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Fundamental but underrepresented: root carbon stocks in African montane forests

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African montane forests harbor some of the greatest biodiversity worldwide, with high levels of species endemism. However, the loss of these forests through fragmentation, deforestation and climate change has been rapidly increasing in recent years. Montane forests in Africa are more susceptible to changes in climate than their lowland counterparts, yet their ecological value is still underrepresented. These montane forests have recently been highlighted as a major aboveground carbon (C) stock. The estimated 149.4 Mg C ha^{-1} from aboveground live trees surpasses estimates from the Intergovernmental Panel on Climate Change for these endangered forests, and exceeds reported values for neotropical montane and lowland forests by up to 70%. Despite the tremendous implications of these findings, coordinated and available research on the C storage potential of the other share of African montane forest biomass, that is in tree roots, is largely missing. Broadly estimated from the allometry of aboveground C stocks and from root:shoot ratios in lowland forests, more than 60 Mg C ha^{-1} can be stored in African montane forest roots, about 40% more than previously determined. While this broad estimation points at the potential importance of root C stocks in African montane forests, it also unveils a far-reaching knowledge gap. Here, we advocate for a more quantitative representation of the root C stock from dominant forest tree species of African tropical montane forests and ultimately for a better grasp on tree C stocks from this endangered ecosystem.

KEYWORDS

allocation, climate change, elevation, endangered forests, root biomass, tropics

Introduction

Tropical roots account for an estimated 18%–21% of total tree carbon (C) content, yet this tree organ is usually misrepresented in tropical C stock estimations (Cairns et al., 1997). Evidence shows that the root biomass allocation of trees increases with elevation on tropical mountains (Kitayama and Aiba, 2002; Leuschner et al., 2007), leading to increased root:shoot ratios and up to four times greater root C allocation in montane than in lowland forests (Moser et al., 2011). This change in biomass and C allocation to roots is partially attributed to greater incidence of strong winds, for which trees grow bigger and develop deeper coarse roots (roots >2 mm in diameter) to improve structural stability and anchorage (Fahey et al., 2016). Further, due to soil phosphorus (P) limitations in highly weathered, wet soils at higher elevations (Silver et al., 1999;

Kitayama and Aiba, 2002; Fahey et al., 2016), trees grow more fine root biomass (roots <2 mm in diameter) (Cavelier, 1992; Kitayama and Aiba, 2002; Moser et al., 2010) to optimize resource uptake (Bloom et al., 1985). Despite this understanding of the greater share of root biomass in tropical montane forests, most observations are from tropical lowlands, while those from montane forests are mostly from the neotropics (Iversen et al., 2021).

A recent study suggests that fine root productivity alone can represent up to three-fourths of total net primary productivity in African montane forests (Sierra Cornejo et al., 2020). Another study suggests that the fine root C stock in African montane forests is almost two times greater than in neotropical montane forests at comparable elevations ($Cstock_{fr} = 4.0$ Mg C ha^{-1} in $n = 2$ African montane forests in Ethiopia; $Cstock_{fr} = 2.4$ Mg C ha^{-1} in $n = 5$ neotropical montane forests in Peru; Huaraca Huasco et al., 2021). Moreover, the C-demanding transfer of tree C to root respiration, exudation, and mycorrhizal fungi is not represented in these allocation studies, further contributing to the underestimation of the C sink of African montane tree roots and of forest ecosystems as a whole. Thus, information on the influence of elevation on root biomass in the C-rich paleotropic montane forests of Africa remains scarce (Lewis et al., 2009; Nyirambangutse et al., 2017).

African montane forest roots remain *terra incognita* in large databases

African montane forests cover about 16% of the global estimated area of tropical montane forests (Scatena et al., 2010), mainly restricted to a few and discontinuous highland areas in western-central, eastern and southern Africa (Figure 1). Recently, African montane forests have become the focus of research attention, because, in addition to their high biodiversity and their ecological and hydrological value (Nyirambangutse et al., 2017; Cuni-Sanchez et al., 2021), these forests have been under particular threat through fragmentation and deforestation (Lézine et al., 2013; He et al., 2023). From 2001 to 2018, 6.4 million ha of the African mountain forests were lost, which represents 10% of their previous extension (He et al., 2023). While this relative montane forest loss rate is the fastest worldwide and further accelerating, a comprehensive representation of African montane forests in global trait databases and in global C cycle projections is absent. Such information will be critical to inform policymakers on sustainable forest management in Africa.

Recent efforts have been directed toward the compilation of trait data into collaborative databases, which enable large-scale modeling of global biogeochemical cycles and climate change effects. They also allow for a relatively rapid look into research trends, and while they do not necessarily represent a systematic review of the literature, they do give an impression of the range of research interests. Currently, the biggest database of coarse and fine root traits (Fine-Root Ecology Database FRED) shows that there are about 50 % less root data points from tropical regions than from temperate regions (Iversen et al., 2021). Further, there are around 27 studies in FRED that have measured root biomass and root production in terrestrial forest ecosystems in Africa since 1953 (Iversen et al., 2021), but only four are from montane forests (Figure 1). When searching specifically for root biomass or production in montane Africa forests using the Web of Science database, we found five additional studies for the continent, from which one includes two forested sites (Figure 1). From these existing root studies in ten montane forests, there is great variability in the methods and root entity used, which impedes trait upscaling and creates a major knowledge gap on root components in African forests. Consequently, sound predictions of the C sink of montane forest ecosystems of the African continent are hindered.

Estimated belowground C stock in African montane forest roots

A recent pantropical review on root:shoot ratios and root biomass has shown great variability in the mathematical construction of allometric equations (Waring and Powers, 2017), likely attributed to the methodological variations used to quantify root biomass and its distribution with depth. The root:shoot ratio of mature pantropical trees ranged from 0.07 to 2.12 g g^{-1} [data from Waring and Powers (2017), excluding seedlings/saplings, and from own recent literature search; Supplementary Table S1], which reflects the tremendous variation in species, age, environmental conditions, and methodologies used. When considering only those studies from lowland forests in Africa, the root:shoot ratio ranged from 0.20 to 0.52, with an average of 0.39 g g^{-1}. If we apply this lowland average to recent findings of aboveground C stocks in African montane forests (Cuni-Sanchez et al., 2021), we can expect more than *c.* 59.3 Mg C ha^{-1} stored in undisturbed African montane tree roots. This is about 41% more than showcased for secondary montane forests in Rwanda (42 Mg C ha^{-1}; Nyirambangutse et al., 2017).

While the above calculations provide a simple estimate of belowground stocks, the allometric equations utilized have not been validated for African montane forests. This is partly because, according to the database from FRED (Iversen et al., 2021), excavation studies of entire root systems from different tree species have not been conducted in the African continent. As a result, it is only possible to estimate root biomass for African montane forests using equations from other ecosystems. Thus, more accurate estimations of root C stocks and sequestration potentials, as well as comparisons with lowland forests and analogues in Southeast Asia and the neotropics, are urgently needed. This will allow for more realistic predictions of the impacts of global changes on montane tree C stocks across the tropics and will aid mitigation measures such as Reducing Emissions from Deforestation and Forest Degradation (REDD+).

Conclusion

Here, we advocate for the development of root biomass allometric equations based on direct methods (e.g., tree excavation and soil pits; Addo-Danso et al., 2016) from the most common tree species along gradients of elevation, climate, forest types, soil type, and successional stage and that follow a standardized trait measurement protocol (Waring and Powers, 2017). These allometric equations will inform current integrative networks of distributed forest plots such as AfriMont (Montane Africa Plot Network), AfriTRON (African Tropical Rainforest Observation Network), and GEM (Global Ecosystem Monitoring Network), which are taking measurements of fine root biomass and production, turnover, and lifespan to generate large root trait datasets for a better understanding of fine root C transfer in African forests.

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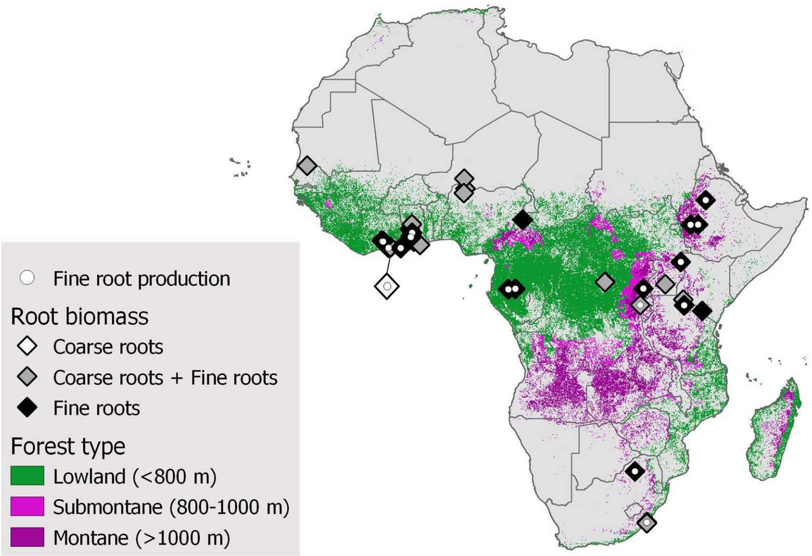

FIGURE 1
Map of the African continent showing the distribution of root biomass studies (white diamonds represent coarse roots, black diamonds represent fine roots, and gray diamonds represent fine and coarse roots) and fine root production (white circles inside diamonds) in forest ecosystems. The data are primarily extracted from the Fine-Root Ecology Database, version 3 (FRED3; Iversen et al., 2021) and complemented by a web of science search. The distinction of lowland forests and montane forests was made combining two geo-raster which contained information on vegetation types (ESA, 2017) and elevation (NOAA National Geophysical Data Center, 2022), respectively. We followed the parameters of 0–800 m for lowland forests, 800–1,000 m for submontane forests as described in Cuni-Sanchez et al. (2021) and define forests at >1,000 m as montane forests.

Similar efforts will be needed to equally ensure a better representation of African coarse roots in trait databases, which play an important role in the whole-tree C budget and in forest biomass allocation patterns. Such an endeavor would provide a much better representation of African tree roots in terrestrial ecosystem models and help to improve our understanding of the contribution of African tropical montane forests to the global C budget. Moreover, soil C stocks might represent the greatest C storage in these forests, so investigations into the influence of the root C stock on soil C sequestration in these forests is also needed. In conclusion, we plead for an extensive exploration of the subsurface biomass in African montane forest ecosystems, for fundamentally improving predictions of the tree C cycle of this endangered ecosystem under conditions of dramatic biodiversity loss and progressing climate change.

Data availability statement

The original contributions presented in the study are included in the article/Supplementary material, further inquiries can be directed to the corresponding author.

Author contributions

DY: Conceptualization, Data curation, Formal analysis, Methodology, Writing – original draft, Writing – review & editing. SA-D: Data curation, Resources, Validation, Writing – review & editing. JP: Resources, Writing – review & editing. IM: Conceptualization, Funding acquisition, Supervision, Validation, Writing – review & editing.

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Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

Supplementary material

The Supplementary material for this article can be found online at: https://www.frontiersin.org/articles/10.3389/ffgc.2023.1273996/full#supplementary-material

References

Addo-Danso, S. D., Prescott, C. E., and Smith, A. R. (2016). Methods for estimating root biomass and production in forest and woodland ecosystem carbon studies: a review. *For. Ecol. Manag.* 359, 332–351. doi: 10.1016/j.foreco.2015.08.015

Bloom, A. J., Chapin, F. S., and Mooney, H. A. (1985). Resource limitation in plants – an economic analogy. *Annu. Rev. Ecol. Syst.* 16, 363–392. doi: 10.1146/annurev.es.16.110185.002051

Cairns, M. A., Brown, S., Helmer, E. H., and Baumgardner, G. A. (1997). Root biomass allocation in the world's upland forests. *Oecologia* 111, 1–11. doi: 10.1007/s004420050201

Cavelier, J. (1992). Fine-root biomass and soil properties in a semideciduous and a lower montane rain forest in Panama. *Plant Soil* 142, 187–201. doi: 10.1007/BF00010965

Cuni-Sanchez, A., Sullivan, M. J. P., Platts, P. J., Lewis, S. L., Marchant, R., Imani, G., et al. (2021). High aboveground carbon stock of African tropical montane forests. *Nature* 596, 536–542. doi: 10.1038/s41586-021-03728-4

ESA (2017) Land cover CCI product user guide version 2. Tech Rep. Available at: https://maps.elie.ucl.ac.be/CCI/viewer/download/ESACCI-LC-Ph2-PUGv2_2.0.pdf

Fahey, T. J., Sherman, R. E., and Tanner, E. V. (2016). Tropical montane cloud forest: environmental drivers of vegetation structure and ecosystem function. *J. Trop. Ecol.* 32, 355–367. doi: 10.1017/S0266467415000176

He, X., Ziegler, A. D., Elsen, P. R., Feng, Y., Baker, J. C. A., Liang, S., et al. (2023). Accelerating global mountain forest loss threatens biodiversity hotspots. *One Earth* 6, 303–315. doi: 10.1016/j.oneear.2023.02.005

Huaraca Huasco, W., Riutta, T., Girardin, C. A. J., Hancco Pacha, F., Puma Vilca, B. L., Moore, S., et al. (2021). Fine root dynamics across pantropical rainforest ecosystems. *Glob. Chang. Biol.* 27, 3657–3680. doi: 10.1111/gcb.15677

Iversen, C., McCormack, M. L., Baer, J. K., Powell, A. S., Chen, W., Collins, C., et al. (2021) *Fine-root ecology database (FRED): a global collection of root trait data with coincident site, vegetation, edaphic, and climatic data*. Version 3.

Kitayama, K., and Aiba, S.-I. (2002). Ecosystem structure and productivity of tropical rain forests along altitudinal gradients with contrasting soil phosphorus pools on mount Kinabalu, Borneo. *J. Ecol.* 90, 37–51. doi: 10.1046/j.0022-0477.2001.00634.x

Leuschner, C., Moser, G., Bertsch, C., Röderstein, M., and Hertel, D. (2007). Large altitudinal increase in tree root/shoot ratio in tropical mountain forests of Ecuador. *Basic Appl. Ecol.* 8, 219–230. doi: 10.1016/j.baae.2006.02.004

Lewis, S. L., Lopez-Gonzalez, G., Sonké, B., Affum-Baffoe, K., Baker, T. R., Ojo, L. O., et al. (2009). Increasing carbon storage in intact African tropical forests. *Nature* 457, 1003–1006. doi: 10.1038/nature07771

Lézine, A.-M., Assi-Kaudjhis, C., Roche, E., Vincens, A., and Achoundong, G. (2013). Towards an understanding of west African montane forest response to climate change. *J. Biogeogr.* 40, 183–196. doi: 10.1111/j.1365-2699.2012.02770.x

Moser, G., Leuschner, C., Hertel, D., Graefe, S., Soethe, N., and Iost, S. (2011). Elevation effects on the carbon budget of tropical mountain forests (S Ecuador): the role of the belowground compartment. *Glob. Change Biol.* 17, 2211–2226. doi: 10.1111/j.1365-2486.2010.02367.x

Moser, G., Leuschner, C., Röderstein, M., Graefe, S., Soethe, N., and Hertel, D. (2010). Biomass and productivity of fine and coarse roots in five tropical mountain forests stands along an altitudinal transect in southern Ecuador. *Plant. Ecol. Div.* 3, 151–164. doi: 10.1080/17550874.2010.517788

NOAA National Geophysical Data Center (2022). *ETOPO1 1 arc-minute global relief model*. NOAA National Centers for Environmental Information.

Nyirambangutse, B., Zibera, E., Uwizeye, F. K., Nsabimana, D., Bizuru, E., Pleijel, H., et al. (2017). Carbon stocks and dynamics at different successional stages in an Afromontane tropical forest. *Biogeosciences* 14, 1285–1303. doi: 10.5194/bg-14-1285-2017

Scatena, F. N., Bruijnzeel, L. A., Bubb, P., and Das, S. (2010). "Setting the stage" in *Tropical montane cloud forests: Science for conservation and management*. eds. L. A. Bruijnzeel, F. N. Scatena and L. S. Hamilton (Cambridge: Cambridge University Press), 3–13.

Sierra Cornejo, N., Hertel, D., Becker, J. N., Hemp, A., and Leuschner, C. (2020). Biomass, morphology, and dynamics of the fine root system across a 3,000-M elevation gradient on Mt. Kilimanjaro. *Front. Plant Sci.* 11:13. doi: 10.3389/fpls.2020.00013

Silver, W. L., Lugo, A. E., and Keller, M. (1999). Soil oxygen availability and biogeochemistry along rainfall and topographic gradients in upland wet tropical forest soils. *Biogeochemistry* 44, 301–328. doi: 10.1007/BF00996995

Waring, B. G., and Powers, J. S. (2017). Overlooking what is underground: root:shoot ratios and coarse root allometric equations for tropical forests. *For. Ecol. Manag.* 385, 10–15. doi: 10.1016/j.foreco.2016.11.007