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Research paper

Process mechanization models for improved Eucalyptus plantation management in Southern China based on the analysis of currently applied semi-mechanized harvesting operations

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A B S T R A C T

Within the last decades ecological and environmental dimensions were in the focus of Chinese forestry and forest research, but forest operations were much less studied. However, a sustainable, efficient, and continuous forest biomass supply is crucial for a socio-economic development in rural areas, and will contribute to national forest management aims. Today, high supply costs and insufficient biomass supply are bottlenecks for bioenergy and wood processing industry in the P.R. China.

The aim of this study was (1) to characterize, and obtain process data of the current harvesting operations in forest plantations in Southern China, (2) to develop a harvesting productivity model based on the current performance, and (3) to develop applicable models for improved mechanized operations. The study was conducted in Eucalyptus (*Eucalyptus grandis x urophylla*) and Mytilaria (*Mytilaria laosensis*) plantations in steep terrain (8.5–27.5°; respectively 15–52%) in Guangxi province, with a tree diameter at 1.3 m height ranging from 9.8 to 15.4 cm. Via conducting time and motion studies, 237.8 h were recorded and 121.5 m^3 were harvested between October 2008 and May 2010.

The clear cut operations are characterized by basic manual work, except motor-manual work for tree felling and cross-cutting. The overall time consumption for harvesting and extraction was 115.07 min m^{-3}, respectively the productivity was 0.58 m^3 h^{-1}. Manual hauling of the logs was identified as the most time consuming activity. Therefore, priority should be given to extraction activities when trying to improve productivity and work safety through mechanization.

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1. Introduction

China has a long standing history in forestry, with dramatic deforestation over the last century [1], but also high afforestation efforts undertaken during the recent decades [2,3]. Today, China's forest area covers about 22% [4,5]. For years, forestry focused on the ecological, and environmental dimension of forests in specific on the establishment of forests on bare land and along rivers for the protection of water resources, and to prevent soil erosion [6]. Logging bans were introduced to protect these new forests. For that reason, most of these forest stands remain unmanaged until today and do not contribute to any wood supply. Parallel to the huge afforestation programs, strict national harvest quota were launched in 1986 [7]. Both developments, nature protection aims and reduced harvesting quota, led to an unbalanced situation between environmental functions of the forests on the one hand, and forest management including wood supply on the other hand, where the ecological, and environmental role of forests is ranked higher than the wood production for bioenergy and industrial purposes [8].

Today, there is an increasing gap existing between wood supply from secondary forests or industrial wood plantations, and a growing wood demand of the wood processing and bioenergy industry [3]. To reduce this discrepancy, the 'Forest Industrial Base Development Program' (FIBDP) was set up in 2001, continuing until 2015 [9]. It is aiming to plant 130,000 km^2 high productive industrial plantations to deliver 130 hm^3 a^{-1} of round wood; 40% of the national annual consumption [9,10]. In the southern region of China, most of the non-coniferous plantations are established with *Eucalyptus* spp. or with *Mytilaria laosensis*. *M. laosensis* is an

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indigenous, rapidly growing tree species with high biomass production rates and desirable wood quality that is very promising for afforestations in southern China and neighboring regions [11,12]. Both tree species, *M. laosensis* and *Eucalyptus* ssp. show very similar habitus: The trunk is straight and the crown is short.

Eucalyptus plantations in southern China are managed in 5–7 years rotation cycles, which is similar to Eucalyptus plantation management in other parts of the world [13], while Mytilaria plantations are managed in longer rotation periods up to 15 years according to its growth rates and depending on the use of its wood [12]. Log dimensions from these plantations are commonly between 2 and 3 m in length and <20 cm in diameter over bark mainly used for plywood – and particle board production, partially as well for pulp or pellet production, as the diameter of the logs is too small for saw log production [14,15].

As research and development on forest management and harvesting operations were not in the focus in the P.R. China for years – in contrast to forestry research on nature protection, tree physiology, and forest growth aspects – educated forest manager and skilled forest workers in the area of forest operations are rare up to today [16]. Additionally, there is a lack of technical guidelines and standards for forest operations existing [8]. Together with low wage rates this led to simple, less structured, and nonprofessional harvesting operations with a low degree of mechanization and resulted in a low efficiency of wood supply [17]. Even for industrial plantation management there is still room for improvement for China compared to international standards: (1) Growth rates in the sub-tropical and tropical south of China range between 10 and 15 m^3 ha^{-1} a^{-1} in average, with 20–25 m^3 ha^{-1} a^{-1} in best cases [18–20]. (2) Fundamental skills on harvesting operations hardly exist. (3) Economic analyses focus on improvements of the stocking volume, the net revenue of Eucalyptus production against growth rates, market prices, and the use of by-products rather than on improving harvesting productivity and work processes [21–23].

Following this, it was the aim of the study (1) to characterize and obtain data on current harvesting methods and performance in Southern China in fast growing tree plantations, namely *Eucalyptus grandis x urophylla* and *M. laosensis*. Harvesting operations were then (2) modeled in a structured harvesting process chain containing single activities in a defined order to be able to set up later on optimization models. The performance was evaluated in terms of time consumption, productivity, and operation costs. Additionally, it was the aim to (3) model advanced processes with a higher degree of mechanization for a possible future development of harvesting operations to support decisions for introducing new harvesting and/or work concepts in P.R. China. This results in an economic comparison of the current and potential harvesting processes.

2. Material and methods

The study was performed in South China in Guangxi province, the ninth largest province of China, bordering with Vietnam. The southern part of Guangxi is dominated by tropical climate with hot and humid summer, and moderate but dry winter. The experimental sites were located in the surrounding of Pingxiang city (latitude, 22 05′ 49''; longitude, 106 45′ 24″). In this region, forest stands are arranged in a small forest belt along the upper part of hills due to the local relief, and common regional land use practices where each valley bottom and the lower part of the hills are dedicated to agricultural use. The hillside extension is seldom more than 50 m. Soil conditions are unfavorable for logging as stands stock on red soils [24,25].

Experiments have been conducted in 8 monoculture stands managed in a forest plantation system. Out of that 3 were planted with *M. laosensis* and 5 with *E. grandis x urophylla*. The spacing was 2 × 3 m in each stand. Stand ages ranged from 19 to 30 years for *M. laosensis* and 3–9 years for *E. grandis x urophylla*. Terrain conditions are classified as steep, with slopes angles of 8.5–27.5°, respectively 15–52% (Table 1). The decision to include Mytilaria stands was made, because no experimental sites of higher age (and subsequently bigger tree diameter and volume) were available for Eucalyptus, due to local harvesting restrictions. Because both tree species show very similar habitus it was expected that the species-related influence on harvesting performance would be marginal. This assumption was later on supported by multiple regression analysis.

A full inventory was carried out on the surveyed sites prior the experiments in order to define stand characteristics (Table 1). The data were acquired with standard equipment (Vertex IV ultrasonic hypsometer, caliper, measuring tape, etc.). Tree heights were derived after drawing a $d_{1.3}$-to-height curve according to [26] based on height measurements of 12–60 trees per site. To determine the harvest volume all logs were counted per plot (see below), the standard log length was known, and a random sample of log mid-diameters was measured. The sample size was 28–100% of all logs per site, depending on the statistically required minimum sample size.

The common semi-mechanized harvesting process – we aimed to analyze at first – is not structured in a tree-by-tree mode. Trees are felled in series at first by the chainsaw operator. The following activities are performed by other but more than one worker at the same time. They do not process tree-by-tree, but quickly switch between trees without finishing the current activity at one tree to come back later again. Therefore, we decided to collect time consumption data on a tree-related basis as far as possible, and plot-related data for those activities that did not follow tree-by-tree operations. For this reason, each site was divided into small plots of 10 × 40 m each, with 28 plots in total (Table 1). On each plot operations were observed, and analyzed in detail. For the further modeling the mean time consumption/productivity per plot was calculated against the diameter of the tree of mean basal area (d_g) of the individual plot, derived from the diameters of all trees of the respective plot.

Time and motion studies were carried out according to international standards of REFA and IUFRO using snap-back time and activity sampling [27,28]. Time consumption was recorded using common stop watches (1/100 min), and paper notes. Measured time was divided into work time (WT), and non-work time (NWT). Due to a too high variation of NWT only WT was further statistically analyzed. WT was split into functional activities with clear recognizable beginning and ending points. In particular these were: Removing vegetation, felling, de-branching, marking assortments, cross-cutting, and extraction. For the time study, each functional activity was further divided into elements, named actions (Table 2) [27]. Those are repeating work elements within single activities that can be summarized to work cycles. The harvesting mode was clear cutting on all sites.

An intensive literature study, and interviews with scientists at the Experimental Center of Tropical Forestry (ECTF), a research institute of the Chinese Academy of Forestry (CAF), were performed to become familiar with the management context of fast growing plantations in Southern China, and the relevance of harvesting operations within that management. The results of this enquiry are not presented in this paper.

For the economic analysis labor cost was set to 10 CNY equals to 1.11 EUR per hour WT (currency conversion from 2011) to ensure consistent results across the study. This labor cost is an average of the wage paid for forest labor in the study region at this time (2011). Actual wages were negotiated daily and might have been slightly

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