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Review Paper

Mixed-species versus monocultures in plantation forestry: Development, benefits, ecosystem services and perspectives for the future

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ABSTRACT

Plantation forests are increasing rapidly in the world in order to alleviate deforestation and degradation of natural forests, along with providing various goods and services. While monoculture plantations have been the dominant type of plantation in practice and well-recorded in research, in the face of intensifying climate change and resource scarcity, there is a growing interest in mixed-species plantations. Agroforestry systems are also catching the attention of foresters, smallholders and landowners. However, there are relatively limited number of studies on successful species mixtures. This paper first reviews the progression of monocultures and mixed-species, followed by the comparisons of advantages, disadvantages and effects on the surrounding natural ecosystems between these two types of plantations. The paper further investigates combinations of species with complementary traits for efficient use of limiting resources associated with improvement in growth development and production of tree species, as well as examining some other challenges in mixed-species. In addition, it is helpful to select and combine tree/crop species in mixtures based on complementary traits that maximise positive and minimise negative interactions and using the advance molecular technologies for genetic analysis. With careful design and proper management, mixed-species plantations with two, three or four species can be more productive and have more advantages in biodiversity, economy and forest health over monocultures. Many researchers are still working on different projects to explore the potential benefits and to promote the applications of mixed-species plantations and agroforestry.

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1. Introduction

Plantation forests are expanding rapidly all over the world. Monocultures have been dominated in practice and well-documented in forest research, but in the face of increasing climate change and resource scarcity, there is a growing interest in mixed-species plantation systems (e.g., Bolte et al., 2004; Spiecker et al., 2004; Hein and Dhôte, 2006; Pretzsch et al., 2010, 2013; 2014; Cavard et al., 2011; Hulvey et al., 2013; Bielak et al., 2014; Forrester, 2014; Löf et al., 2014; Pretzsch, 2014; Neuner et al., 2015; Metz et al., 2016; Pretzsch and Rais, 2016; Pretzsch and Schütze, 2016; Zeller et al., 2017; Coll et al., 2018). Higher diversity of tree species increases the number of ecological niches, which can further increase the number of associated species, for example, plants in understory and animals by providing them with a better habitat (Larjavaara, 2008). However, there are limited examples of successful mixed-species plantations, especially mixtures with indigenous tropical tree species (but see Amazonas et al., 2018). The mechanisms of mixing effects in mixed-species plantations and optimal for particular conditions species combination with complementary traits are largely unknown. In addition, another land use management system, agroforestry, which also involves elements of mixed-species, is catching the attention of foresters, smallholders and landowners. It is essential to study and understand these kinds of mixed-species systems and their potential socio-economic and ecosystem benefits that could be obtained.

In this review paper, the importance of species diversity to ecosystems and the positive and negative aspects of mixed-species will be discussed first, followed by discussion on the general plantation forestry trends. The history and current development of monocultures and mixed-species in forest plantations will be reviewed, respectively. In addition, the advantages and disadvantages of monocultures and mixed-species plantations, along with the effects to the surrounding natural ecosystems will be studied and compared with the support of several species examples. The paper will also examine whether mixed-species plantations can obtain higher productivity than monocultures, as well as other challenges associated with mixed-species. The paper will further focus on the reasons of fewer studies on species mixtures with native tropical tree species and mixtures with non-nitrogen fixing trees. Moreover, identification of complementary traits is difficult. Therefore, in this review, combinations of species with complementary traits will be investigated for efficient use of limiting resources, in association with improvement in growth development and production of tree species. It will also discuss different design and management operations that are suitable for adopting species mixtures. Various ongoing projects and programs related to mixed-species will be explored for the future of forestry and agriculture.

2. Importance of biodiversity

Biodiversity refers to the variety of organisms, including microorganisms, plants, and animals in different ecosystems, such as deserts, forests, coral reefs, etc. (Altieri, 1999; Hamilton, 2005; Carnus et al., 2006; Gugerli et al., 2008). It could be partitioned as diversity within species, between species and of ecosystems or ecological diversity including molecular, population and genetic diversity (Convention on Biological Diversity United Nations, 1992; Swift et al., 2004; Srivastava and Vellend, 2005; Mace et al., 2012). The most commonly used representation of ecological diversity is species diversity, which is defined as the number of species and abundance of each species living within a certain location (Hamilton, 2005). However, as it has been pointed out in many publications (e.g., Rajora, 1999; Rajora and Mosseler, 2001; Rajora and Pluhar, 2003), genetic diversity is the most important component of biodiversity. Indeed, it is a basis of all biodiversity and foundation of ecosystem sustainability and stability. More than one genotype is needed for forestry plantations in order to address the biodiversity and climate change issues.

Many species are interconnected and dependent on one another for survival. They perform important ecosystem functions and offer different ecosystem services to support life on Earth and human economies, for instance, water quantity and quality, seed and pollen dispersal, soil formation, nutrient cycles, regulation of pests and human diseases, carbon storage and climate regulation, waste management and cultural services (Balvanera et al., 2006, 2013; Carnus et al., 2006; Mace et al., 2012; Mergeay and Santamaria, 2012). Ecosystems with higher species diversity can be more efficient and are generally more stable and resistant to disaster than those with fewer species, as a substantial number of species consist of many different traits, which can contribute to various functions (Lohbeck et al., 2016). Tropical rainforest is an ecosystem with the greatest biodiversity on Earth. Lefcheck et al. (2015) demonstrated that species-rich communities support higher levels of ecosystem functions. They also showed data that herbivore biodiversity had stronger effects on ecosystem multifunctionality than plant biodiversity, and these effects were consistent in aquatic and terrestrial habitats. Communities with higher diversity of animals also accumulate more biomass (Schneider et al., 2016). It is fundamental to have keystone species, which is either a plant or animal that helps maintain species diversity and the health of ecosystems (Balun, 2017). Without keystone species, the ecosystems would be dramatically altered and species would be adversely affected.

Nowadays, biodiversity is threatened by climate change, pollution, overexploitation of natural resources and habitat loss (Pereira et al., 2012). Loss of biodiversity weakens species connections and impairs the ecosystems, leading to extinction of species and local populations, which will disrupt ecological services. For instance, insects, birds, bats and other animals are known as pollinators. Declines in honey bee (*Apis mellifera*) populations may result in a loss of pollination services with negative impacts on ecology and economy for fruit crops and flowers, which will eventually affect the maintenance of wild plant diversity, wider ecosystem stability, agricultural production, human welfare and global food security (Potts et al., 2010). Not only terrestrial but also regional marine ecosystems, including estuaries, coral reefs, coastal and oceanic fish communities