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Tree dieback affects climate change mitigation potential of a dry afromontane forest in northern Ethiopia

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ABSTRACT

Extreme climatic events such as droughts are likely to result in huge and long-lasting effects on regional ecosystem health if large numbers of foundation tree species continue to die. Although deforestation is severe in the Ethiopian highlands, some remnants of dry afromontane forests still exist. However, the resilience of these forests under climate change scenarios is unknown. Therefore, we studied (1) the extent and spatial patterns of standing dead stems along an elevational gradient and (2) the effects of dieback on forest carbon sequestration potential and aboveground carbon stocks, in *Juniperus procera* and *Olea europaea* dominated dry afromontane forest in northern Ethiopia, using allometric models combined with tree ring analysis. *Juniperus procera* and *Olea europaea* constitute 67% of the total tree population. Tree dieback affected a quarter of the total population. This loss is critical because 92.2% of snags belong to *J. procera* and *O. europaea*, which are the foundation species of the study forest. The total estimated mean aboveground C-stock was 19.3 (±3.9) Mg C ha^{-1}. Of this estimate, snags contributed 34.5% of total C-stock. The estimated annual C-sequestration potential of the study forest was 0.33 (±0.03) Mg C ha^{-1} year^{-1}, which is 27% less when compared to the pre-tree dieback C-sequestration potential. We found a decreasing trend in tree dieback with increasing elevation, which implies that the aboveground C-stocks and climate change mitigation potentials of the forest, was highly affected at lower elevations which is the drier part of the landscape. Tree ring analysis showed that trees reach medium-sized stem diameter (i.e., 20–25 cm) after no less than 100 years, indicating that the effect of forest dieback on C-sequestration potential and ecosystem function is long-lasting. Our results provide information on the magnitude of tree dieback and its long-lasting impact on forest carbon fluxes and forest ecosystem services. Evidently, the results substantiate the importance of protecting such forest to maintain the quality of the environment and to reduce efforts and cost for forest restoration after major loss. Finally, the information gained by this study provides baseline information for comparison of future carbon sequestration estimates.

1. Introduction

Tropical forests play key roles in mitigating climate change (Saatchi et al., 2011). The reduction of tropical forest degradation and carbon emission from tropical forests have been proposed as one way to stabilize the atmospheric carbon cycle and to minimize impacts of future climate change (e.g., Corbera et al., 2010). However, climate change and anthropogenic stress factors are accelerating the rate of tropical forest degradation and increasing CO_2 emission (Gibbs et al., 2007). In line with this, studies in Africa (Kherchouche et al., 2012), Asia (Nieuwstadt and Sheil, 2005), Australia (Fensham et al., 2009), Europe (Dobbertin et al., 2007), and America (Williams et al., 2010) have reported drought induced tree dieback, which diminishes ecosystem services that humans can obtain from forests (Gonzalez et al., 2012). Concerns about forest degradation and reduction in the associated ecosystem services are rising because the frequency of drought events, temperature increase, and heat waves are projected to increase in the future (IPCC, 2007). Particularly, areas that are already rather dry are the most likely to become even drier in the future (Dai, 2012), indicating that many dryland forests and woodland areas are more vulnerable to climate-induced forest dieback (Allen et al., 2010; Peng et al., 2011). In this regard, ongoing climate change might accelerate tree mortality especially in countries like Ethiopia,

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where dryland areas cover 72% of the total land area (Lemenih and Kassa, 2011).

The ecosystem services that can be generated from the dry afromontane forests of Ethiopia, are threatened due to forest degradation induced mainly by anthropogenic pressures, including extensive forest resources utilization and land use changes (Bongers et al., 2006; Tesfaye et al., 2014; Zeleke and Hurni, 2001). In the study forest, *J. procera* and *O. europaea* are dominant and so that they are regarded as foundation tree species (e.g., Ellison et al., 2005).

Earlier studies conducted in the northern dry afromontane forests of Ethiopia have generated substantial information on population structure (Wassie et al., 2010), biodiversity (Aerts et al., 2006; Aynekulu et al., 2012), natural regeneration (Aynekulu et al., 2009), and soil seed bank (Lemenih and Teketay, 2006). However, these studies did not investigate the aboveground biomass and carbon dynamics, the extent of tree dieback and the associated loss of aboveground carbon and annual carbon sequestration potential of the remnant dry afromontane forest.

As a result, the importance of the remnant dry afromontane forests of Ethiopia for climate change adaptation and mitigation and their resilience against increasing drought is hardly known. However, such information is critical to design forest conservation strategies that help reducing the impacts of climate change (Chidumayo et al., 2011). Thus, the objectives of this study were to (i) investigate the current extent of forest degradation due to tree dieback, (ii) quantify the effects of tree dieback on aboveground carbon stock and carbon sequestration potential of the study forest, and (iii) determine growth dynamics of foundation tree species. Based on former studies (e.g., Ellison et al., 2005, 2010) we hypothesized that declining of foundation tree species (e.g., *J. procera* and *O. europaea*) from the system may have long-lasting effects on forest fundamental ecosystem processes and services.

2. Methods and materials

2.1. Study area and forest

This study was carried out in the Desa'a dry afromontane forest, located (13°36′ to 13°56′N and 39°48′ to 39°51′E) in the semiarid agro-ecological zone of Tigray region, northern Ethiopia (Fig. 1). The study area lies in the transition zone between the *Acacia-Commiphora* woodland and shrubland in the Afar lowlands (1400 m.a.s.l) and the dry evergreen afromontane forest and grassland complex in the Tigray highlands (2800 m.a.s.l). Topographically, the study area is mountainous and nearly 45% of the area has slope inclination greater than 30% (Aynekulu, 2011). The geological structure is diverse, playing a major role for soil variability. A large part of Desa'a forest is characterized by shallow soils and frequent rock outcrops of Enticho sandstone and Crystalline Basement (Asrat, 2002). The dominant soil types are Leptosols, Cambisols, Vertisols, Regosols, and Arenosols (Aynekulu, 2011). Desa'a forest is a dry afromontane forest dominated by *Juniperus procera* and *Olea europaea subsp. cuspidatae.* Some of the other co-occurring tree species (hereafter, other species) in the study forest are *Solanum schimperianum* Hochst. ex A. Rich, *Dodonaea viscosa Jacq*, *Maytenus senegalensis* (Lam.) Exell, *Carissa edulis* Vahl, *Rhus sp. nov. A*, and *Clutia lanceolata* Forssk, in decreasing order of abundance (Aynekulu et al., 2009).

2.2. Climate characteristics of the study area

The regional climate shows a distinct seasonality in precipitation with a unimodal rainfall pattern. The peak rainy season lasts from July to August and the dry season from October to June. Based on data obtained from the National Meteorological Agency of Ethiopia for the years 2006–2013, the mean annual rainfall at the nearest climate station (i.e., Atsibe station, 13°53′N; 39°44′E; 2711 m.a.s.l.) was 602.1 (±62.1) mm. The mean minimum and maximum monthly mean temperatures were 9.2 (±0.6) °C and 19.9 (±0.42) °C, respectively (Fig. 2).

2.3. Field measurements, sample collection and wood density measurement

We established five transects perpendicular to the main slope, considering topographic variation, tree size and species composition. In total, 57 plots of 50 m × 50 m size were set up at 100 m elevational intervals. In each plot, we measured biometric parameters such as stem diameter (D) at breast height (1.3 m above the ground) and tree height (H) for individual living trees and snags (i.e., standing dead trees) using diameter tape and clinometer, respectively. We documented the geographic coordinates of each plot and derived the elevation data from a topographic map (1:50,000). To minimize errors, we did not measure the height of strongly bent trees or snags that have lost the total crown area. The proportion of trees without height measurement was 20.5%, 21% and 28.3% for *J. procera*, *O. europaea* and other species, respectively.

To determine the tree age and annual radial increment rate, we collected 20 stem discs from different living trees and snags of *J. procera*. The samples were transported to the dendrochronological laboratory of the World Agroforestry Center-(ICRAF), Nairobi, Kenya, and air-dried and sanded. To determine wood density, we used the stem discs harvested for ring analysis. We extracted wood samples of about five cm width from each disc that include the sapwood and heartwood parts of the discs. For wood density measurement, the samples were rehydrated for one day (Martínez-Cabrera et al., 2009) and the wood density was analyzed as described by Williamson and Wiemann (2010): a beaker with enough size to hold the sample was filled with water and placed on an electronic balance of 0.01 g precision. Then, the wood sample was carefully immersed in the water. The displacement weight by the sample was recorded and converted to sample fresh volume using the formula: displacement weight (g)/density of water at a standard temperature and pressure. Afterward, the samples were placed in the oven for 72 h at 105 °C to obtain dry mass. Wood density (ρ) of *J. procera* was calculated from dry weight to fresh volume ratio. For *O. europaea* and all other co-occurring tree species, values of ρ were derived from the global wood density database (Zanne et al., 2009). From this database, a species-specific wood density, 0.913 g/cm^3 was obtained for *O. europaea.* For other species, an average wood density value of ρ = 0.58 g/cm^3 calculated from 279 tropical Africa tree species was used.

2.4. Site-specific tree height-diameter allometry

Tree height (H) is one of the most important predictor in quantifying aboveground forest biomass and carbon fluxes (Chave et al., 2014). Although, the inclusion of H as predictor can considerably improve the accuracy of forest aboveground biomass estimations (Chave et al., 2005; Feldpausch et al., 2012), measuring tree height is difficult, especially in a mixed-species tropical forest (Feldpausch et al., 2011). To overcome this problem, tree height is usually derived from regional or continental-scale H:D models. However, the H–D relationship may considerably vary between species, vegetation structures, geographical locations and due to climatic factors (Feldpausch et al., 2011; Osman et al., 2013). Hence, it is crucial to develop site-specific H:D relationships for accurate estimation of H from observed D, for improving the accuracy of local biomass estimates (Ketterings et al., 2001; Osman et al., 2013).