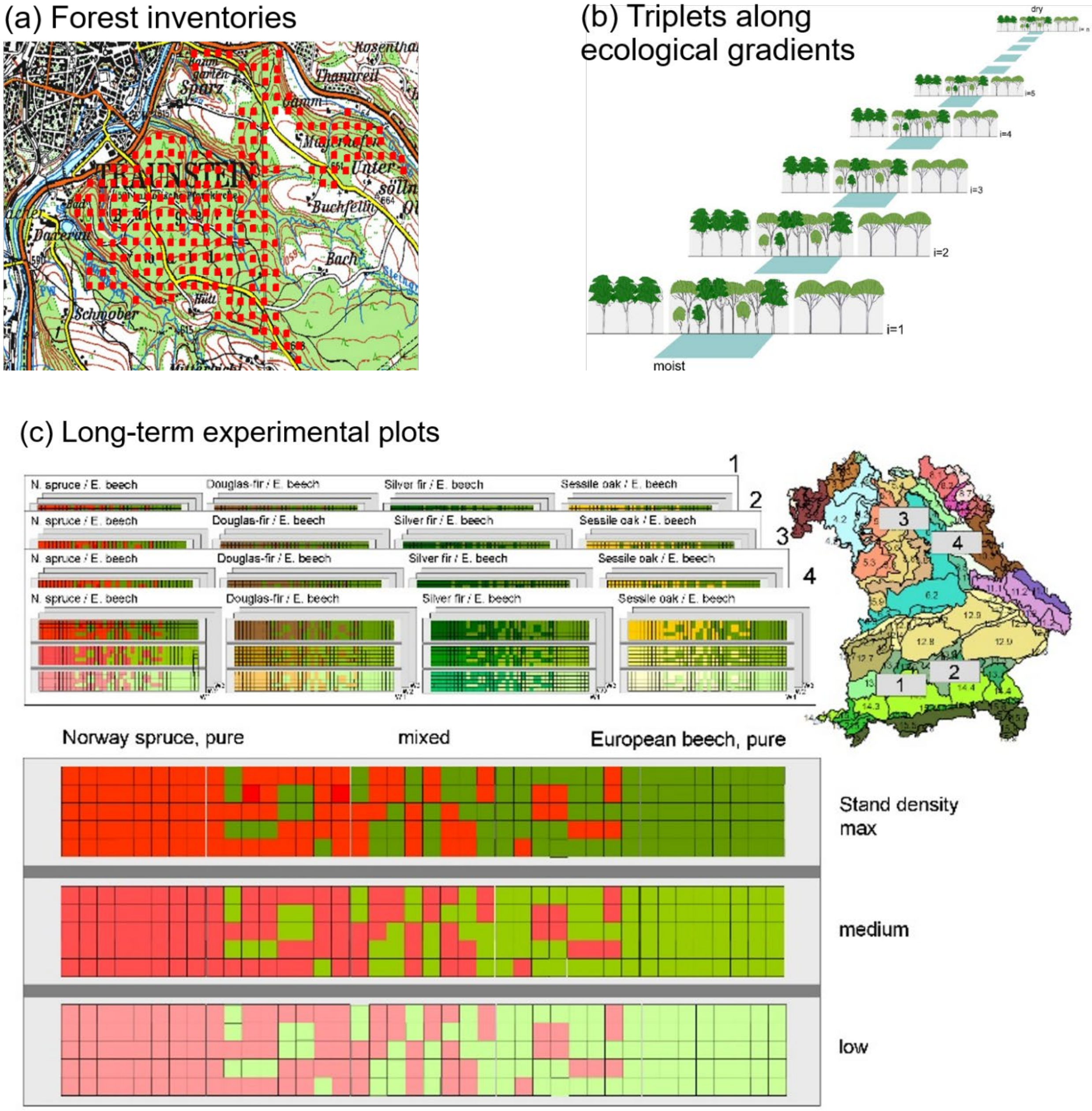


Figure 9: Leveraging inventory data (a), temporary plots (b), and especially long-term experiments (c) to advance our understanding of mixed stands (Pretzsch 2019).

Importantly, once new knowledge regarding mixed stands’ behavior has been acquired, it needs to be integrated into simulation models (Bravo et al. 2019) for scenario analyses (e.g., scenarios of different silvicultural prescriptions) and forest management planning (e.g., assessing what constitutes a sustainable annual cut). These models may be set up using information regarding forest structure and diversity derived from current inventories (Figure 10, left). Their output should include information concerning production, ecology, and socio-economy (Figure 10, right). Taken together, this may enable us to analyze different silvicultural treatment options (e.g., setaside, thinning from above, selection thinning) in terms of the above mentioned six criteria of sustainable ecosystem management (Figure 2).

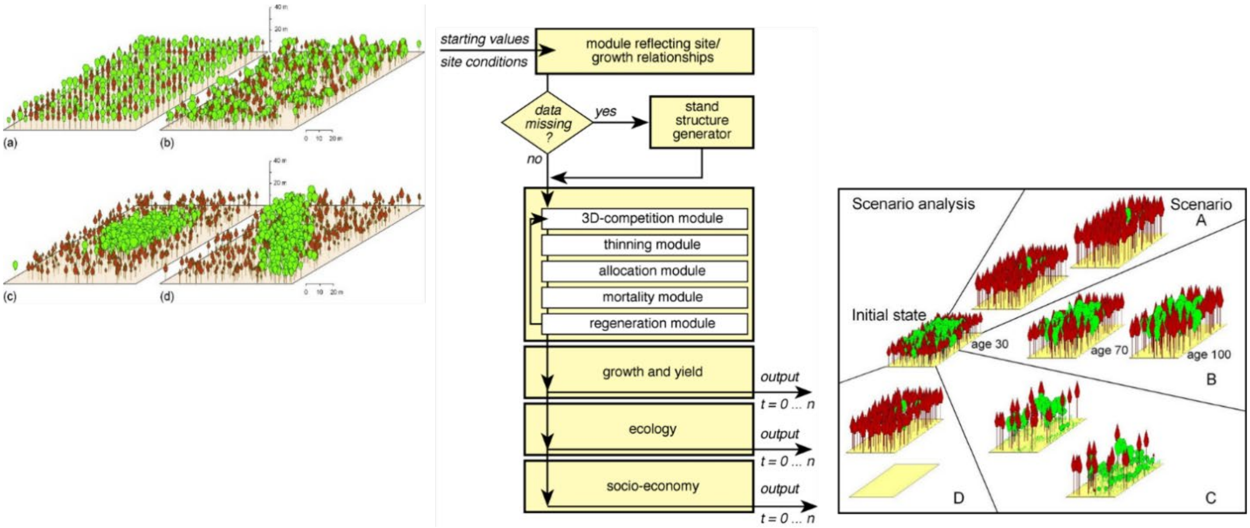
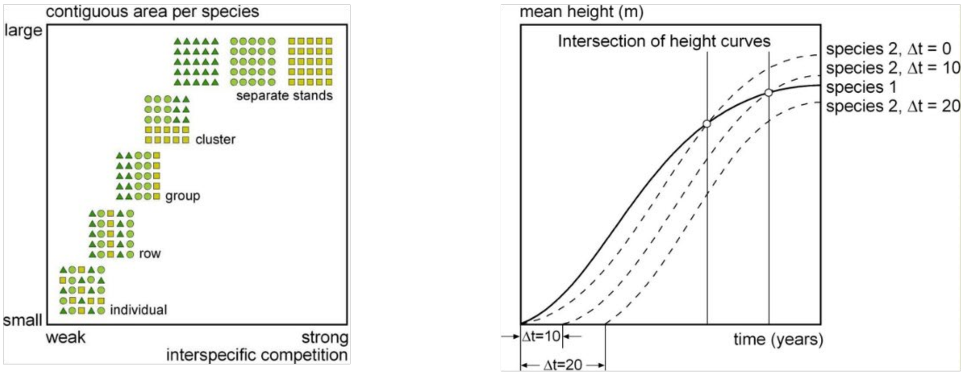


Figure 10: Models for knowledge integration, scenario analyses, and forest management planning (according to Pretzsch 2009).

Finally, we require simplified silvicultural prescriptions which, among other things, help us analyse how best to mix species in space and time (Figure 11a), how to thin in order to maintain the mixture, or how to transfer existing monocultures to mixed species stands.

For training and teaching purposes, marteloscope plots can be useful (Figure 11b). They combine real, existing forest stands with digital twins: the stand is spatially represented in a handheld computer. Specific trees can be selected for thinning on the plots and marked in the computer. The computer can then simulate the effect of these thinnings and compare different options regarding multiple criteria. This approach can reveal the effects of different management variants (e.g., spacing, thinning, mixing, final harvest, regeneration) on structure, diversity, growth, C-storage etc. The marteloscope approach is suitable for teaching integrative forest management and its beneficial effects on ecosystem services (Krumm et al. 2019, Soucy et al. 2016). Figure 11b shows marteloscopes in Krumbach/Germany and Portillo/Spain. The marteloscope approach might be extended to agro- and agroforest systems.

(a) Silvicultural prescriptions how to mix in space and time



(b) Marteloscopes in Spain and Germany for teaching and training

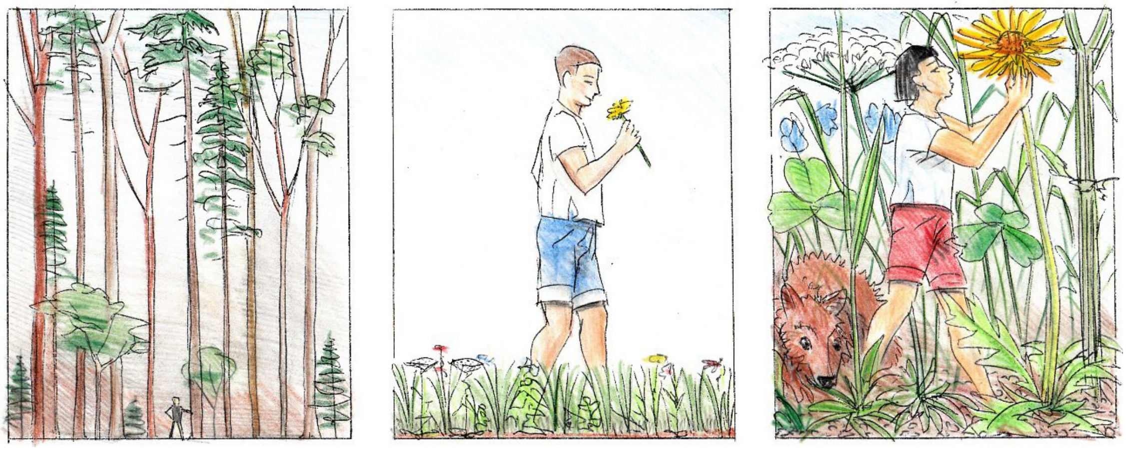
Figure 11: Demonstration plots and marteloscopes for training and teaching. (a) Douglas-fir- beech-in Krumbach/Germany and (b) juniper-pine-oak close to Portillo/Spain.

Interim summary 2: Forest owners need information to make decisions; and there is a lack of such information for planning, establishment, and steering of more complex forest stands. We need long-term experiments to acquire knowledge of structure and growth dynamics of mixed-species stands. We need statistical models for scenario analyses and planning. We further need simplified silvicultural prescriptions and teaching and training tools such as marteloscopes.

4 Revealing mechanisms of competition, competition reduction, and facilitation

The scale of forests and our ability to measure and model them offers a huge potential and advantage when analyzing these systems. In a Central European forest, the size ratio between a human body and a tree is 1:20. That means we can enter forests and measure individual trees, their size, position, inclination, distances and also their interactions with other trees, including competition and facilitation. We can do this nearly without disturbances, without artifacts. We can walk around in forests without causing much damage (Figure 12a). We even can enter forests with TLidar, i.e., mobile CT scanning, or take wood samples such as increment core, without causing significant damages or disturbances.

In contrast, in agricultural systems, such as grassland or vegetable crops, the size ratio between humans and plants can be as low as 1:0.2; i.e., it is difficult to enter the systems, to measure individual plant traits for understanding plant-plant competition, competition reduction, facilitation, without causing disturbances or artifacts (Figure 12b).



(a) (b) (c)

Figure 12 The size ratio between humans and plants in forest science is more conducive to spatially explicit research of tree-tree interaction and mixing effects than that in agricultural sciences. (a) the size ratio between humans and plants is 1:20 in mature forest systems, (b) but only 1:0.2 in agricultural systems. (c) Similar to Lewis Carroll's Alice in Wonderland (Carroll 1865), humans would need to be 100 times smaller to get similar access to agricultural plants as to forest plants.

The human body would need to be 100 times smaller than it is to gain the same access and similar options of entering, measuring and scanning agricultural systems as for forest systems (Figure 12c). This would require a shrinking, similar to Lewis Carroll's (1865) Alice in Wonderland. For her, a mouse was terribly big, and a mousehole a large, dangerous cave. On the other hand, thanks to her small size, she could have measured herbs and legumes just as easily as we measure trees in forests. As long as we do not figure out how to shrink like Alice, agricultural science can benefit from forest science when it comes to individual plant-based research and modelling.

With these theoretical considerations about the spatial dimension of forest- versus agroecosystems it is aimed to clarify that thanks to their spatial dimension, even-aged monospecific stands can be relatively easily measured throughout their whole stand development (Figure 13, a-c). The same is true for even-aged and mixed uneven-aged stands. Their structure can be followed individually and spatially through classical methods (caliper, hypsometer, increment cores) or remote sensing techniques (TLidar, electronical dendrometers, mobile CT).

Thanks to easy accessibility, tree and stand development can be followed spatially explicitly over decades or even the whole lifetime of trees and stands, as shown schematically in Figure 13.

Without any active management, Darwinian forces become visible in forest stands (Figure 13a). A very few tall trees claim most of the resources and space (Grams and Lüttge 2011). They dominate and overgrow the other trees. The resulting stand structure is composed of a few strongly growing, tall trees and multiple slowly growing, small trees. Without silvicultural interventions, the growth of a few initially dominating trees, e.g. twin trees or predominant trees, is maximized. Hence, a lack of management can maximize individual tree growth, but not the growth per unit area, i.e. not the stand productivity. Conversely, strong homogenization also causes suboptimal growth as the growing space and resources are not fully leveraged, especially in the mature stand development phase (Figure 13b).

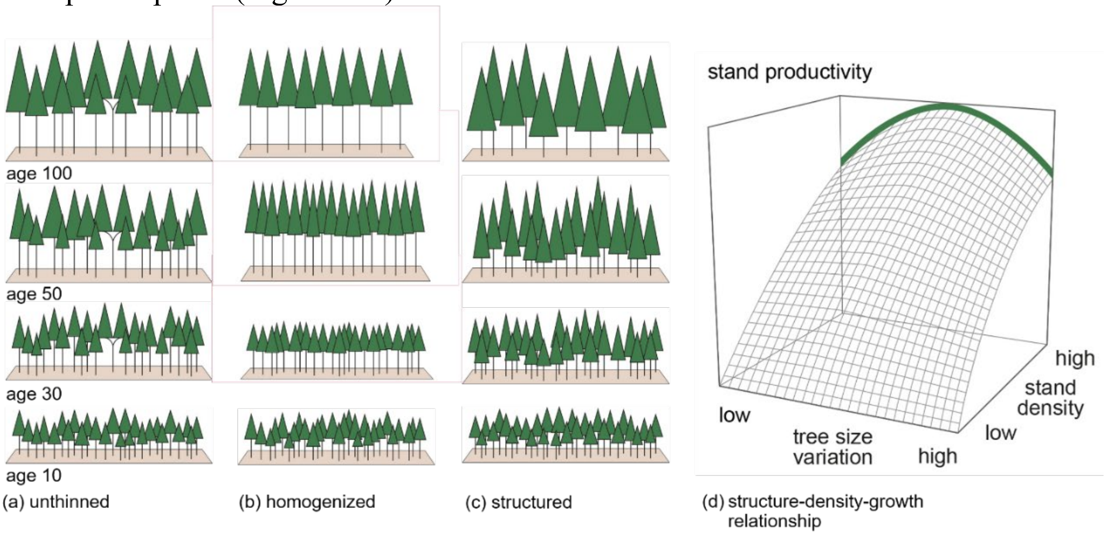


Figure 13 The structural diversity of mono-specific stands can significantly affect their productivity. Unthinned or homogenized stands (a and b) produce less than stands with a medium structural diversity (c). (d) Even within stands with the same density productivity can vary. Mean size heterogeneity and structural diversity can increase productivity by 10-25 % (according to Pretzsch et al. 2024).

Recent studies show that mean structural heterogeneity (Figure 13c) of forest stands can significantly increase stand productivity (Pretzsch et al. 2024). There seems to be an optimal relationship between structure and productivity. Strongly homogeneous and heterogeneous stands are suboptimal in productivity per unit area, whereas moderately structured stands can produce 10-25 % more. This is because moderate structural heterogeneity enables a better use of resources distributed over multiple layers and tree sizes in a stand. Resultantly, extremely inhomogeneous unthinned stands and stands homogenized by thinning from below (thinning the small trees) produce less than stands with a medium structural diversity (Figure 13d).
Productivity can increase asymptotically in relation to the number of species in a given stand (Figure 14). There are exceptions to this rule: for example, Douglas-fir, Norway spruce, and eucalyptus are outperformers in terms of productivity and are difficult to beat in mixtures, at least not over one or two rotations (Liang et al. 2016, Forrester and Pretzsch 2015, Körner 2005).

In most cases, however, mixed stands grow more than the weighted mean of neighboring monocultures. A main reason for this overyielding of mixed compared to monospecific stands is that in mixed stands, tree shapes and sizes are often more diverse (e.g., due to the different tree allometry, light demand, growth velocities). Consequently, the trees can exploit the available space and light resources more efficiently. Stand density is often higher in mixed compared to monospecific stands, and complementary traits can reduce competition for resources and space (Grams and Lüttge 2011). Overyielding increases with greater complementarity of the structural and functional traits of the mixed species. Figure 14, right shows mixture of species with different crown shapes which can better exploit the available canopy space for growth. Overyielding may increase by 10-15% in mixtures of similar tree species, and by 20-30% in stands with high complementarity.

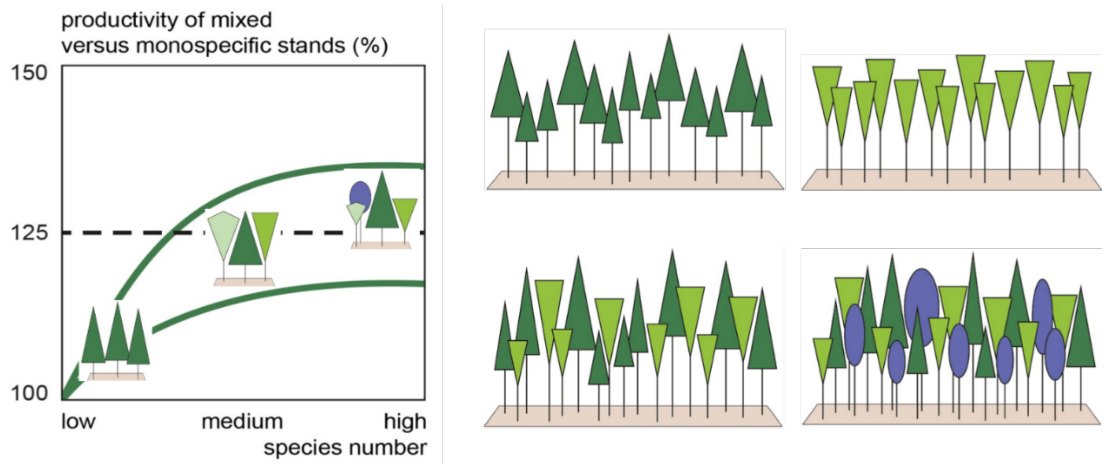


Figure 14 Stand productivity generally increases asymptotically with increasing species diversity. The strength of the mixing effect depends on the complementarity of the species ensemble (according to Jactel et al. 2018, Liang et al. 2016).

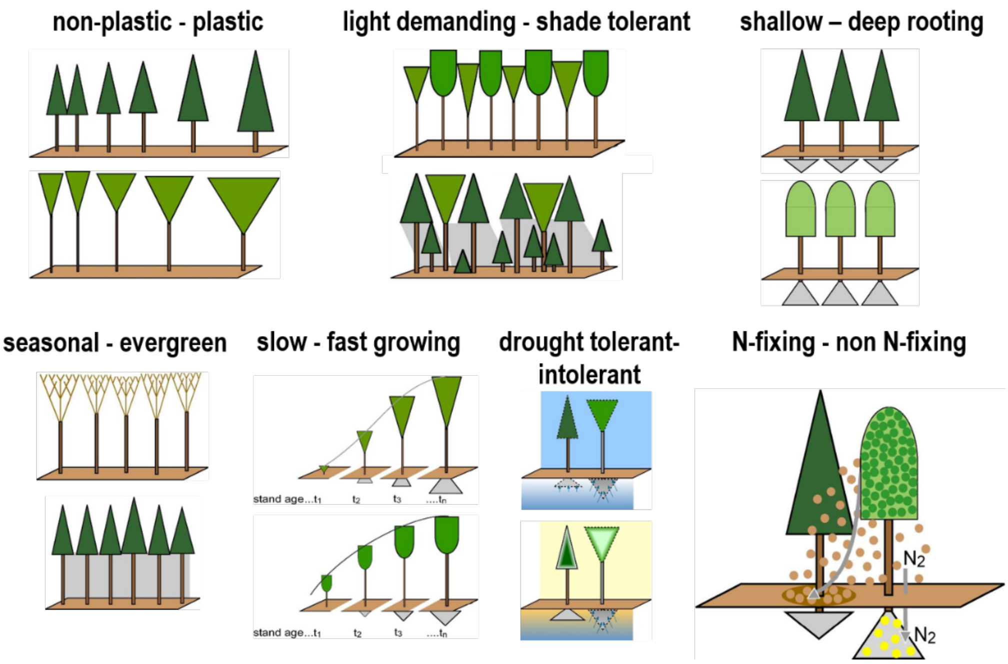


Figure 15 Mixing effects depend on the structural and functional characteristics of the combined tree species. Combining complementary traits, such as allometrically non-plastic with plastic, or seasonal with evergreen species can reduce competition. Conversely, combining drought tolerant, deep rooting with drought intolerant, shallow rooting species, or N-fixing with non-N-fixing tree species (Bravo-Oviedo et al. 2018) can enhance facilitation.

Significant overyielding can be expected when combining phenotypically non-plastic and plastic, light demanding and shade tolerant, shallow and deep rooting, seasonal and evergreen, or slow and fast growing tree species (Bravo-Oviedo et al. 2018), as shown in Figure 15.
In addition, overyielding can be affected through facilitation (Figure 15) such as hydraulic lift (Hafner et al. 2017, Pretzsch et al. 2013), N-fixing tree species (Forrester et al. 2006), or shading trees and protecting smaller trees against extreme temperatures and drought (Grote et al. 2016, Pretzsch et al. 2022). These beneficial effects of competition reduction or facilitation can be achieved simply through the smart selection of species and design of mixtures.
For a smarter knowledge-based design of productive and resource-efficient mixed species stands, we need more empirical studies: experiments with different species ensembles, site conditions, and mixing patterns as experimental factors.

Interim summary 3: The size ratio of humans and trees makes forests an ideal system to analyze and model tree-tree relationships such as competition, competition reduction, and facilitation.
Mean structural diversity leads to the highest productivity. Mixed species stands are more heterogeneous, and their canopies more densely packed, than monocultures. Competition reduction and facilitation can increase mixed species stand productivity. Differences in

the trees' structural and functional characteristics are key to understanding mixing effects and the extent of overyielding.

5 Cross-sectoral perspectives. There is only one biodiversity, one carbon, one health, one sustainability

The clearings during the Middle Ages resulted in the classic segregation between forests, and agricultural and urban ecosystems (Figure 16a). This segregation, commonly observed as rings around cities (with different systems and homogenizations within the rings) was first described by von Thünen (1783-1850) (see Samuelson 1983, von Thünen 2022). The resulting concept of the "von Thünen rings" (Figure 16a) greatly simplified the product utilization, transport, planning, and continuous management.

At the same time as ecosystems were segregated at the landscape-level, a segregation took place in the sciences: a division into the sectors and faculties of forest science, agricultural science, and urban and landscape planning. This institutional segregation in science, teaching, and planning exists to this day. The segregation between and the homogenization within the forestry and agriculture sector were even more consolidated by the trends towards monocultures in forestry in the last two centuries (Liu et al. 2018, Yaffee 1999) and by the green revolution in agriculture since the middle of the last century (Crews et al. 2018, Glaeser 2010).

Within these segregated sectors and fields of science, many parallel developments and inadvertent duplications of discovery occurred. The self-thinning processes were analyzed and modeled by Reineke (1933) in forest science and by Yoda et al. (1963) in agriculture. Plant allometry was explored by Niklas (1994) and Enquist et al. (2001) in forests and by Weiner (2004) and Weiner and Thomas (1992) in agriculture. Mixing effects and overyielding were described by Kelty (1992) in forestry and Vandermeer (1992) in agroscience. Experiments with the design by Nelder (1962) were used and further developed for knowledge in both sectors (Pachas et al. 2018, Uhl et al. 2015). Finally, individual plant models were invented in parallel in forest and agricultural sciences (Grimm 2013, Fourcaud et al. 2008).

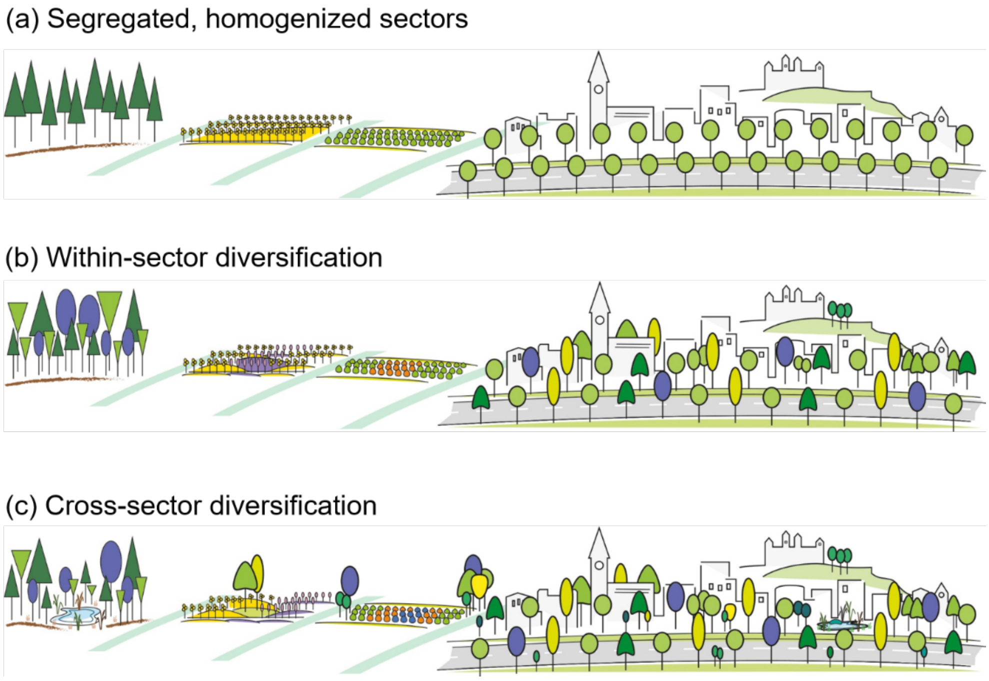


Figure 16 From homogenization to diversification at different spatial scales. (a) Classic segregation between forest, agriculture, and urban ecosystems (from left to right). (b) Diversification at the sector level. (c) Cross-sectoral diversification, e.g., through open areas or humid biotopes in forests, agroforest systems, or tiny forests and urban food gardens in urban areas.

So far, we have mainly focused on the potential of diversification to enrich and improve ecosystem services within the forestry sector (Figure 16b). However, the very same trend of diversification of structure and species as it was described in forestry is emerging in agronomy and urban areas: cereals are mixed with legumes, and new species are introduced in urban areas. Urban planners are becoming increasingly aware that alleys with only one species are more vulnerable to pathogen attacks or climate change, and now mix provenances or species to mitigate the risk of total damages. Similarly, the multiplicative effect of diversification on ecosystem service provision applies not only to forests but also to other sectors. At the same time, forestry and these other sectors also face similar challenges (Figure 2) such as promoting biodiversity, increasing carbon stock, improving social services like landscape esthetics, human recreation and health (Martin-Guay et al. 2018). We think that this calls for a stronger cooperation in both science and practice.

If we do this, different sectors can benefit and learn from each other: For examples, forest systems may offer a useful spatial resolution and good accessibility; agricultural systems a high temporal resolution enabling fast experiments; and urban areas a high relevance and level of knowledge about the effect of trees on human health and wellbeing (e.g. shading, cooling, air humidification, allergic risks). This interaction across sectors may lead to greater scientific productivity and maybe even to an overyielding of knowledge.

The within-sector diversification in terms of biodiversity, carbon, or health is crucial. But we need to remember that there is no isolated forestry biodiversity, agriculture biodiversity, urban biodiversity, no forestry carbon, agriculture carbon and urban carbon, no isolated forestry health, agricultural health, or urban health. There is only one biodiversity, one carbon cycle, and one health (Adisasmito et al. 2022, Zinsstag et al. 2011). And there is also only one sustainability (Lüttge 2024, Goodland 1995, von Carlowitz 1713).

This suggests a cross-sectoral diversification as show in Figure 16c. Imagine open areas and humid
biotopes in otherwise continuously covered forests. Trees enriching agricultural areas. Imagine tiny forests in urban areas (planting patches of multispecies to increase biodiversity), pair planting of urban trees (to distribute risk and enhance facilitation), and urban food gardens (crops in urban areas for food supply nearby). This kind of diversification may even have exponential effects on various ecosystem services.

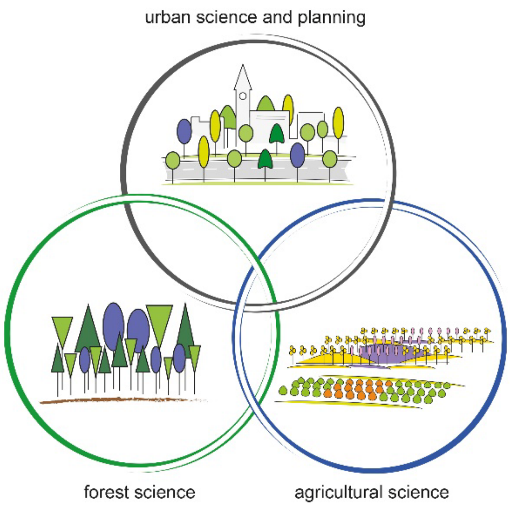


Figure 17: Cross-sectorial analyses, models, management prescriptions between forest science, agricultural science, and urban science as research perspective.

Forests and agriculture systems cover 68% of the earth surface. Together with urban areas (1-2 %), they constitute approximately 70% of the earth surface. They are essential to the future of our globe and human life. Recognizing the "One Biodiversity, One Carbon, One Health, One Sustainability" paradigm and re-opening the borders between the established sectors to work towards common research, teaching, training, and planning (Figure 17) is a great, innovative, cross-sectoral perspective.

De nuevo, mi más sincero agradecimiento por el honor de poder estar aquí hoy, por su tiempo y por su atención.

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7 References

Adisasmito, W. B., Almuhairi, S., Behravesh, C. B., Bilivogui, P., Bukachi, S. A., Casas, N., ... & Zhou, L. (2022). One Health: A new definition for a sustainable and healthy future. *PLoS pathogens*, *18*(6), e1010537.

Aggestam, F., Konczal, A., Sotirov, M., Wallin, I., Paillet, Y., Spinelli, R., ... & Winkel, G. (2020). Can nature conservation and wood production be reconciled in managed forests? A review of driving factors for integrated forest management in Europe. *Journal of Environmental management*, *268*, 110670.

Begon ME, Harper JL, Townsend CR (1998) Ökologie. Spektrum Akademischer Verlag, Heidelberg, 750 p.

Bollmann, K., & Braunisch, V. (2013). To integrate or to segregate: balancing commodity production and biodiversity conservation in European forests. *Integrative approaches as an opportunity for the conservation of forest biodiversity*, *18*.

Boncina, A. (2011). Conceptual approaches to integrate nature conservation into forest management: a Central European perspective. *International Forestry Review*, *13*(1), 13-22

Bravo, F., Fabrika, M., Ammer, C., Barreiro, S., Bielak, K., Coll, L., ... & Bravo-Oviedo, A. (2019). Modelling approaches for mixed forests dynamics prognosis. Research gaps and opportunities. *Forest Systems*, *28*(1), eR002.

Bravo-Oviedo, A., Pretzsch, H., & del Río, M. (Eds.). (2018). Dynamics, silviculture and management of mixed forests (Vol. 31). Berlin: Springer.

Carlowitz von HC (1713) Sylvicultura Oekonomica oder Haußwirthliche Nachricht und Naturmäßige Anweisung zur wilden Baum-Zucht. JF Braun, Leipzig

Carroll, L. (1865) Alice's Adventures in Wonderland, Macmillan, London

Crews, T. E., Carton, W., & Olsson, L. (2018). Is the future of agriculture perennial? Imperatives and opportunities to reinvent agriculture by shifting from annual monocultures to perennial polycultures. *Global Sustainability*, *1*, e11.

del Río, M., Pretzsch, H., Alberdi, I., Bielak, K., Bravo, F., Brunner, A., ... & Bravo-Oviedo, A. (2016). Characterization of the structure, dynamics, and productivity of mixed-species stands: review and perspectives. *European journal of forest research*, *135*, 23-49.

del Río, M., Pretzsch, H., Ruíz-Peinado, R., Ampoorter, E., Annighöfer, P., Barbeito, I., ... & Bravo-Oviedo, A. (2017). Species interactions increase the temporal stability of community productivity in Pinus sylvestris–Fagus sylvatica mixtures across Europe. *Journal of Ecology*, *105*(4), 1032-1043.

del Río, M., Pretzsch, H., Ruiz-Peinado, R., Jactel, H., Coll, L., Löf, M., ... & Bravo-Oviedo, A. (2022). Emerging stability of forest productivity by mixing two species buffers temperature destabilizing effect. *Journal of Applied Ecology*, *59*(11), 2730-2741.

Dieler, J., Uhl, E., Biber, P., Müller, J., Rötzer, T., & Pretzsch, H. (2017). Effect of forest stand management on species composition, structural diversity, and productivity in the temperate zone of Europe. *European Journal of Forest Research*, *136*, 739-766.

EEA (2023) European Environment Agency, An introduction to Europe's protected areas, https://www.eea.europa.eu/en/topics/in-depth/biodiversity/an-introduction-to-europes-protected-areas, access 13032024

Enquist BJ, Niklas KJ (2001) Invariant scaling relations across tree-dominated communities. Nature 410: 655-660

Enquist, B. J., West, G. B., Charnov, E. L., & Brown, J. H. (1999). Allometric scaling of production and life-history variation in vascular plants. *Nature*, *401*(6756), 907-911.

Forrester, D. I., & Pretzsch, H. (2015). Tamm Review: On the strength of evidence when comparing ecosystem functions of mixtures with monocultures. *Forest Ecology and Management*, *356*, 41-53.

Forrester, D. I., Bauhus, J., Cowie, A. L., & Vanclay, J. K. (2006). Mixed-species plantations of Eucalyptus with nitrogen-fixing trees: a review. *Forest Ecology and Management*, *233*(2-3), 211-230.

Fourcaud, T., Zhang, X., Stokes, A., Lambers, H., & Körner, C. (2008). Plant growth modelling and applications: the increasing importance of plant architecture in growth models. *Annals of Botany*, *101*(8), 1053-1063.

Glaeser, B. (Ed.). (2010). *The Green Revolution revisited: critique and alternatives* (Vol. 2). Taylor & Francis.

Goodland, R. (1995). The concept of environmental sustainability. *Annual review of ecology and systematics*, *26*(1), 1-24.

Grams, T. E., & Lüttge, U. (2011). Space as a resource. *Progress in Botany 72*, 349-370.

Griess, V. C., Acevedo, R., Härtl, F., Staupendahl, K., & Knoke, T. (2012). Does mixing tree species enhance stand resistance against natural hazards? A case study for spruce. *Forest Ecology and Management*, *267*, 284-296.

Grimm, V., & Railsback, S. F. (2013). Individual-based modeling and ecology. In *Individual-based modeling and ecology*. Princeton university press.

Grote, R., Gessler, A., Hommel, R., Poschenrieder, W., & Priesack, E. (2016). Importance of tree height and social position for drought-related stress on tree growth and mortality. *Trees*, *30*, 1467-1482.

Hafner, B. D., Tomasella, M., Häberle, K. H., Goebel, M., Matyssek, R., & Grams, T. E. (2017). Hydraulic redistribution under moderate drought among English oak, European beech and Norway spruce determined by deuterium isotope labeling in a split-root experiment. *Tree Physiology*, *37*(7), 950-960.

Harvey, C. A., Komar, O., Chazdon, R., Ferguson, B. G., Finegan, B., Griffith, D. M., ... & Wishnie, M. (2008). Integrating agricultural landscapes with biodiversity conservation in the Mesoamerican hotspot. *Conservation biology*, *22*(1), 8-15.

Hooper, D. U., & Dukes, J. S. (2004). Overyielding among plant functional groups in a long-term experiment. *Ecology Letters*, *7*(2), 95-105.

Hulvey, K. B., Hobbs, R. J., Standish, R. J., Lindenmayer, D. B., Lach, L., & Perring, M. P. (2013). Benefits of tree mixes in carbon plantings. *Nature Climate Change*, *3*(10), 869-874.

Huuskonen, S., Domisch, T., Finér, L., Hantula, J., Hynynen, J., Matala, J., ... & Viiri, H. (2021). What is the potential for replacing monocultures with mixed-species stands to enhance ecosystem services in boreal forests in Fennoscandia?. *Forest ecology and management*, *479*, 118558.

Jactel, H., Bauhus, J., Boberg, J., Bonal, D., Castagneyrol, B., Gardiner, B., ... & Brockerhoff, E. G. (2017). Tree diversity drives forest stand resistance to natural disturbances. *Current Forestry Reports*, *3*, 223-243.

Jactel, H., Gritti, E. S., Drössler, L., Forrester, D. I., Mason, W. L., Morin, X., ... & Castagneyrol, B. (2018). Positive biodiversity–productivity relationships in forests: climate matters. *Biology letters*, *14*(4), 20170747.

Kelty MJ (1992) Comparative productivity of monocultures and mixed stands. In: Kelty MJ, Larson BC, Oliver CD (eds) The ecology and silviculture of mixed-species forests. Kluwer Academic Publishers, Dordrecht, pp 125-141

Kelty, M. J. (1992). Comparative productivity of monocultures and mixed-species stands. In *The Ecology and silviculture of mixed-species forests: a Festschrift for David M. Smith* (pp. 125-141). Dordrecht: Springer Netherlands.

Knoke, T., Ammer, C., Stimm, B., & Mosandl, R. (2008). Admixing broadleaved to coniferous tree species: a review on yield, ecological stability and economics. *European journal of forest research*, *127*, 89-101.

Kobler, J., Hochbichler, E., Pröll, G., & Dirnböck, T. (2024). How to Optimize Carbon Sinks and Biodiversity in the Conversion of Norway Spruce to Beech Forests in Austria?. *Forests*, *15*(2), 359.

Körner, C. (2005). An introduction to the functional diversity of temperate forest trees. In *Forest diversity and function: temperate and boreal systems* (pp. 13-37). Berlin, Heidelberg: Springer Berlin Heidelberg.

Krumm, F., Lachat, T., Schuck, A., Bütler, R., & Kraus, D. (2019). Marteloscopes as training tools for the retention and conservation of habitat trees in forests. *Schweizerische Zeitschrift für Forstwesen*, *170*(2), 86-93.

Liang, J., Crowther, T. W., Picard, N., Wiser, S., Zhou, M., Alberti, G., ... & Reich, P. B. (2016). Positive biodiversity-productivity relationship predominant in global forests. *Science*, *354*(6309), aaf8957.

Liu, C. L. C., Kuchma, O., & Krutovsky, K. V. (2018). Mixed-species versus monocultures in plantation forestry: Development, benefits, ecosystem services and perspectives for the future. *Global Ecology and conservation*, *15*, e00419.

Locatelli, B., Pavageau, C., Pramova, E., & Di Gregorio, M. (2015). Integrating climate change mitigation and adaptation in agriculture and forestry: opportunities and trade-offs. *Wiley Interdisciplinary Reviews: Climate Change*, *6*(6), 585-598.

Lüttge, U. (2024) Nachhaltigkeit und der zweite Hauptsatz der Thermodynamik, Umgang mit dissipativen Strukturen auf allen Ebenen unseres Daseins, Naturwissenschaftliche Rundschau, 77 (3): 139-141.

Ma, S., & Zhuge, M. (2024). Ecological agriculture traits: Constructing an integrated agricultural system for sustainable development. *Geographical Research Bulletin*, *3*, 2-5.

Marquard, E., Weigelt, A., Temperton, V. M., Roscher, C., Schumacher, J., Buchmann, N., ... & Schmid, B. (2009). Plant species richness and functional composition drive overyielding in a six-year grassland experiment. *Ecology*, *90*(12), 3290-3302.

Martin-Guay, M. O., Paquette, A., Dupras, J., & Rivest, D. (2018). The new green revolution: sustainable intensification of agriculture by intercropping. *Science of the total environment*, *615*, 767-772.

MCPFE (2006) Joint Position of the MCPFE and the EfE/PEBLDS on the Pan-European Understanding of the Linkage between the Ecosystem Approach and Sustainable Forest Management. In *Ministerial Conference on the Protection of Forests in Europe*. Geneva Warsaw, 15 p.

Milad, M., Schaich, H., Bürgi, M., & Konold, W. (2011). Climate change and nature conservation in Central European forests: A review of consequences, concepts and challenges. *Forest ecology and management*, *261*(4), 829-843.

Niklas KJ (1994) Plant Allometry. Univ Chicago Press, Chicago, IL

Nelder JA (1962) New kinds of systematic designs for spacing experiments. Biometrics, 18 (3): 283-307

Pachas, A. N. A., Shelton, H. M., Lambrides, C. J., Dalzell, S. A., & Murtagh, G. J. (2018). Effect of tree density on competition between Leucaena leucocephala and Chloris gayana using a Nelder Wheel trial. I. Aboveground interactions. *Crop and Pasture Science*, *69*(4), 419-429.

Pardos, M., Del Río, M., Pretzsch, H., Jactel, H., Bielak, K., Bravo, F., ... & Calama, R. (2021). The greater resilience of mixed forests to drought mainly depends on their composition: Analysis along a climate gradient across Europe. *Forest Ecology and Management*, *481*, 118687.

Paul, C., Brandl, S., Friedrich, S., Falk, W., Härtl, F., & Knoke, T. (2019). Climate change and mixed forests: how do altered survival probabilities impact economically desirable species proportions of Norway spruce and European beech?. *Annals of Forest Science*, *76*(1), 1-15.

Paut, R., Sabatier, R., & Tchamitchian, M. (2019). Reducing risk through crop diversification: An application of portfolio theory to diversified horticultural systems. *Agricultural systems*, *168*, 123-130.

Pittelkow, C. M., Liang, X., Linquist, B. A., Van Groenigen, K. J., Lee, J., Lundy, M. E., ... & Van Kessel, C. (2015). Productivity limits and potentials of the principles of conservation agriculture. *Nature*, *517*(7534), 365-368.

Pretzsch (2009) Forest dynamics, growth, and yield (Vol. 684). Berlin: Springer.

Pretzsch, H. (2014). Canopy space filling and tree crown morphology in mixed-species stands compared with monocultures. *Forest Ecology and Management*, *327*, 251-264.

Pretzsch, H. (2016). Ertragstafel-Korrekturfaktoren für Umwelt-und Mischungseffekte. *AFZ Der Wald*, 14:2016, 47-50

Pretzsch, H. (2019). *Grundlagen der Waldwachstumsforschung*. Springer-Verlag, Heidelberg.

Pretzsch, H., & Biber, P. (2016). Tree species mixing can increase maximum stand density. *Canadian Journal of Forest Research*, *46*(10), 1179-1193.

Pretzsch, H., & Schütze, G. (2009). Transgressive overyielding in mixed compared with pure stands of Norway spruce and European beech in Central Europe: evidence on stand level and explanation on individual tree level. *European Journal of Forest Research*, *128*, 183-204.

Pretzsch, H., & Zenner, E. K. (2017). Toward managing mixed-species stands: from parametrization to prescription. *Forest Ecosystems*, *4*, 1-17.

Pretzsch, H., Del Río, M., Grote, R., Klemmt, H. J., Ordóñez, C., & Oviedo, F. B. (2022). Tracing drought effects from the tree to the stand growth in temperate and Mediterranean forests: insights and consequences for forest ecology and management. *European Journal of Forest Research*, *141*(4), 727-751.

Pretzsch, H., Forrester, D. I., & Bauhus, J. (2017). Mixed-species forests. *Ecology and management. Springer, Berlin*, *653*.
Pretzsch, H., Hilmers, T., & del Río, M. (2024). The effect of structural diversity on the self-thinning line, yield level, and density-growth relationship in even-aged stands of Norway spruce. *Forest Ecology and Management*, *556*, 121736.
Pretzsch, H., Schütze, G., & Biber, P. (2018). Drought can favour the growth of small in relation to tall trees in mature stands of Norway spruce and European beech. *Forest Ecosystems*, *5*(1), 1-19.
Pretzsch, H., Schütze, G., & Uhl, E. (2013). Resistance of European tree species to drought stress in mixed versus pure forests: evidence of stress release by inter-specific facilitation. *Plant Biology*, *15*(3), 483-495.
Reineke LH (1933) Perfecting a stand-density index for even-aged forests. J Agr Res 46: 627-638
Rousseau J-J (1762) Du Contract Social. German Ed (1977) Gesellschaftsvertrag. Reclam, Stuttgart
Samuelson, P. A. (1983). Thünen at two hundred. *Journal of Economic Literature*, 1468-1488.
Soucy, M., Adégbidi, H. G., Spinelli, R., & Béland, M. (2016). Increasing the effectiveness of knowledge transfer activities and training of the forestry workforce with marteloscopes. *The Forestry Chronicle*, *92*(4), 418-427.
Uhl, E., Biber, P., Ulbricht, M., Heym, M., Horváth, T., Lakatos, F., ... & Pretzsch, H. (2015). Analysing the effect of stand density and site conditions on structure and growth of oak species using Nelder trials along an environmental gradient: experimental design, evaluation methods, and results. *Forest Ecosystems*, *2*, 1-19.
Vandermeer, J. H. (1992). *The ecology of intercropping*. Cambridge university press.
von Gadow, K., Zhao, X. H., Tewari, V. P., Zhang, C. Y., Kumar, A., Rivas, J. J. C., & Kumar, R. (2016). Forest observational studies: an alternative to designed experiments. *European Journal of Forest Research*, *135*, 417-431.
von Thünen, J. H. (2022). Der isolierte Staat in Beziehung auf Landwirtschaft und Nationalökonomie. Walter de Gruyter GmbH & Co KG.
Weiner, J. (2004). Allocation, plasticity and allometry in plants. *Perspectives in Plant Ecology, Evolution and Systematics*, *6*(4), 207-215.
Weiner, J., & Thomas, S. C. (1992). Competition and allometry in three species of annual plants. *Ecology*, *73*(2), 648-656.
Yaffee, S. L. (1999). Three faces of ecosystem management. *Conservation Biology*, *13*(4), 713-725.
Yoda KT, Kira T, Ogawa H, Hozumi K (1963) Self-thinning in overcrowded pure stands under cultivated and natural conditions. J Inst Polytech, Osaka Univ D 14:107-129
Zhai, L., Coyle, D. R., Li, D., & Jonko, A. (2022). Fire, insect and disease-caused tree mortalities increased in forests of greater structural diversity during drought. *Journal of Ecology*, *110*(3), 673-685.
Zinsstag, J., Schelling, E., Waltner-Toews, D., & Tanner, M. (2011). From "one medicine" to "one health" and systemic approaches to health and well-being. *Preventive veterinary medicine*, *101*(3-4), 148-156.

8 Picture credits

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Figure 5: made for this lecture exclusively
Figure 6: according to Begon et al. (1998), Paul et al. (2019), and Pretzsch et al. (2013)
Figure 7: according to Forrester and Pretzsch (2015), Liang et al. (2016), Pretzsch and Biber (2016)
Figure 8: (left) photos L. Steinacker, H. Pretzsch, (right) photos BFW, Wien, Österreich; LBV, Bayern; waist-up-Porträt, racorn; BMEL; FVA, Baden-Württemberg
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Figure 10: Pretzsch, H. (2019) Grundlagen der Waldwachstumsforschung. Springer-Verlag.

Figure 11: (top) Pretzsch, H., & Zenner, E. K. (2017). Toward managing mixed-species stands: from parametrization to prescription. *Forest Ecosystems*, *4*, 1-17. (bottom) L. Steinacker, Felipe Bravo-Oviedo
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