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Lindenleaf sage (*Salvia tiliifolia*) in the Tigray highlands, Ethiopia

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Abstract

Lindenleaf sage (*Salvia tiliifolia* Vahl) is an annual plant native to Mesoamerica that thrives in tropical, seasonally dry environments. It was introduced to Ethiopia in the late 20th century and made its way to the Tembien highlands in Tigray in 2018. With its many branching stems and profusion of seeds, this upright pioneer plant becomes dominant in the herbaceous layer of intensively used rangeland and roadsides before spreading to areas with other land uses, including agricultural land. Visual observations show that *S. tiliifolia* is not prevalent in areas with less grazing pressure. Farmers uproot *S. tiliifolia* from their crops, which is rather simple, because this species is easily recognized and its roots do not withstand much force. On rangeland, weeding is labor-intensive. As an alternative, we recommend converting rangelands into managed exclosures to maximize grass production, with initial *S. tiliifolia* removal. Natural vegetation regrowth in infested places would keep the most significant *S. tiliifolia* seed supply under control and reduce the species' invasion of farmlands.

Introduction

Native to Mesoamerica, lindenleaf sage or *Salvia tiliifolia* Vahl (Lamiaceae) (Figure 1) is mostly found in tropical, seasonally dry habitat (Kew 2024; Standley and Williams 1973); it has expanded to other parts of the world, including Ethiopia. There, the growth of grasses in rangeland is strongly suppressed by *S. tiliifolia* (Supplementary Figure S1).

In its native Mexico, *S. tiliifolia* grows as weed in crops, but also in ruderal environments or in the borders and clearings of native vegetation (González-Gallegos et al. 2016; Pichardo et al. 2009). In recent centuries, the plant has been transported to other continents, most probably accidentally together with commercial products. Deliberate transplantation of *S. tiliifolia* seems unlikely, as the species does not exhibit a high ornamental value with its small and short-lived flowers and its weedy behavior (Froissart 2008); for instance, Clebsch does not include it in her compilation of ornamental salvias (Clebsch 1997). The global expansion of *S. tiliifolia* has been quite rapid since 1980 (Supplementary Figure S2).

In South Africa, *S. tiliifolia* has been in the Pretoria area since the 1940s (M van Dalsen, iNaturalist, personal communication, September 23, 2024), but it became a menace in many parts of the country after 2010 (Anonymous 2015). There, it grows in dense stands in both sunny and partially shaded sites; overruns rocky hillsides, roadsides, waste sites, and urban open spaces; and prefers moist places (Anonymous 2015, 2024). It competes with native species and may eventually supplant them (Anonymous 2024). In southern China, *S. tiliifolia* first appeared in the 1990s and is regarded there as having a high risk of becoming an invasive plant (Hu et al. 2013).

Salvia tiliifolia spreads by seeds that drop when the plant dries after the rainy season (Supplementary Figure S3); the seeds may be transported to adjacent places by mammals and birds (Anonymous 2024). In its region of origin, Mesoamerica, it is not considered a major problem, although it occurs as weed in coffee (*Coffea arabica* L.) orchards (Standley and Williams 1973). Further, it grows in secondary vegetation along roads and at the edges of field crops. It usually does not grow in large numbers. Whereas *S. tiliifolia* is weeded out from croplands along with other species (Molina-Freaner et al. 2008), there are no targeted weed control programs for it. The situation is different in other continents. In southern China, it was suggested that land managers monitor the species and take action to stop its spread (Hu et al. 2013). In South Africa, *S. tiliifolia* is regarded as a difficult plant to control, because it just keeps growing back and cannot be eradicated until every plant in an area is removed (K Campbell, iNaturalist, personal communication, September 25, 2024); it is therefore recommended that plants be uprooted before they flower and set seed (Anonymous 2015).

Figure 1. *Salvia tiliifolia* in Hagere Selam, Tigray, Ethiopia (13.6511°N, 39.17583°W, 2,610 m a.s.l.), in (A) flowering (September 25, 2024) and (B) dry stages (November 23, 2023).

In Ethiopia, *S. tiliifolia* is a recent invasive exotic species, first formally collected and described near Kombolcha in 1996 (Demissew 1996). It is now quite widespread over the Ethiopian highlands. Whereas naturalists (Supplementary Figure S4) and field inventories (Atsbeha 2012; Bersisa et al. 2021; Dagne and Birhanu 2023) reported observations on the occurrence of *S. tiliifolia*, there are few publications about the behavior and environmental preferences of this new invasive species in Ethiopia. Near Harar in eastern Ethiopia, *S. tiliifolia* was observed to be the dominant herbaceous species in coffee plantations, with highest mean field density and highest relative abundance (32%) (Bersisa et al. 2021). In 2012, the species was reported around Aksum in Tigray (Atsbeha 2012). Most studies in Ethiopia (Atsbeha 2012; Bersisa et al. 2021; Demissew 1996) explicitly mention that the species has no local name (except "new weed"), which stresses its relatively recent introduction. In the Tigray region, where we studied it, farmers are very worried by this invasive species, especially as they are already coping with the social, agronomic, and environmental impacts of the recent Tigray war (Nyssen et al. 2023; Weldegiargis et al. 2023).

Here we discuss the spread of *S. tiliifolia* in the Tigray highlands (northern Ethiopia), and efforts to control it. For management options on communal lands, the systematic removal approach is contrasted with the nature-based approach, that is, the restriction of ranging livestock to allow native vegetation to outcompete *S. tiliifolia*.

Materials and Methods

Plant Traits

Salvia tiliifolia is an erect, short hairy, annual herb with many branched stems, between 20-cm and 1.6-m high (Figure 1). The soft, bright green leaves are arranged in pairs that alternate at a 90° angle from one another. The leaves are simple, ovate with a truncate base, serrate margin, usually with wide teeth. *Salvia tiliifolia* has tiny blue flowers, upper calyx lip with three veins, corolla 4- to 10-mm long, clustered in spikes up to 30-cm long. The calyx elongates to 10 mm in fruit, enclosing three-angled ovoid nutlets (mericarps), brown and irregularly marbled with a darker tone (Anonymous 2015, 2024; Pichardo et al. 2009; Standley and Williams 1973). The seeds (mericarps) are known as "chía" or "chía cimarrona" and constitute a staple food in Mexico and Central America, next to the cultivated *Salvia hispanica* L., the species commercially known as chía (Ayerza and Coates 2005; Martínez Hernández 2017; Pichardo et al. 2009).

Field Investigation in Tembien

The research region, the Tembien area is situated between 30 and 120 km west of Mekelle, the regional capital of Tigray. The geology of the area is made up of Precambrian metamorphics, Mesozoic sedimentary rocks, Tertiary volcanics, and Quaternary lava flows (Gebreyohannes et al. 2010). A network of deeply incised rivers defines the landscape, with elevations between 1,500 and 2,900 m. A stepped geomorphology was produced by selective erosion as a result of the alternation of different lithologies (Coltorti et al. 2007; Nyssen et al. 2006).

The region is classified as hot semiarid (BSh) by the Köppen climate classification (Peel et al. 2007). The depth of annual rainfall ranges from 500 to 900 mm (Jacob et al. 2013). Most rain falls in the main rainy season, which usually lasts from June to September. Except for the rainy season, when there are fewer sunshine hours and more rainfall, monthly potential evapotranspiration exceeds monthly rainfall. In one of the major towns, Hagere Selam, yearly rainfall from 2016 to 2022 ranged from 770 to 850 mm, 7% to 18% over the long-term normal. There is a tendency toward increased precipitation and warmer temperatures over time. While the rainy season in 2024 was unusually wet, the drought in 2023 was accompanied by anomalies in rain seasonality (J Nyssen et al. 2024b).

In this mountainous area, the farming communities typically use steeper slopes as communal rangeland and more level areas for crops. Free grazing is still the dominant way of feeding livestock and has even expanded due to the Tigray War (J Nyssen et al. 2024b). Oxen (*Bos* sp.) are used for farm operations such as plowing and threshing in the small-scale family farms of Tigray, which follow a permanent farming system based on cereals (Westphal 1975). Goats (*Capra hircus*) and sheep (*Ovis aries*) are also raised, primarily as a safety net in case of emergencies (Nyssen et al. 2008). Because crop cultivation has been practiced in Tigray for at least three millennia, the agricultural system has been gradually optimized (Blond et al. 2018; D'Andrea 2008). After harvest, stubble grazing occurs on cropland as well. Over the past 40 yr, many sloping lands—both rangelands and marginal croplands—have been turned into exclosures, fenced from human and livestock interference (Aerts et al. 2009; Nyssen et al. 2008). Linear landscape features, including cliffs and gullies, act as demarcations for these exclosures, with regulations outlining their use. Unlike open grazing land, where those with larger herds tend to monopolize the available biomass, exclosures facilitate communal collection and sharing of grasses, fostering equity within the community. Therefore, in Tigray, the transformation of an area of rangeland into an exclosure is a decision made with considerable deliberation. The natural vegetation is mainly open *Olea–Acacia* woodland, remnants of the primary dry Afromontane evergreen forests (Asmelash and Rannestad 2024). The woodlands have a low, single-story, discontinuous canopy and comparatively

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few tree species. Under this open canopy, grasses and herbaceous vegetation appear during the rainy season (Aerts 2019).

To investigate *S. tiliifolia*'s rapid spread in Ethiopia's semiarid Tigray region, and how to control it both on privately managed cropland and on communally owned rangeland and exclosures, we carried out field observations on its distribution and density in various habitats of Tembien between November 2023 and October 2024 (Nyssen 2024), during both the growing and dry seasons. Forty-three different sites were visited, and open-ended interviews (Albudaiwi 2017) were conducted at 14 locations with community members who were present on-site.

Results and Discussion

Salvia tiliifolia Invasion in Tembien

Salvia tiliifolia arrived suddenly but relatively late in Tembien. Raf Aerts (K.U. Leuven University), who made extensive inventories of plant species in Tembien during the period 2001 to 2006, confirmed that this species was absent at the time (personal communication). Farmers commonly mention ca. 2018 as the time of the plant's arrival around Hagere Selam, where it has invaded rangelands surrounding the town, particularly those with heavy livestock browsing (Supplementary Figures S1 and S5). There are several native *Salvia* species in the study region with their own local names (*Salvia schimperi* Benth., *Salvia merjamie* Forssk., *Salvia nilotica* Juss. ex Jacq.), which do not have such an invasive behavior (Edwards 1991; Endeshaw et al. 2000; November et al. 2002; Seegeler 1983).

Besides rangeland near towns, we observed *S. tiliifolia* as a dominant species in nearly all types of grazed areas: open *Eucalyptus* or *Acacia* woodlands, formal waste dumps, rocky gorges, coarse alluvial deposits, and sides of footpaths and dirt roads. The plants showed stunted growth under the shadow of trees, however, and seeds do not fully mature in such places. *Salvia tiliifolia* was conspicuous, but not dominant, in the herbaceous layer in places with less grazing pressure, such as grass strips between cropped parcels, gullies, and banks of ephemeral waterways, as well as on permanently moist places such as banks of grassed waterways and at the edges of a permanent springs. We have not seen *S. tiliifolia* in rainfed and irrigated croplands, because the species is weeded out at early growth stage. There were no observations in exclosures with dense vegetation. In some pocket areas with various land cover, *S. tiliifolia* was also absent. The dominance of *S. tiliifolia* in the herbaceous layer of grazed areas seems an extreme manifestation of the typical mechanism by which invasive species proliferate in rangelands. Browsing livestock continually remove the other herbs while avoiding the unpalatable *S. tiliifolia*, except for occasional browsing of the infructescence. The low grass and other herbs are further suppressed by *S. tiliifolia*. Visual observations show that *S. tiliifolia* is not prevalent in places with reduced grazing pressure, such as exclosures. Quantitative ecological research on this aspect would be appreciated.

Voucher Specimen

Ethiopia, Tigray, Dogu'a Tembien: Hagere Selam, northern part of the town, in secondary vegetation on side of gravel road. 13.65139°N, 39.17250°W, 2,633 m a.s.l. February 5, 2025. Getachew Gebremedhin 1 (LUX herbarium, specimen no. MNHNL178636).

Figure 2. *Salvia tiliifolia* was weeded out of this wheat field in Hech'i (13.64028°N, 39.20472°W, 2,258 m a.s.l.) but left to grow at its edge (November 2023). On the right, *Nicotiana glauca*.

Pathways of the Invasion

Demissew (1996) suggests that *Salvia tiliifolia* arrived in Ethiopia through weed-seed contaminated food aid in the 1980s. Grain trade is a known pathway for the introduction of alien plants (Ikeda et al. 2022). The fact that *S. tiliifolia* was first formally observed near Kombolcha, which was a hub for international food aid since the Ethiopian famine in 1983 to 1985 (Augenstein 2020) supports this interpretation. On the other hand, no extensive surveys have been done, and the plant may also have been otherwise introduced and traveled along roads. Similarly, tree tobacco (*Nicotiana glauca* Graham), a woody noxious invasive species in the study area (Figure 2), is also said to have come in that period with food aid; yet specimens of the plant had already been collected in a garden in Addis Ababa in 1960 and at Haromaya University campus in 1975 (Nyssen 1997).

The pathways of *S. tiliifolia* spread need to be studied further; the spread over the Ethiopian highlands would logically have followed roads, as dusty lorries transport thousands of seeds of alien plants (Bajwa et al. 2018; Khan et al. 2018) to suitable environmental conditions. The extent to which multiple traffic and war disturbances may have contributed to this spread is unknown. Further, seed dispersal by runoff water was evidenced in the study area by the presence of *S. tiliifolia* on sediment deposits in ephemeral streams down from major infested areas.

The wetter conditions in the study area in the last decades and particularly in recent years (J Nyssen et al. 2024b), jointly with increasing temperatures, may have created a niche for the species, in line with observations of natural vegetation and crop belts that shift up the mountains in northern Ethiopia (Jacob et al. 2017; Nyssen et al. 2015). The fact that *S. tiliifolia* spread in South Africa was observed to be strongly subdued in dry years (K Campbell, iNaturalist, personal communication, September 25, 2024) supports this hypothesis.

The large extent and dominance of the plant, with its specific phenology (annual pattern of *S. tiliifolia*'s life cycle) would be ideal for studies using multispectral satellite imagery with high spatiotemporal resolution. The plant with its dark bluish-green color appears in July, occupies large patches, and grows up to the end of September, when it rapidly decays to homogenous brown-

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Figure 3. At Jira, *Salvia tiliifolia* grows densely along footpaths (A, 13.68472°N, 38.95750°W, 1,991 m a.s.l.), while it is totally absent from the adjacent exclosure (B, 13.67972°N, 38.96028°W, 1,920 m a.s.l.). Both photos taken in October 2024: courtesy of (A) Gebrekidan Mesfin; (B) Miro Jacob.

yellowish patches. These colors are unique among the background vegetation and therefore can be picked up through multispectral imagery analysis, which allows detailed studies of its current extent, as well as pathways of diffusion over the last decades.

Salvia tiliifolia Management on Cropland in Tigray

According to local farmers, *S. tiliifolia* is now the main weed to be removed from croplands in Tigray; it grows rapidly and even suppresses other weed species. On well-managed farmlands, one will generally not observe full-grown *S. tiliifolia* (Figure 2). The farmers in the study area have experience with manually uprooting *S. tiliifolia*. While the work in itself is quite easy, because the species is very recognizable and the roots do not resist much (Supplementary Figure S6), it involves additional workload and is a burden, particularly for women and children. However, and depending on time constraints, it is often not weeded out from farm boundaries (Figure 2) and rangeland near farmlands, which will be a source of *S. tiliifolia* seed in the next cropping season.

Salvia tiliifolia Management on Communal Lands

The conventional strategy has long been the extensive and methodical clearance of invasive plants before they set seed (Engel et al. 2024; Mack and Foster 2009; Parmesan and Hanley 2015). Whereas it is impossible to totally "get rid of" the invasive plant in this way, it may subdue the growth in that area in the next year, and annual repetitive removal may exhaust the seedbank (Anonymous 2015, 2024). In the study area, experimental community weeding of *S. tiliifolia* on rangeland showed that 45 person-days ha^{-1} are necessary for an initial manual *S. tiliifolia* removal operation (J Nyssen et al. 2024a; Supplementary Figure S7).

Conversely, in communal lands where free grazing is forbidden (exclosures), we observed that *S. tiliifolia* is totally absent, particularly at locations away from roads (Figure 3). Also, we observed that *S. tiliifolia* has a stunted growth in shady places with seeds that do not fully mature. Locally, *S. tiliifolia* coexists with other herbs in peri-urban exclosures, but it does not dominate. In such cases, the grasses and herbs—including *S. tiliifolia*—are all harvested together (Supplementary Figure S8) to serve as fodder for livestock. In contrast to thistles for instance, withered *S. tiliifolia* is accepted by farmers as a part of the harvested hay. Establishing exclosures therefore seems the most cost-effective strategy to control *S. tiliifolia* while sustaining fodder production. In this nature-based approach (Ammondt and Litton 2012; Ngondya and Munishi 2022; Tracy et al. 2004), the recovery of herbaceous and woody vegetation in newly established exclosures would be sped up

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by *S. tiliifolia* removal in the first years. Conversely, opening the exclosures for free grazing to relieve the fodder crisis caused by the *S. tiliifolia* invasion would only result in the exclosures being invaded by *S. tiliifolia* due to selective grazing. All in all, the mere protection of the indigenous vegetation enables subduing *S. tiliifolia* at a lower economic cost (Lázaro-Lobo and Ervin 2021; Leuzinger and Rewald 2021; B Nyssen et al. 2024).

The ability of *S. tiliifolia* to dominate rangelands and suppress grasses, particularly in areas of intensive livestock grazing, underscores the urgent need for effective management strategies. Field observations and local knowledge suggest that a combination of weeding on cropland and the establishment of exclosures, where only haymaking but no grazing is allowed, may offer the most sustainable approach to controlling its spread.

Supplementary material. Supplementary Figures S1 to S8 are available as Supplementary Material at https://doi.org/10.1017/inp.2025.14

Data availability. Species observation locations (with photographs) are reported in the iNaturalist database and reported as a reference to Nyssen (2024).

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