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Analyzing the impact of climate and management factors on the productivity and soil carbon sequestration of poplar plantations

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ABSTRACT

It is crucial to investigate how climate and management factors impact poplar plantation production and soil carbon sequestration interactively. We extracted above-ground net primary production (ANPP), climate and management factors from peer-reviewed journal articles and analyzed impact of management factor and climate on the mean annual increment (MAI) of poplar ANPP statistically. Previously validated mechanistic model (ED) is used to perform case simulations for managed poplar plantations under different harvesting rotations. The meta-analysis indicate that the dry matter MAI was 6.3 Mg ha^{-1} yr^{-1} (n=641, sd=4.9) globally, and 5.1 (n=292, sd=4.0), 8.1 (n=224, sd=4.7) and 4.4 Mg ha^{-1} yr^{-1} (n=125, sd=3.2) in Europe, the US and China, respectively. Poplar MAI showed a significant response to GDD, precipitation and planting density and formed a quadratic relationship with stand age. The low annual production for poplar globally was probably caused by suboptimal water availability, rotation length and planting density. SEM attributes the variance of poplar growth rate more to climate than to management effects. Case simulations indicated that longer rotation cycle significantly increased soil carbon storage. Findings of this work suggests that management factor of rotation cycle alone could have dramatic impact on the above ground growth, as well as on the soil carbon sequestration of poplar plantations and will be helpful to quantify the long-term carbon sequestration through short rotation plantation. The findings of this study are useful in guiding further research, policy and management decisions towards sustainable poplar plantations.

1. Introduction

Hybrid poplars are among the most widely cultivated hardwood species for pulp and timber production due to their fast growth rate, high light-use efficiency and photosynthetic capacity, strong tolerance to biophysical stress, ease of vegetative propagation and adaptation to a wide variety of soils (Weih, 2004). There is recognition that fast-growing, high-yield plantations will be important in meeting an increasing global demand for wood and biofuel products to substitute fossil fuels and carbon intensive materials such as steel (Canadian Council of Forest Ministers, 2001; Somerville et al., 2010). Understanding how poplar tree grows has become critically important in recent years as the climate warms and estimates of biomass of forest products (including bioenergy products) and stored forest carbon (50 per cent of forest biomass) are needed.

Poplar growth rate vary considerably and are affected by the influence of genetics, climate, and management factors on survival, competition, and vigor of the stand (Mead, 2005). The specific response of poplar growth to climate varies across *Populus* species (Pan et al., 1997), tree size (Mérian and Lebourgeois, 2011), age (Copenheaver et al., 2011), stand structures (Linares et al., 2010; D'Amato et al., 2013), edaphic or productivity gradients (Orwig and Abrams, 1997; Leonelli et al., 2008), and genetic variability across populations (McLane et al., 2011). Although climate influences tree growth, other management practice such as nitrogen fertilization, harvesting practice and planting density can interact with climate to further affect tree growth (Davis et al., 2012). Past studies linking tree growth with climate have often failed to consider the interacting effects of stand characters and management practices. This likely over-simplifies climate-growth relationships and the potential effect of climate and management practice on both tree- and stand-level productivity. Separating the

Abbreviations: ANPP, above-ground net primary production; ED, Ecosystem Demography model; GDD, growing degree days; MAI, mean annual increment of ANPP; P_a, annual precipitation; P_s, growing season precipitation; SEM, structural equation model; SOC, soil organic carbon; SRF (C), short rotation forestry (coppice); T_{ave}, annual average temperature; T_{max}, annual maximum temperature; T_{min}, annual minimum temperature

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impact of climate and management factors on tree growth is useful to guide plantation management in adapting to future climate change conditions.

The cultivation of fast-growing woody plants within short rotation forestry (SRF) can provide a potentially important source of wood production, environmental protection and economy income. Woody species managed by short rotation forestry (SRF) have multiple advantages over annual crops which include enhanced biological diversity, greater carbon sequestration, and reduced inputs of labor, pesticides and fertilizers (Hill et al., 2006; Baum et al., 2009; Don et al., 2011). Rotations shorter than 3 years, however, could lead to reduced yields after several rotations due to physiological problems including stump aging and depletion of carbohydrate reserves (Auclair and Bouvarel, 1992) and causes the depletion of nitrogen due to greater consumption of nitrogen than the supply. The maximum biomass productivity is expected with harvest cycles of 3–11 years (Sartori and Lal, 2006). As poplar increased in age, there was a major reduction in nutrient concentrations in the leaves, indicating that nitrogen limitation might become more evident when poplar stand gets older (Wang et al., 2013). Although aboveground woody biomass is the economically important component of SRF ecosystems, enhanced carbon sequestration in roots and soil has a large impact on CO_2 mitigation and the ecological benefits of SRF related to conservation, water and soil protection, recreation or climate-change mitigation and adaptation are likely to acquire economic value in the future (Calfapietra et al., 2010). SRF can rapidly accumulate C in stable components such as stems, branches and coarse roots, while at the same time cycling C and nutrients to the soil through more labile litter pools consisting of leaves, twigs and fine roots (Sartori and Lal, 2006; Meiresonne et al., 2006). Observed patterns of soil organic carbon (SOC) dynamics under SRF include short-term losses (Hansen, 1993), long term gains (Hansen, 1993; Makeschin, 1994) and no changes (Ulzen-Appiah et al., 2000). Therefore, determining the optimal rotation cycle will not only be beneficial to poplar yields but also the carbon sequestration level. While the yield potential of poplar has been tested by many on-farm studies and has been modeled and reviewed extensively, to date there have been no quantitative reviews on how climate and management practice affect poplar productivity interactively. And information is scarcer on how rotation cycles affect carbon sequestration in the soil (Anderson-Teixeira et al., 2009).

Structural equation modeling is a scientific methodology that aspires to make a strong and explicit connection between empirical data and theoretical ideas (Bollen, 1989; Kline, 2005). It can partition causal influences among multiple variables, allowing the separation effects of different predictors (Grace, 2006). In the present study, we will analyze the effect of climate and management factors on the mean annual increment of poplar ANPP (MAI) intensively and provide guidelines for plantation management to optimize poplar yields and soil carbon sequestration in SRF based on a new, updated quantitative literature review. A structural equation model will be applied to separate the partial effect of climate and management factors on poplar ANPP. We will further run a well-calibrated model on a case site to test the effect of two different rotation cycles on carbon sequestration in poplar SRF.

Sustainable forest management practices could maximize carbon sequestration and maintain stand quality and productivity; therefore, the primary goal of this study was to examine the effect of climate and management practice on the growth of poplar across broad geographical ranges. Such quantitative information out of meta-analysis and mechanical models will be used to (1) understand the productivity variability of poplar plantations under different circumstances; (2) identify the key factors impacting poplar MAI and soil carbon sequestration and separating different impacts of climate and management factors on poplar productivity; (3) evaluating the effect of different harvesting cycles on SRF carbon sequestration.

2. Methods

The peer-reviewed journal articles used to construct the database for this meta-analysis were obtained by searching the Science Citation Index (SCI) of the Institute of Scientific Information and Chinese Journal Full-text Database (CJFD). The inclusion of journal articles in Chinese ensured the completeness of the growth information for poplar plantation, as poplar plantation area in China is not negligible but journal articles published in Chinese often being excluded in meta-analysis due to languages barriers. The list of articles obtained was subsequently cross-checked with references cited in a large number of review articles and books to ensure the inclusion of all articles containing data relevant for this meta-analysis. Any article published before the end of 2014 that includes the following information was included: (1) biomass of poplar plantation; (2) site location; (3) management information on planting density, stand age, nitrogen fertilization level. Trials with pathogen or disease attacks were excluded from the analysis. In total, 29 peer-reviewed articles from China, 28 from other countries were included in this meta-analysis (Appendix A and B). Meteorological data was obtained from published articles or nearby meteorological stations if available or from LOCCLIM (v. 1.0 FAO, Rome, Italy) for a given site when climate data were not available (Wang et al., 2010). Growing degree days (GDD) were calculated in the growing season with the base temperature of 10 °C. The growing season is defined from last frost in spring to the first frost season in autumn or the date of harvest. We assumed studies conducted at different sites, yields from different treatments (e.g. fertilizer treatments), and different growing seasons were independent. In our analysis, studies in which plants were grown under environmental stresses (e.g., drought, low nutrients, light deficiency and etc.) were excluded. The database of poplar plantation contains climate information including annual average (T_{ave}), maximum (T_{max}) and minimum temperature (T_{min}), GDD, growing season precipitation (P_s), annual precipitation (P_a), site information (site location, longitude, latitude, altitude, soil type), management routine (planting date, rotation scheme, nitrogen level, planting density, stand age, herbicide), biomass and soil C. For studies with more detailed growth information, carbon storage in leaves, branches, trunk, roots and litter are also included in the database. Graphical data were extracted from the articles using digitizing software (GET DATA GRAPH DIGITIZER v. 2.22).

Data were firstly sorted and tested for normality. Squared-root transformed MAI were then analyzed using mixed model analysis of variance. The random effects in the mixed model framework were used to account for site-to-site variability that were not accounted for by the fixed-effect covariates but which potentially caused treatments within sites to not be independent (e.g. soil types, soil micro fauna and etc.). Similarly, species random effects account for the differences that could not be accounted for as fixed effects due to limited and unbalanced replication data (Wang et al., 2010). Stepwise regression was conducted to screen a best model to describe MAI (only two way interactions were considered in the analysis). A mixed model taking individual studies and species as random effects was conducted to test the fixed effects of annual average (T_{ave}), maximum (T_{max}) and minimum temperature (T_{min}), GDD, growing season precipitation (P_s), annual precipitation (P_a), stand age, planting density, *N* and their interactions on MAI.

Prior to evaluating multivariate models, bivariate relations between all variables in the model were assessed. We examined scatterplots for the presence of outliers, evidence of skewness or kurtosis, and non-linear relationships up to second-order