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Research article

Effects of exotic *Eucalyptus spp.* plantations on soil properties in and around sacred natural sites in the northern Ethiopian Highlands

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Abstract: Species of the genus *Eucalyptus* (common name eucalyptus) are widely planted all across Ethiopia—including on large areas of land previously allocated to food production. In recent decades eucalyptus has also increasingly been planted on lands around and within "church forests," sacred groves of old-aged Afromontane trees surrounding Ethiopian Orthodox Tewahido churches. These revered holy sites have long been recognized for their cultural values and also for their ecosystem services—including their potential to support species conservation and restoration, as church forests are some of the only remaining sanctuaries for many of Ethiopia's indigenous and endemic plant and animal populations. Ethiopian Orthodox church communities have a long history of planting and nurturing indigenous tree seedlings to sustain church forest groves. However, due to the fast-growing nature of eucalyptus combined with its widely recognized socio-economic benefits (as fuelwood, charcoal, construction wood, etc.), this introduced species has been widely planted around church forests—in some cases even replacing native tree species within church forests themselves. In many developing country contexts the introduction of exotic eucalyptus has been shown to have ecological impacts ranging from soil nutrient depletion, to lowering water tables, to allelopathic effects. In this study, we collected soil samples from indigenous forest fragments (church forests), adjacent eucalyptus plantations, and surrounding agricultural land to examine how eucalyptus plantations in Ethiopian Orthodox church communities might impact soil quality relative to alternative land uses. Soil properties, including organic matter, pH, total nitrogen, and total phosphorus were measured in samples across 20 church forest sites in South Gondar, East Gojjam, West Gojjam, Awi, and Bahir Dar Liyu zones in the Amhara Region of the northern Ethiopian Highlands. Findings indicate that although soil in eucalyptus stands is more acidic and has lower organic matter and nutrient levels than nearby church forests, eucalyptus plantations also exhibit consistently higher organic matter and nutrient levels when compared to adjacent agricultural land. These findings suggest that eucalyptus planting could potentially benefit soil fertility on land that has been degraded by subsistence agriculture.

Keywords: Eucalyptus; agricultural land; church forests; Ethiopia; soil properties

1. Background

Eucalyptus spp. (common name eucalyptus) are a group of trees native to Australia, with a small number of species also indigenous to Indonesia, the Philippines, and New Guinea [1,2]. Eucalyptus dominates most of the natural forests in their natural habitat, growing in a range of diverse climates and soil types [3]. In Ethiopia, eucalyptus tends to outperform other exotic species and native species alike in terms of production and farmer income generation—this can be attributed to a number of biological and physiological characteristics including high fecundity [1], rapid growth rates [4], allelopathic properties [5] and a tolerance for a wide range of soil and climate niches [2,3,6]. Eucalyptus species are also tolerant of severe periodic moisture stress and low soil fertility with xeromorphic leaves (structural modifications that enable the reduction of water loss) and specialized ecto- and endomycorrhizae systems that increase nutrient uptake [2,7,8]. Furthermore, eucalyptus leaves contain oils and phenolic compounds that increase resistance to insects and non-palatability to grazers [2,9]. Perhaps most importantly, many eucalyptus species are easy to cultivate for fuel wood, timber, and charcoal due to their ability to coppice readily, tolerance for low quality sites, and low maintenance requirements. In addition to wood products, eucalyptus trees are useful for non-wood products such as honey, and can also act as shelterbelts, erosion control, land reclamation, and drainage systems [9,10]. Collectively, these characteristics contribute to the efficacy of eucalyptus as a major production tree species grown by smallholder farmers on depleted and deteriorated agricultural land in the northern Ethiopian Highlands [11].

On the other hand, with many of the traits that allow eucalyptus species to thrive in degraded environments also come potentially negative ecological effects, such as soil nutrient depletion and soil degradation. The potential negative impacts of eucalyptus plantations on soil quality and other ecosystem services have been intensively studied. Studies conducted across many tropical and sub-tropical regions cite high demand for soil nutrients as an important drawback to eucalyptus plantations [7,12,13]. High rates of soil nutrient uptake in *Eucalyptus spp.* are due in part to the combined effect of fast growth and the inability to fix nitrogen [2]; consequently in both the short- and long-term eucalyptus plantation establishment has been shown to have detrimental effects on soil quality and fertility [14,15]. By degrading soils, eucalyptus may render land less suitable for future growth of crops and natural forests alike [10]. However, the ultimate impacts of eucalyptus production on degraded agricultural land remains fiercely debated—indeed, a small, more recent literature has indicated that eucalyptus may even have the potential to have positive impacts on soil fertility in degraded and treeless lands of Ethiopia, by increasing decayed litter content [2,6,9,11,12,16].

1.1. Impacts of eucalyptus on soil nutrient depletion and fertility

In order to keep up with their fast growth and to substitute for their inability to fix nitrogen, eucalyptus species have specialized nutrient uptake systems of ecto- and endomychorrhizae that can greatly increase rates of nutrient uptake [2]. In areas where there are crops nearby, this can make eucalyptus a problematic competitor. For instance, Chanie et al. found that eucalyptus decreased both soil nutrients and crop (maize) yield up to 20 m away from the eucalyptus trees in the Lake Tana Plain of Ethiopia, and additionally, soil hydrophobicity (water repellency) became a problem [15]. Fast growing and short rotation tree plantations such as eucalyptus also use escalated amounts of nutrients from the soil in comparison to slow-growing species [9,17]. Monoculture forest activities such as eucalyptus plantations may further affect soil chemical characteristics if the organic litter is continuously raked, prohibiting nutrient recycling [18].

In addition to soil fertility and nutrient content, eucalyptus has been found to have impacts on topsoil retention and soil erosion [9-11,19,20]. Some studies have concluded that eucalyptus can worsen soil erosion as an indirect result of frequent disturbance from repeated harvesting [20,21]. Others argue that eucalyptus plantations can help control soil erosion on sloped or degraded sites, but their efficacy depends on environmental factors such as intensity of rainfall, soil condition, slope and the presence of ground vegetation and litter cover [19]. Though few Ethiopia-specific case studies exist, the limited evidence available suggests that eucalyptus may be an ineffective choice for erosion control [19,21]—rather, eucalyptus trees are generally expected to lead to an increase in soil loss due to the reduced understory cover in densely planted eucalyptus areas [21,22].

1.2. Potential positive impacts of eucalyptus on soil properties

Other recent evidence from the literature suggests that eucalyptus may not always have negative effects on topsoil retention and soil nutrient availability. If planted properly, for example, eucalyptus can act as shelterbelts for crops [2,11]. Wind erosion is especially prominent in dry areas with light soils where there are few tree roots or other vegetation to hold the topsoil [2]. The extensive lateral root systems of eucalyptus species can make them good candidates for wind barriers even in dry, sandy soils [9]. *Eucalyptus globulus*, for instance, has a strong tap root and lateral root system that makes it a very reputable species protection from erosion in catchment areas, and has been widely planted for this purpose [23,24].

Evidence is also mixed on the circumstances under which eucalyptus plantations will have a negative impact on soil nutrients. A study done by Yitaferu et al. examined the impacts on soil when eucalyptus plantations were converted to cropland in the Amhara region of Ethiopia [6]. The results of this study showed that with the exception of available phosphorus, the measured nutrient content and soil quality was higher in areas where land use had changed from eucalyptus to cropland in the last three years than in areas that were permanently under food crops [6]. Yitaferu et al. concluded that it may be possible to convert eucalyptus woodlots to cropland without detrimental effects on soil fertility and the productivity of the subsequent crop growth. It has even been argued that eucalyptus could positively impact soil fertility through decayed litter in areas where the land has been previously degraded by intensive agriculture [2].

1.3. Case study of Ethiopian Orthodox church forests in the northern Ethiopian Highlands

In northern Ethiopia, where native tree populations are already scarce, there is concern that eucalyptus expansion may adversely affect the function of what little natural forest remains.

Afromontane forests have largely disappeared in the northern Ethiopian Highlands, with the remaining fragments of natural forest found almost exclusively in thousands of "church forests," small fragments of indigenous forest governed by followers of the Ethiopian Orthodox Tewahido Church [25-27]. In addition to serving as places of worship, church forests serve as in situ conservation sites and hotspots for biodiversity, hosting numerous indigenous trees and plant species of Ethiopia [28]. Sacred natural sites such as church forests also provide unique opportunities for future restoration of indigenous forests in the degraded Ethiopian Highlands [29]. But the land surrounding these natural forest fragments is increasingly eucalyptus-dominated [26,27], as church communities recognize the socio-economic benefits tied to eucalyptus including its roles as a fast-growing supply of fuelwood and timber and a key source of income [6,9,15,30]. To the extent that the introduction of eucalyptus to land around and within church forests increases nutrient depletion and land degradation, there is concern that eucalyptus expansion may complicate current and future forest restoration efforts in and around these sacred natural sites. In adjacent agricultural land, impacts on crops and livelihoods can also be linked to the introduction and expansion of eucalyptus to church forests affecting the environment in which food crops are able to grow [15].

This study adds to the increasing literature surrounding the debate on the ecological impacts of eucalyptus stands in Ethiopia by analyzing the impacts of eucalyptus on soils of former agricultural land around indigenous church forest fragments. The objective of this work was to 1) quantify organic matter, pH, total nitrogen, and total phosphorus in 80 sampling points across 20 rural agrarian communities in the Amhara National Regional State, and 2) observe the effects of *Eucalyptus spp.* on these soil parameters in comparison to other land uses.

2. Methods

2.1. Study sites

To examine the possible impacts of eucalyptus planting on soils around indigenous forest fragments in northern Ethiopia we sampled soils from 20 different church forest communities, including samples within native forest vegetation, at the edge of natural forests, in adjacent eucalyptus plantations, and in surrounding agricultural land. The sample of 20 church forests was comprised of 11 in South Gondar Zone, three in East Gojjam Zone, two in West Gojjam Zone, one in Awi Zone, and one in Bahir Dar Liyu Zone (Figure 1, Table 1).

Study sites were identified using aerial images from Google Earth and the following criteria:

- The forest must have at least one patch of eucalyptus bordering the indigenous forest, and that eucalyptus patch must border the indigenous trees of the church forest for at least 10 consecutive meters.
- Forests that were completely eucalyptus, as many newer church forests are, were not considered. Rather, the forests selected must have sufficient indigenous forest area to have a 10-m by 10-m plot of indigenous trees towards the core of the forest that would not overlap with a 10-m by 10-m plot of indigenous forest bordering the eucalyptus.
- There must also be agricultural land in close proximity to the church.

On the ground, accessibility was also considered. Churches that were more than 3 km from the main road were not easily accessed due to lack of efficient transportation. Some church leaders or priests also refused access to their forest upon arrival. Some of the Google Earth images were taken during the wet season, in which much of the image was very green it was difficult to distinguish trees from small shrubs or grass, resulting in some of the forests being much more degraded upon arrival than anticipated. With these additional considerations, 20 church forests were included in the final sample for soil collection.

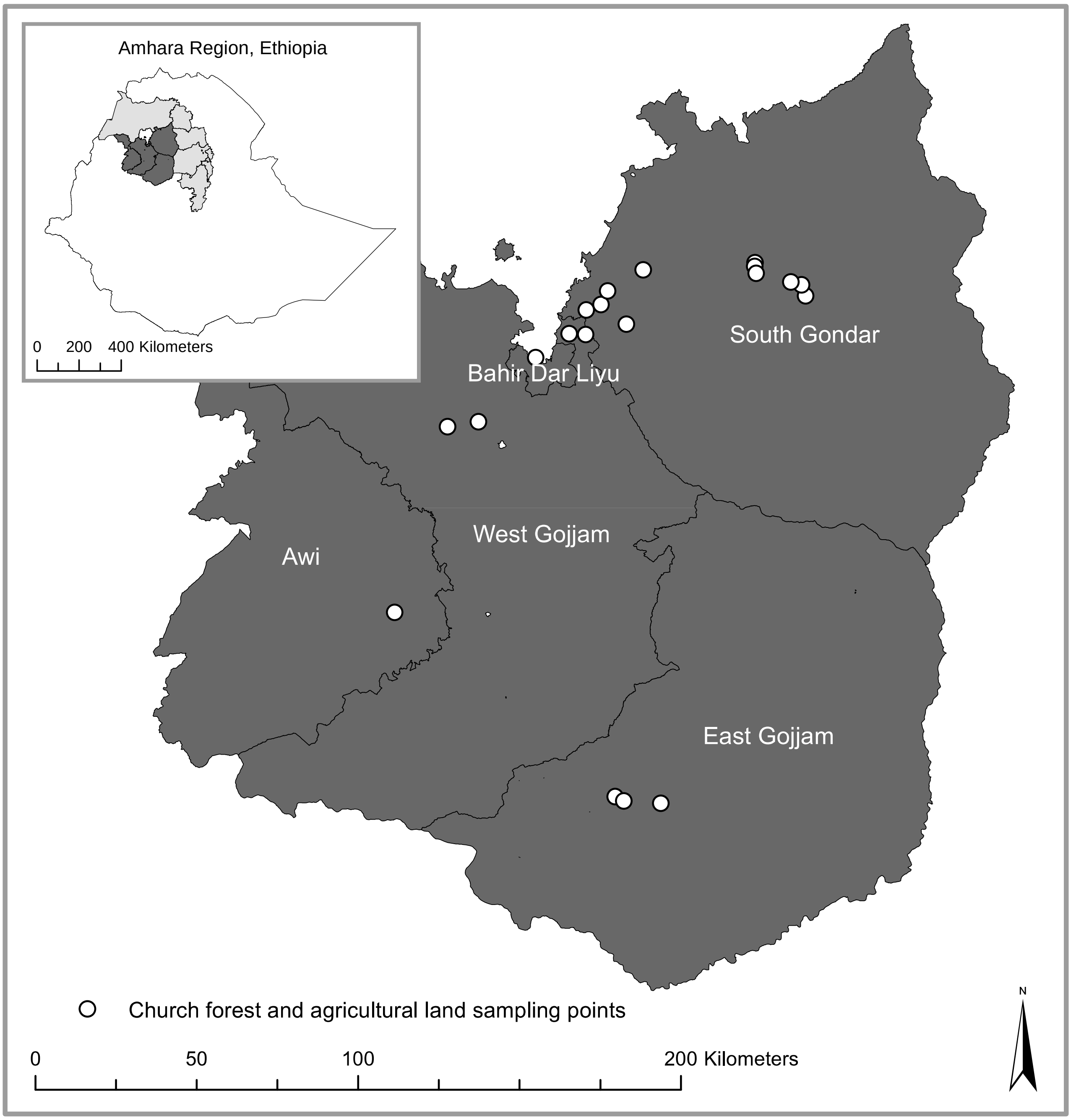

Figure 1. Map of South Gondar, East Gojjam, West Gojjam, Awi, and Bahir Dar Liyu zones in the Amhara region. The church forests and neighboring eucalyptus plantations and agricultural lands visited for soil collection in each zone are represented by the points.

Table 1. Church identification by name, zone, GPS coordinates (decimal degrees), elevation, and annual precipitation. Total forest area, eucalyptus area within the total forest area, and percent cover of eucalyptus in the total forest area are also shown.

Church Name	**Zone**	**Latitude**	**Longitude**	**Elevation** (m)	**Annual Precipitation** (mm)	**Total Forest Area** (ha)	**Eucalyptus Area** (ha)	**Percent Eucalyptus Cover** (%)
Abagerima Mariam	West Gojjam	11.678	37.506	1907	1075	5.05	2.28	45.07
Addis Mariam	East Gojjam	10.371	37.620	2411	890	3.98	0.398	10.0
Asketes Teklehaimanut	East Gojjam	10.366	37.724	2409	887	7.67	1.52	19.8
Azawar Kidana Miharet	South Gondar	11.790	38.131	2900	729	5.35	0.268	5.01
Bale Xavier	Awi	10.897	36.969	2543	1047	5.48	0.497	9.07
Bata Lemariam	Bahir Dar Liyu	11.613	37.364	1798	1076	4.64	0.339	7.31
Debrasena Mariam	South Gondar	11.852	37.990	2650	866	11.9	0.204	1.71
Enkuhar Micahel	South Gondar	11.861	37.668	1883	1089	6.03	0.850	14.1
Fisa Michael	South Gondar	11.747	37.507	1873	1097	7.03	0.827	11.8
Idonga Mariam	West Gojjam	11.432	37.203	2023	1195	2.03	0.085	4.18
Mashenkoro Giorgis	South Gondar	11.708	37.621	2046	1045	4.71	0.351	7.45
Robit Bata	West Gojjam	11.680	37.459	1857	1075	7.99	0.983	12.3
Sarna Mariam	South Gondar	11.820	38.120	2777	743	3.73	0.238	6.38
Simadibera Mariam	West Gojjam	11.417	37.114	1991	1196	7.45	1.46	19.6
Tsegur Kidana Miharet	South Gondar	11.881	37.986	2622	866	3.63	0.872	24.0
Tsegur Michael	South Gondar	11.871	37.985	2659	866	5.07	3.25	64.1
Wadebuko Giorgis	South Gondar	11.828	38.088	2670	743	3.84	0.821	21.4
Wonchet Mariam	South Gondar	11.763	37.548	1933	1097	7.11	0.107	1.51
Woynima Mariam	East Gojjam	10.383	37.595	2252	890	1.96	0.107	5.46
Zahara Michael	South Gondar	11.800	37.567	1907	1152	9.09	0.115	1.27

2.2. Soil sampling methods

Four soil sampling sites were identified at each forest: one within the interior of the indigenous forest, one at the edge of the indigenous forest bordering the eucalyptus stands, one within the eucalyptus stands, and one in the agricultural land adjacent to the church forest (Figure 2).

Figure 2. An example of the locations of each 10-m by 10-m plot at Debrasena Mariam Church: one in the interior of the forest, one on the edge of the forest, one in the eucalyptus plantation, and one in the surrounding agricultural land.

At each location, a 10-m by 10-m plot was approximated, and five 10-cm cores were taken using a soil core. Samples were taken from depths of 0 to 10 cm from the surface of the ground. The five cores taken at each location were mixed into one sample to be analyzed. The cores were taken randomly, with each core being no less than 2 m away from the other core locations (exceptions were made when instructed not to sample on or near grave sites, forcing cores to be taken closer to one another). Coring near the roots of trees was avoided to the extent possible in order to avoid microhabitat effects under particular species of trees. The five cores were taken at each location were mixed into one sample. At all four sites, canopy cover was also recorded at the center of each plot. Using a spherical densiometer (Robert E. Lemmon forest densiometers, Model-C), the raw number of quarter squares not covered by canopy (where the light hit the densiometer and there was no forest cover) was recorded in the four cardinal directions (north, east, south, and west).

The interior forest soil sample was taken as close to the center of the church forest as possible, but outside of the central clearing in the church forest, as this is a spiritual area where the church building sits. The edge sample was taken at the intersection of the indigenous forest and alongside a eucalyptus patch. Eucalyptus sampling plots were only done in the plantations bordering the indigenous forest; eucalyptus in mixed forests was not sampled, but where applicable its presence was recorded. In the eucalyptus plots, the average diameter at breast height (DBH), eucalyptus age, ownership of the plantation (by the church or by adjacent private smallholders), and the landuse type present prior to the eucalyptus plantation were all recorded as well. The agricultural sample was taken at least 20 m away from any eucalyptus to minimize influence.

2.3. Soil analysis methods

Soil samples were analyzed at Brookside Laboratories for organic matter, pH, available nitrogen (nitrate and ammonium), and Olsen's phosphorus. Organic matter was measured using loss on ignition at 360 °C, a method described by Schulte and Hopkins [31]. This procedure estimates soil organic matter by the loss of weight in a sample heated at a temperature high enough to burn organic matter but not high enough to decompose carbonates. The sample is first dried to remove moisture, then weighed, heated to 360 °C for two hours and weighed again after the temperature cools down to below 150 °C. Soil pH was determined using a 1:1 soil to water extract of the soil using deionized water [32]. Available nitrogen was approximated by the summation of nitrate and ammonium concentrations, both of which were extracted from soils using KCl [33]. Available phosphorus was measured using the Olsen method, due to the low acidity associated with soil in the Ethiopian Highlands, generally between 5.5 and 6.7 in the Lake Tana area [34]. This method estimates the availability of phosphorus in soils by extraction using alkaline sodium bicarbonate solution and determining the phosphorus concentration in the extract colorimetrically [35].

2.4. Statistical analysis methods

Using R version 3.1.2, data were submitted to non-parametric tests, including a Kruskal-Wallis one-way analysis of variance test. If analysis of variance showed statistically significant differences among the four treatments ($p \leq 0.05$), additional analysis was conducted to assess the differences between each pairing of treatments using Mann-Whitney-Wilcoxon tests. Additional multiple regression analyses were run using R to explore the effect of several independent predictor variables on our measured soil properties.

3. Results

3.1. Soil quality by sampling location

There were significant differences found across the 20 sampled church forests between the interior, edge, eucalyptus, and agriculture plots for each of the measured soil properties: organic matter, pH, total nitrogen (N), and total phosphorus (P) (Figure 3).

3.1.1. Organic matter

Organic matter content differed significantly between the interior, edge, eucalyptus, and agriculture plots of the 20 study sites ($p < 0.001$) (Figure 3). The mean organic matter contents of the interior (16.5%) and edge (15.4%) plots were not significantly different (Table 2). Both the mean organic matter contents of the interior and edge plots were, however, significantly different from the mean organic matter content of the eucalyptus (7.71%) and agriculture plots (4.83%). Soils in eucalyptus stands also had significantly higher organic matter content than agricultural soils ($p < 0.001$). Additional analysis amongst only the church forest sites where eucalyptus plots were known to previously have been farmland ($n = 7$) yielded a significant difference between the mean organic matter content across the eucalyptus plots (8.70%) and the agriculture plots (5.13%, $p < 0.01$).

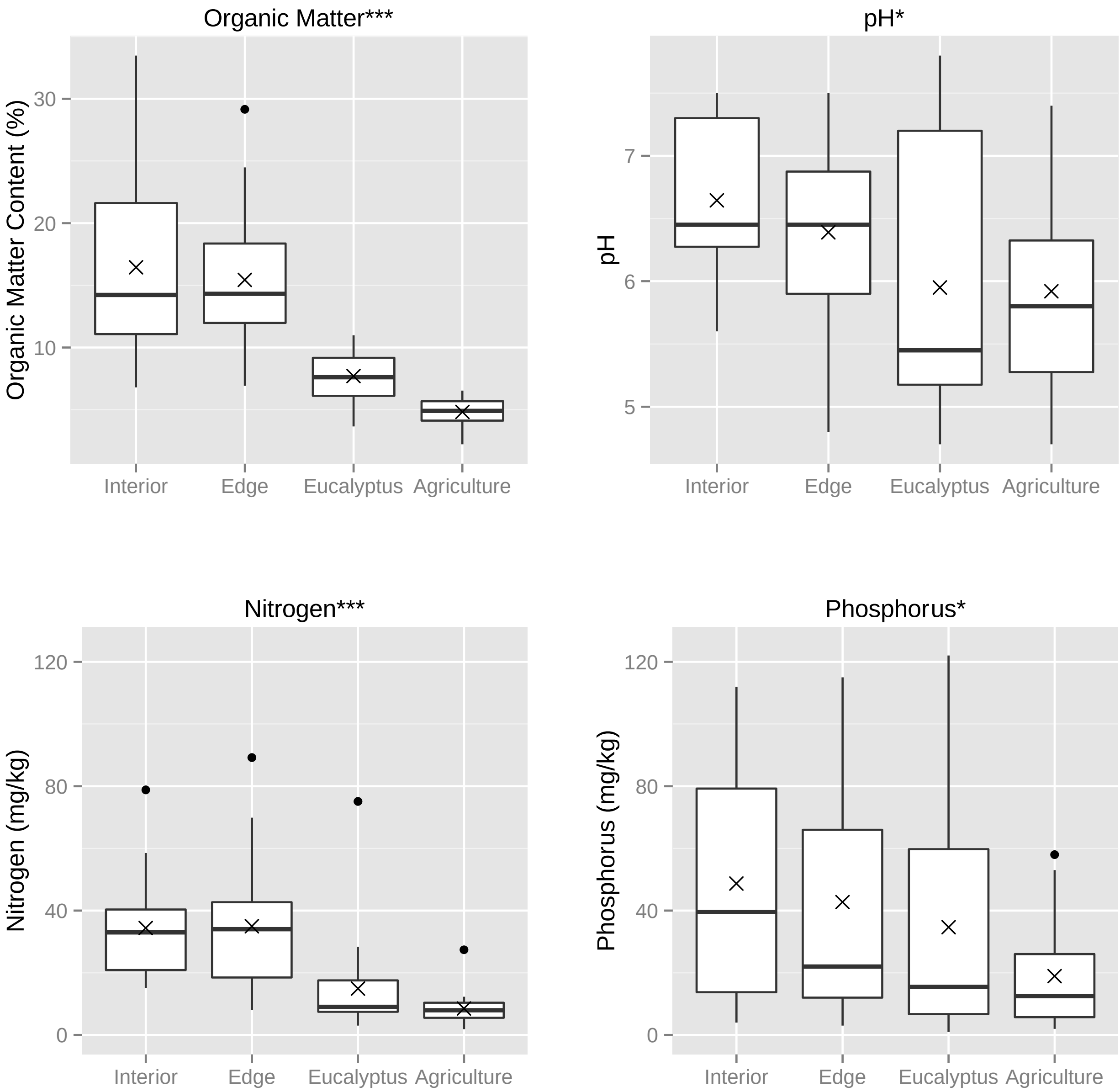

Figure 3. The distribution of organic matter content (%), pH, nitrogen (mg/kg), and phosphorus (mg/kg) among the 20 sampled church forests. The line within each boxplot indicates the median value for that plot location (interior, edge, eucalyptus, or agriculture), and the "X" marks the mean value. Significance levels (denoted with asterisks) reflect the results of Kruskal-Wallis one-way analysis of variance tests and identify where there were significant differences between locations of the measured soil properties (*$p < 0.05$, **$p < 0.01$, ***$p < 0.001$).

3.1.2. Soil pH

The samples collected in our study reflect a moderately weak acid range, with mean pH values of 5.92–6.65 at the four plot locations (Figure 3). There was a significant difference found in the mean pH levels of the interior, edge, eucalyptus, and agriculture plots ($p < 0.05$) (Figure 3). Pairwise significant differences in pH occurred between the interior (pH of 6.65) and eucalyptus plots (5.95, $p < 0.05$), and the interior and agriculture plots (5.92, $p < 0.01$) (Table 2). The edge plots also had a greater mean pH value (6.39) than both the eucalyptus and agriculture plots, following the predicted trend, but the differences were not significant. The mean pH levels of the interior and edge plots were not significantly different from each other, nor were they significantly different in the eucalyptus and agriculture plots.

Table 2. The differences in soil property values (first location minus second location) between each pairing of the interior, edge, eucalyptus, and agriculture plots. The significance of results was calculated using Whitney-Mann-Wilcoxon tests.

	Organic Matter (%)	**pH**	**Nitrogen** (mg/kg)	**Phosphorus** (mg/kg)
Interior-Edge	1.10	0.255	−0.585	1.40
Interior-Eucalyptus	8.75***	0.695*	19.5***	14.1
Interior-Agriculture	11.6***	0.725**	25.8***	29.8**
Edge-Eucalyptus	7.74***	0.440	19.9**	12.7
Edge-Agriculture	10.6*	0.470	26.4***	29.4*
Eucalyptus-Agriculture	2.88***	0.030	0.0993	15.8

Signif. codes: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

3.1.3. Nitrogen

Similar patterns in significant differences were observed between interior, edge, eucalyptus, and agriculture plots for measured nitrogen content ($p < 0.001$). The mean nitrogen levels were not statistically different between the interior plots (34.4 mg/kg) and edge plots (35.0 mg/kg), nor between the eucalyptus plots (14.9 mg/kg) and agriculture plots (8.55 mg/kg) (Table 2). However, there were significant differences in nitrogen levels between the interior and agriculture plots ($p < 0.001$), the interior and eucalyptus plots ($p < 0.001$), the edge and agriculture plots ($p < 0.001$), and the edge and eucalyptus plots ($p < 0.01$) (Table 2). Across our church forest study sites, nitrogen was also positively correlated with organic matter content, by a factor of 1.83 mg/kg for every percent increase in organic matter ($p < 0.001$).

3.1.4. Phosphorus

Finally, there was a statistically significant difference between the phosphorus levels of the interior, edge, eucalyptus, and agriculture plots of the sampled church forests ($p < 0.05$). Unlike total nitrogen and organic matter, the eucalyptus plots did not have a mean phosphorus level (34.7 mg/kg) that was statistically different from either of the indigenous plots (interior and edge) (Table 2). The mean phosphorus content of the agriculture plots (18.9 mg/kg), however, was significantly lower than the interior plots (48.7 mg/kg, $p < 0.01$), as well as the edge plots (47.3 mg/kg, $p < 0.05$). Phosphorus levels also shared a strong positive correlation with nitrogen levels across all soil samples ($p < 0.01$). Additionally, phosphorus had a positive correlation with organic matter content ($p < 0.01$).

3.2. Additional factors associated with soil quality

Multiple regression analyses controlling for additional factors that could partially explain differences in soil properties between the interior, edge, eucalyptus, and agriculture plots at the 20 church forest study sites largely support the results of bivariate analyses.

Elevation is a factor that could impact the soil properties at the study sites. Across the indigenous forest plots (both the interior and edge plots), there is an increase in organic matter as elevation increases ($p < 0.05$). There is also a significant negative correlation between elevation and pH ($p < 0.05$). The species of eucalyptus is another source of potential variability that is in part accounted for by controlling for elevation: in our sample *E. globulus* was exclusively grown above 2500 m (2504–2900 m in our study sites), and *E. camaldulensis* at elevations lower than 2500 m (1788–2429 m in our study sites), consistent with published geographical distributions of these two major species [9]. Rainfall is also highly correlated with elevation (adjusted $R^2 = 0.769$, $p < 0.001$). For this reason, elevation is included in our final regression model, but eucalyptus species and rainfall are not.

Canopy cover is another possible explanatory variable, varying dramatically across the interior (93.2%), edge (86.9%), eucalyptus (70.5%), and agriculture (0.00%) plots ($p < 0.001$). All paired statistical tests for average canopy cover across the four sampling locations were statistically significant with a p-value of less than 0.001. Consequently, canopy cover was tightly correlated with the four categorical locations (adjusted $R^2 = 0.942$, $p < 0.001$). Because these two variables were strongly associated, our final regression model (Table 3) includes sampling location only. A notable positive relationship also exists between canopy cover and organic matter content ($p < 0.01$) when excluding the agriculture plots (which all had a canopy cover of 0%).

Our final regression model also groups interior and edge values into a single category of "indigenous forest," as the interior and edge plots have statistically insignificant mean differences for nearly all soil properties.

Table 3. Multiple regression models for organic matter, pH, nitrogen, and phosphorus based on elevation and location of the plot. Interior and edge have statistically insignificant mean values for all soil properties, so they are combined in this model, and the combined "indigenous forest" is used as a reference level. The agriculture and eucalyptus locations are included as dummy variables.

	Coefficient			
	Organic matter (%)	**pH**	**Nitrogen** (mg/kg)	**Phosphorus** (mg/kg)
(Intercept)	6.62 (±3.15)*	8.13 (±0.599)***	40.4 (±11.3)***	11.05 (±25.1)
Elevation	0.0041 (±0.001)**	−0.001 (±0.0003)**	−0.003 (±0.005)	0.016 (±0.011)
Location Eucalyptus	−8.21 (±1.21)***	−0.574 (±0.230)*	−19.8 (±4.33)***	−13.2 (±9.65)
Location Agriculture	−11.1 (±1.21)***	−0.599 (±0.230)*	−26.1 (±4.24)***	−29.1 (±9.65)**
Adj. R^2	0.575	0.153	0.342	0.097

Signif. codes: *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$

The final regression model suggests that controlling for elevation, soils in eucalyptus plots have 8.21% less organic matter ($p < 0.001$) than indigenous forest (interior and edge plots) and soils in agriculture plots have 11.1% less organic matter content ($p < 0.001$). Soil pH decreases by 0.574 ($p < 0.05$) in the eucalyptus plantations and by 0.599 ($p < 0.05$) in the agricultural land in comparison to the indigenous forest. Eucalyptus plots have 19.8 mg/kg less nitrogen ($p < 0.001$) and agriculture plots have 26.1 mg/kg less nitrogen ($p < 0.001$) than the indigenous forest. The difference in phosphorus between eucalyptus and the indigenous plots is insignificant, but there is a significant 29.1 mg/kg decrease in phosphorus in the agricultural plots in comparison to the indigenous forest plots.

4. Discussion

4.1. Comparison of soil quality in different land-use types

As there is much economic incentive to plant eucalyptus, it is important to understand the potential environmental impacts eucalyptus species may provoke. The degradation of soil by eucalyptus is of one area of particular concern; some studies have highlighted cases in which eucalyptus plantations have rendered soils unfit for future agricultural use, therefore reducing future economic benefits [10,19]. In this study of 20 church forests and their surrounding eucalyptus plantations and agricultural land, indigenous forest soils were of overwhelmingly higher quality amongst four soil properties than either eucalyptus or agricultural soils. Organic matter, pH, and soil nutrients are all important considerations of soil health, as there needs to be enough organic matter and nutrients and a favorable pH range to ensure plant growth [36]. These soil characteristics are all interdependent and closely related. Soils in the natural Afro-montane forests were more abundant in organic matter, nitrogen, and phosphorus, and were less acidic than soils in the adjacent eucalyptus stands, as well as surrounding cropland. Consistent with past research this suggests that native trees, though requiring greater time and care than introduced eucalyptus species, serve an important role in soil nutrient upkeep and fertility [11,37].

However, in comparison to the soil in neighboring agricultural fields, eucalyptus soils yielded similar or superior levels of the measured soil properties. Eucalyptus plots had a greater abundance of organic matter than agricultural fields, suggesting that agriculture may be a less beneficial landuse for accruing soil organic matter. There was no significant difference in pH between the eucalyptus and agriculture plots, suggesting that in comparison to agricultural practices, eucalyptus may have comparable effects on soil acidity, consistent with recent work by Chanie et al. [15]. Likewise, there was no significant difference in nutrient levels between the eucalyptus and agriculture plots.

4.2. Impacts of environmental factors on soil quality

The greater levels of organic matter in the indigenous forests in comparison to the eucalyptus plantations and agricultural fields can be partially attributed to extended canopy cover and increased productivity in dense, indigenous forests. There are many layers of vegetation in the understory of church forests in comparison to monoculture plantations made up of a single species, such as eucalyptus, and greater numbers of animal organisms contributing additional organic material [10,38]. Though lower than natural forest soils, the organic matter content found in eucalyptus plantations is nevertheless significantly greater than in agricultural lands, in part because there is notably more canopy cover in the eucalyptus stands. This difference in canopy cover may lead to increasing volumes of leaf litter and other organic material available to the soil in eucalyptus plantations relative to agricultural fields with few shade trees.

In addition to improving soil structure, soil water, soil aeration, and soil temperature, organic matter supplies essential nutrients to the soil [36,38]. As organic matter input increases in the soil due to increased litter falling from the forest or plantation canopy, micro-organisms break down the organic matter, generating more nutrients, including nitrogen and phosphorus [39]. Both nitrogen and phosphorus are associated with the amount of organic matter found in our soil samples, as organic matter acts as a major source of nutrients to the soil [36]. Nitrogen and phosphorus levels were higher in the indigenous forest than in the eucalyptus and agricultural areas, where there are also significantly higher amounts of organic matter.

Elevation is another environmental factor that may impact the soil properties at each church forest site. Across the indigenous forest plots (both the interior and edge plots), there is an increase in organic matter as elevation increases. Soil organic matter accumulation at higher elevations is likely driven by a reduction in decomposition rates rather than an increase in primary productivity [40-42]. Decreased soil temperature at higher elevations generally results in decreased litter decay and soil organic matter decomposition rates, often resulting in higher organic matter content, but subsequently lower soil nutrient levels as there is less soil microbial activity [41]. Elevation can also play a role in the pH of soil, as our results demonstrated that higher elevation corresponds to a more acidic pH [40].

Decreased rainfall may also have had an influence on soil health. Changes in precipitation can affect vegetation, which in turn has impacts on soil organic matter cycle [43]. Low levels of precipitation can also influence the runoff rate and formation of surface crusts, which can affect erosion and cause additional land degradation [43].

4.3. Effect of agricultural management practices on soil properties

The more degraded status of the soils in agricultural fields and eucalyptus plantations in comparison to natural forests may also be indicative of the varying management practices of these different sites. Constant tillage and continuous cultivation for food crops and similarly the frequency of cultivation and harvest of plantation species such as eucalyptus can negatively impact the quality of soils [20,38]. The repeated cultivation of crops exhausts soils of their available nutrients, and the constant tending of agriculture fields leaves very little organic material on the ground to break down into available nutrients. Harvesting and site preparation within eucalyptus plantations can increase the loss of nutrients occurring, as well, via erosion, leaching, and transfer to the atmosphere [44]. Monoculture forestry activities such as eucalyptus plantations may prohibit nutrient recycling if the organic litter is frequently raked, therefore limiting the amount of organic material that can be broken down into organic matter in the soil [2,9,18].

Stable or higher nitrogen and phosphorus levels in the eucalyptus plots in comparison to the agriculture plots could also be explained by the significantly different quantities of organic matter, due to the obvious difference in leaf litter. Agricultural fields, which are cultivated and harvested more frequently than eucalyptus plantations, can lose a lot of additional nutrients and organic matter in its topsoil [45]. Though fertilizers can add large amounts of nitrogen and phosphorus to the soil in agriculture lands, they are also being actively used by the crops and at times cannot compensate quickly enough for the amount of nutrients being taken up by the crops, and the soil can become impoverished.

The addition of fertilizer can simultaneously affect the pH of the soil. Soil acidity intensifies with exhaustive farming over a number of years with the use of fertilizers or manures [38,46]. The agricultural land surrounding all of the church forests sites have been cultivated for long periods of times, and where available, fertilizers and manure have been used to maximize crop production, potentially reducing acidic pH levels in agriculture plots relative to indigenous forest plots. Likewise, the afforestation of eucalyptus species can also acidify soil, as indicated in multiple studies in the past [30,47,48]. Eucalyptus species can influence the acidity of soil with their fast-growing ability, as growth is a function of nutrients extracted from the soil [30,49,50].

4.4. Eucalyptus plantation management considerations

With significantly higher levels of organic matter, and comparable pH and nutrient levels to agricultural soils, this case study in the church forests of the northern Ethiopian Highlands offers that eucalyptus may not always be as detrimental to soil properties as previous studies have suggested. On the contrary, our findings are more consistent with studies suggesting that revegetation, even with an exotic plantation species, might have the potential to restore soil fertility through improvement in soil organic matter content, available nutrients, cation exchange capacity, increased biological activities as well as improvement in physical conditions of the soil [51]. We find that the soil of eucalyptus plantations that were planted on land that was previously used for agriculture fared better than present-day agricultural land neighboring the present-day eucalyptus plantations. This suggests that it is possible that eucalyptus planting could have a positive influence on soil organic matter, and subsequently nutrient availability, in areas that have been previously degraded through the cultivation of food crops. Yitaferu et al. have made similar speculations, as they suggested that future conversion of eucalyptus to cropland could potentially increase the productivity of subsequent crops [6].

However, in employing eucalyptus in whole or in part as a solution for improving previously degraded agricultural soils, there is also an array of management strategies to consider. The ultimate impact of eucalyptus on soils is a product of both species-specific characteristics and management-related decisions. In the case of eucalyptus plantations where the trees are regularly harvested after coppicing, as is common practice in northern Ethiopia and our church forest study sites, there is a substantial loss of soil nutrients over time [30]. Both soil nutrient levels and soil pH tend to decrease after the first eucalyptus coppice, after the initial establishment of the eucalyptus plantation [30]. In comparison to other plantation type trees, like the indigenous *Juniperus procera*, eucalyptus species, specifically the species *Eucalyptus globulus* that is commonly found in the Ethiopian Highlands, typically have lower soil nutrient contents [52]. With short cropping rotations and lack of intercropping, like with most food crops, the loss of nutrients must be made up for through the addition of fertilizers [19]. However, fertilizer use remains low in northern Ethiopia [53] and the need to purchase and apply fertilizers reduces the economic benefits of the species. A possible alternative to monoculture eucalyptus stands as a means of soil improvement is planting mixed stands, particularly with leguminous *Acacia* or *Albizia* trees. These species have been shown to form associations with eucalyptus species in their natural habitat [2], and *Acacia* trees in particular were observed in the eucalyptus plantations near several of the church forest sites we sampled. These trees' nitrogen-fixing capability not only improves the ability of eucalyptus to grow, but can greatly improve soil fertility and nutrient availability.

Litter management is another consideration that shapes the ultimate soil impacts of eucalyptus production and alternative land-use management. Our study showed that there were significant correlations between litter on the ground, as reflected in canopy cover, and subsequent organic matter and nutrient levels. In many places across Ethiopia, especially more developed areas, the litter is collected as fuel or removed to reduce fire risk. Removal of the organic material that accumulates in eucalyptus stands in addition to disturbance by humans and livestock can compound the inefficacy of eucalyptus as a barrier to soil erosion [2,10,19]. Additionally, litter collection further robs soils of nutrients [2,9]. If left alone, the accumulated litter under eucalyptus stands can be incorporated into the soil system to slow down runoff and improve soil infiltration, and shelter loose soil from being easily eroded [2,23]. Likewise, frequent cultivation and harvesting can make the soils more prone to runoff and erosion [54], so limiting human disturbance and tillage in eucalyptus plantations could also prove to be beneficial for soil quality. However, some recent studies have shown that no-till practices may not have as positive of an impact on soil organic matter and nutrient retention as previously cited [55,56]. Rather, conservation practices may be more dependent on the density and type of plant cover present, the soil's physical and chemical properties, the slope, and microbial utilization rates [55].

4.5. Study limitations

Eucalyptus may have some additional drawbacks that are not considered in this study. Though increased levels of organic matter should function as a source of food for soil microbes and thereby help enhance and control their activities [36], the toxins found in eucalyptus leaves and litter can inhibit microbes from getting the intake that they need [9]. Eucalyptus is alleged to affect the diversity and abundance of plantation understory species, including negatively impacting the productivity of crops through the release of allelochemicals from eucalyptus leaves and litter [2,20,57]. These allelochemicals found in eucalyptus species can significantly reduce the seed germination, radicle elongation, and growth of crops [57]. Eucalyptus plantations have also been proven to be unsuitable habitat for herbaceous annual species in the understory [7]. The toxins present in the eucalyptus leaf litter can impede on the growth of forbs and grasses and decrease the natural biodiversity of the area.

Eucalyptus trees also take up a great amount of water from the soil and as a result can affect water availability, competing with crops and other vegetation for water and depleting the water table [2,9-11]. Their high water requirements and deep root systems can give them a relative advantage over other plants in terms of water usage, which can be particularly damaging if eucalyptus trees are planted in arid regions [10,11]. Other studies argue that eucalyptus is in fact more efficient at using water than many crops and plants, consuming less water per unit of biomass produced [2,8,58,59]. However, it is acknowledged that the sheer density of eucalyptus planting can aggravate water depletion [58], regardless of the species' potential efficiencies in water use.

5. Conclusion

Soil quality and composition is a significant indicator of ecosystem health, and thus the impacts of smallholder eucalyptus planting on agricultural land can have great implications for larger development issues such as food security [60,61]. The impacts of eucalyptus species on soil health remain hotly debated among scientists and development practitioners [6,10,11]. Our results indicate that soils in eucalyptus stands surrounding Ethiopian Orthodox church forests are more acidic and have lower levels of organic matter and nutrients than soils in adjacent indigenous forest. However, there is also evidence that eucalyptus plantations exhibit higher organic matter and nutrient levels in comparison to nearby agricultural land, and no significant decrease in soil pH. With a small sample size and possible differences in management, it is not possible to say conclusively that the replacement of agricultural crops with eucalyptus stands in particular can improve soil quality. But these findings suggest that while eucalyptus stands are less favorable for soil quality than indigenous forest, eucalyptus planting could nevertheless potentially benefit soil fertility on land that has been previously degraded by extensive cultivation.

Though in our analysis eucalyptus stands appear to be more favorable than agricultural crops in terms of the four observed soil properties, this conclusion is not without significant caveats. There are other ecological effects of eucalyptus on agricultural land that are not tested in this study, but nevertheless are important considerations in eucalyptus systems, such as water use and the allelopathic impact of eucalyptus trees on neighboring crops and forests [10,11,20,57]. It should also be strongly emphasized that indigenous trees—as represented by both the interior and edge plots in this study—were found to play even more significant roles in soil quality, providing far greater advantages in all four studied characteristics than eucalyptus stands. Indigenous tree planting would also have less detrimental effects on other environmental properties in the long term, and therefore preference should be given to planting indigenous tree species where possible.

In addition to potential agricultural soil rehabilitation, our study emphasizes the management considerations surrounding eucalyptus planting around church forests—some of the last fragments of natural forest in Ethiopia—where changes in soil fertility may have both short- and long-term implications for native forest regeneration. Further research needs to be done to understand the roles eucalyptus planting might play as part of integrative strategies for soil rehabilitation and natural forest restoration in the degraded highlands of Ethiopia.

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Conflict of interest

The authors declare no conflict of interest.

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