CORRESPONDENCE:

Radar backscatter and forest biomass

To the Editor — In relation to the use of radar backscatter to estimate forest biomass, Woodhouse *et al.*[1] state that our study[2] provides an extreme example of a common analytical error, namely fitting a log function instead of a sigmoidal function. In fact, there is almost no difference between these functions, because the slope of the log function is very small in higher biomass ranges.

Furthermore, they criticize us for using the fitted function and not the data to calculate the saturation. The authors make the incorrect statement that the fitted function is used to project sensitivity to aboveground biomass (AGB) values higher than 600 tonnes per hectare (t ha^{-1}). Most studies on radar and AGB estimate the saturation through visual interpretation. In contrast, we calculated the saturation level on the basis of the radiometric accuracy of the radar data and a chosen accuracy level. We used two accuracy levels (50 and 100 t ha^{-1}) and clearly state in the paper that “within the accuracy interval of 50 t ha^{-1} the estimations are supposed to be accurate whereas estimations within the 100 t ha^{-1} accuracy interval are only indicators for the spatial AGB distribution.” We found a maximum saturation of 300 t ha^{-1} at the accuracy level of 50 t ha^{-1} and emphasized that the 100 t ha^{-1} saturation level is not accurate enough for a reliable AGB estimation.

Woodhouse *et al.* contest the wording ‘direct measurement’. However, we stated prominently that “no remote sensing can directly measure biomass”. If the whole abstract is read, it is clear that we speak of AGB estimations based on radar, even if we use the term ‘direct measurement’.

By using the term ‘direct AGB estimation/measurement’, we refer to the ‘direct remote sensing approach’ to estimate AGB, introduced by Goetz *et al.*[3], for which radiometric satellite measurements are calibrated to field-based AGB values. In contrast, the ‘indirect AGB estimation’ refers to the ‘stratify and multiply approach’ which links a biomass value determined for a specific vegetation type to a remote-sensing-based land-cover map.

In our opinion, it makes sense to emphasize the difference between these two completely different biomass estimation approaches as they lead to differing results, which we also showed in our paper[2]. ❒

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CORRESPONDENCE:

Forest biomass and the science of inventory from space

To the Editor — Although we agree that the term ‘direct measurement’ of aboveground biomass in the remote-sensing literature is inappropriate, Woodhouse *et al.*[1] wrongly criticize some valid results in the literature and paint a misleading picture of the current state of the art in radar remote sensing.

Aboveground biomass (AGB) can only be measured directly by destructively harvesting trees, and measuring the mass by scales calibrated to an internationally acceptable standard[2]. In all field inventory and remote-sensing techniques, measurements of forest attributes are used in a model to estimate biomass and report errors[3]. However, the studies cited by Woodhouse *et al.*[1] explicitly identify their methods as indirect estimations and provide associated errors, using the term to distinguish estimates based directly on backscatter from those that first estimate height and then use this to infer biomass.

Quantifying uncertainty is challenging for both field inventory and remote-sensing estimations[3,4]. Uncertainty is quantified in terms of accuracy and precision, with accuracy being the difference between an estimate and the true value, and precision being the reproducibility or the variance among repeated estimates[2]. Thus, good accuracy is always more difficult to obtain than good precision. A precise estimate of forest biomass can usually be achieved with both replicated remote-sensing or field inventory estimates. For precise radar estimates of AGB, remote-sensing estimates must be corrected for factors such as changing soil moisture or topography[5]. However, field-inventory methods also suffer from methodological biases[3]. With careful selection of ground data for calibration of radar models, relative error of about 20% can be achieved on biomass for forest stands with mixed species and complex landscapes[5]. Hence, radar or lidar remote-sensing techniques from space can provide systematic and accurate estimates of AGB. Once calibrated with limited but unbiased forest inventory samples, such estimates not only represent an alternative to conventional field inventory methods but, unlike field inventory data, allow spatially refined gridded maps of biomass to be produced over time[6].

Radar backscatter is sensitive to vegetation fresh biomass[7]. At long wavelengths (0.7 m or longer), radar penetrates deep into the canopy and the backscatter energy depends on a combination of variables including the size, number density, and the water content and wood specific gravity of branches and stems. However, radar backscatter suffers from gradual loss of sensitivity as biomass increases. The phenomenon referred to as 'saturation' occurs often in radar backscatter at shorter wavelengths, but is not unique to radar and forests, and can occur in all types of remote-sensing measurements, even for non-woody vegetation. However, at longer wavelengths (>0.7 m), radar backscatter remains sensitive to a wide range of AGB.

Variation in tree density may impact radar backscatter, but does not cause loss of sensitivity. In spatially heterogeneous forests, the largest source of error in deriving the relationship between radar backscatter and biomass is from the geometry of measurement and the difference between the biomass sensed by radar and that sampled on the ground. The ground data are too often based on small inventory plots, leading to large errors that are often ignored. By increasing the plot size used for remote-sensing calibration, the relationship improves significantly[5].

Woodhouse *et al.*[1] criticize the use of regression models that convert the backscatter into AGB, which are derived using collections of sites spanning a range of forest types. Mixing data across forest types to sample a wider range of AGB is a common statistical approach used not only in most remote-sensing studies but also repeatedly in field estimation, where inventory data from a limited number of trees is used to predict AGB values over the full range of trees from different regions. Regardless of the type of models used, prediction never implies accuracy.

A systematic radar observation at long wavelengths from space, as recommended by European Space Agency's BIOMASS mission, accompanied by remote-sensing-specific field inventory data provides the only way to circumvent the limitations of field inventory-only biomass monitoring at the global scale. Extending current studies beyond the landscape scale is a priority if radar remote sensing is to fulfil its potential in the context of the Reducing Emissions from Deforestation and Forest Degradation programme (www.un-redd.org). ❐

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CORRESPONDENCE:

Drought-induced decline in Mediterranean truffle harvest

To the Editor — With a price of up to €2,000 kg^{-1} the Périgord black truffle (*Tuber melanosporum*; hereinafter truffle) is one of the most exclusive delicacies[1]. However, harvests of this ectomycorrhizal ascomycete have declined in its natural Mediterranean habitat[2], despite cultivation efforts since the 1970s[3]. Satisfying explanations for the long-term decrease in both natural and planted truffle yields are lacking. Understanding microbial below-ground processes remains challenging because experimental settings generally don't have the necessary degree of real-world complexity[4], long enough mycological observations are scarce[5] and quantitative information from natural truffle habitats and plantations is usually not available[2,3,6].

Here we seek to understand how climate can affect truffle production, either directly, or indirectly via their symbiotic host plants. We did this by analysing annual inventories of regional truffle harvests from northeastern Spain (Aragón), southern France (Périgord), and northern Italy (Piedmont and Umbria) (Supplementary Fig. S1 and Table S1). We found that changes in truffle production (tons yr^{-1} from 1970–2006) were most similar between Aragón and Périgord ($r = 0.59$; $p < 0.001$), and non-significant between Périgord and Piedmont–Umbria ($r = 0.12$). The observed regional-scale coherency probably originates from common climatic cues that synchronize truffle fruiting among large parts of the western Mediterranean Basin. Spanish and French truffle harvests showed significant positive correlation with summer rainfall ($r = 0.72$ and 0.43; $p < 0.001$), whereas lower agreement was found between Italian truffle production and precipitation ($r = 0.22$; Supplementary Fig. S2). These different sensitivity levels seem reasonable as the Italian truffières are generally experiencing twice as much summer rainfall as the Spanish areas, with the French sites ranging in between (Supplementary Fig. S3).

When averaging the three truffle records (Supplementary Table S1), their subcontinental mean correlates positively and negatively at the 99.9% significance level with gridded June–August precipitation totals and temperature maxima ($r = 0.60$ and -0.57), respectively (Fig. 1a,b). Natural and cultivated Mediterranean truffle yields — seasonally restricted to November–February[3] — depend on variations in summer climate[6], with wet and cold conditions promoting fruit body formation. Given the symbiotic fungi–host association[7], we postulate that competition for summer soil moisture between host plants and their mycorrhizal