Arachis pintoi cover cropping increases drought survival of Citrus latifolia in an intercrop with Coffea arabica

Samuel Coulbourn Flores
samuel.flores@slu.se

Swedish University of Agricultural Science Faculty of Veterinary Medicine and Animal Science: Sveriges Lantbruksuniversitet Veterinarmedicin och husdjursvetenskap https://orcid.org/0000-0002-3869-8147
Dora Trejo Aguilar
Jacob Bañuelos

Research Article

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Abstract

Aims:

Once rare, extended droughts are becoming more frequent in parts of the wet tropics, impacting rain-fed production of major commodities including citrus and coffee. We hypothesized that the dense, deep-rooted, perennial cover crop *Arachis pintoi* would keep soil cool and moist during drought, protecting young *Citrus latifolia* trees.

Methods:

We measured moisture (NDMI) and vegetation (gNDVI) index using Sentinel2 multispectral imaging. We also made ground measurements of leaf stomatal conductance, soil temperature, and soil aggregation.

Results:

A. pintoi cover cropped plots had significantly higher NDMI and gNDVI, lower soil temperature, and larger soil aggregate cross-sectional area, in particular when compared to bare soil. After a rain and in full sun, *C. latifolia* transpiration spiked in bare soil but not in *A. pintoi* cover cropped plots. Zero *C. latifolia* trees died from drought in full-sun, cover-cropped plots. Similarly, zero died in shaded, bare-soil plots. In contrast, 6 (of 27) trees in full-sun, bare-soil conditions died.

Conclusions:

A. pintoi appears to maintain soil conditions that are conducive to *C. latifolia* survival during the dry season. The effect appears to be mostly due to shading, as cover cropping becomes dispensable under partial tree shade. Remote sensing detected treatment effects despite small experimental plot sizes. The higher post-rain leaf transpiration suggests *C. latifolia* may contribute to soil drying in bare soil. Higher vegetation index and soil aggregation suggest cover cropping may provide additional long term benefits in soil carbon sequestration.

Introduction

The Cumulative Water Deficit is deteriorating throughout tropical rainforests on all three continents where it was observed in 26 years of historical C-band radar (which penetrates clouds but only partially penetrates canopies) images from multiple satellite sources (Tao et al., 2022). This makes drought a serious threat to agriculture in the wet tropics;(Merga and Beksisa, 2023) it reduces Persian lime (*C. latifolia*) weight (Rivera-Hernández et al., 2022) and directly contributes to increasing coffee (*C. arabica*) prices (Massrie, 2025).

Intense solar radiation and lack of canopy cover can result in large fluctuations in soil temperature. (Jarrah et al. 2022) Soil temperature fluctuations critically influence root growth. High soil temperature depletes soil nitrogen (by mineralization) and carbon (by increasing microbial respiration and reducing microbial biomass) (Tian et al. 2023). Understanding how to modulate soil thermal environments has become essential for designing resilient production systems under accelerating climate variability. Cover crops modify the the soil–atmosphere interface through shading, increased albedo, reduced wind speed, and greater incorporation of organic residues, thereby reducing daily maximum temperatures, mitigating evaporative losses, improving soil porosity and water infiltration (Akchaya et al. 2025), and stabilizing soil moisture (Al-Shammary et al. 2025).

C. latifolia can be intercropped with *C. arabica* due to compatible interrow distances; this combination has not been earlier reported. Shade trees increase drought survival of *C. arabica* (Massrie, 2025) while also increasing biodiversity and yielding a second crop. The three-species *C. latifolia - C. arabica - A. pintoi* system has reasons to provide improved drought and economic resilience as well as ecosystem services (Merga and Beksisa, 2023; Tao et al., 2022).

Environmental benefit of *Coffea arabica*

C. arabica performs many services to the ecosystem and to its intercrops. At higher planting densities (similar to those of this work), *C. arabica* can increase storage of carbon and nutrients. Soil carbon sequestration has been found to be negative at low tree densities (under 700 trees/ha) (Noponen et al., 2013). However if litter and above-ground carbon is considered, coffee can store around 40 t C/ha, per measurements in Ethiopian agroforestry systems (Niguse et al., 2022). Globally over 10 Mha are under coffee cultivation, arguing for a significant carbon storage potential.

Intercropping with *C. arabica* increases fruit productivity of *Macadamia integrifolia*, as well as growth of mahogany and rubber trees. This effect has been attributed to the favorable microclimate under the *C. arabica*, including increased nutrients and soil shading, (Perdoná and Soratto, 2015) presumably better conserving moisture. *C. arabica* can also decrease acidity and erosion in soil (Pavan et al., 1999).

C. arabica intercropped with one additional species has more beneficial effects on soil carbon, microbial biomass and activity, and soil compaction, compared to a monoculture (de Carvalho et al., 2024; Pavan et al., 1999). In that work, a three-species intercrop (such as that performed here) was suggested for future study. The contribution of *A. pintoi* to soil moisture management, climate buffering, and soil physical resilience has not been fully elucidated in the context of tropical perennial agriculture.

Benefits of *Arachis pintoi*

Arachis pintoi is a perennial peanut variety widely used as an agricultural cover crop. It can lower soil temperature (Blanco-Canqui and Ruis, 2020) while increasing soil moisture, carbon, nitrogen, potassium, calcium, magnesium, sodium, electrical conductivity, and pH. It tolerates drought of about 13 weeks (by some measures). *A. pintoi* had a positive effect on the stem diameters of fruit trees intercropped with it, arguably more than could be obtained with chemical fertilizer (Dornelles et al., 2016). It conserved soil moisture better than four other cover crops, purportedly because as a perennial it maintains leaves across the seasons, and as its higher C/N ratio makes for slower degradation. It tolerates partial shade, and is thus suited to coffee plantations. *A. pintoi* has several useful qualities:

1. It is low growing (usually under 30cm) which means it never grows high enough to shade young trees. This also means mowing gives it an advantage over taller weeds.

2. It closes to form dense foliage, reducing soil evaporation by reducing solar radiation (Unger and Vigil, 1998) and wind velocity at the soil surface.

3. It has a tap root that can exceed 1m and so can access water in deep soil layers

4. It can endure many weeks of drought without loss of foliage.

For all its advantages, there are many conditions for which *A. pintoi* is inappropriate. It may compete with some crops for water, dry soils due to transpiration, (Unger and Vigil, 1998) and so may be more suited for humid rather than semi-arid regions. The buried peanuts may attract rodents (Johns, 1994). It has slow growth, does not compete well with fast-growing grasses, and can be difficult to establish (Vidhya et al., 2024). It also had negative effects on banana fruit size (Johns, 1994). For maize it has been shown to reduce erosion and increase N, P, and organic C, but decrease corn yield (Sumiahadi et al., 10 2018). The prior literature makes no mention of the use of *A. pintoi* with *C. latifolia* or *C. arabica*.

Sustainability of Persian lime production

Hectares under Persian lime production in Veracruz have increased in recent years, driven by a high price in the US market. However the increase is not considered sustainable, due to increasingly variable temperature and precipitation. Increases in temperature and changes in precipitation have been particularly harmful to citrus (Valdés-Rodríguez et al., 2023) and are likely to continue intensifying in Veracruz, (Castillo-Martínez et al., 2022) as in other citrus growing regions. Another sustainability issue arises from the consumption of fertilizer, water, land, and labor (Castillo-Martínez et al., 2022). Thus it is urgent to make Persian lime production drought resistant and control its environmental impact.

Intercropping often results in increased water use efficiency. Much of this is due to shading. Water redistribution has been observed, suggesting that shallow rooted trees like *C. latifolia* may benefit from intercropping with relatively deep rooted species such as *C. arabica* and *A. Pintoi* (Liu et al., 2025).

Root systems of *C. arabica, A. pintoi*, and *C. latifolia*

The roots of plants respond postembryonically to resources, soil hydrology and chemistry, plant spacing, pruning, etc. making it impossible to make strict statements. However root characteristics are clearly relevant to the success of an intercropping system. Here we summarize expert opinion on root depths of these three species and speculate as to how they may interact.

C. arabica has roots up to 3m deep according to (Ferreira et al., 01 2019). Other authors report root depths of 80cm (Partelli et al., 2020). *A. pintoi* roots can grow to 1.2 m deep (Partelli et al., 2020; Tropical Grasslands, 1995). *C. latifolia* is widely considered to have shallow roots. In an irrigated orchard in Brazil, at least half of water extraction was found at soil depth between 0 and 375mm, and none below 875mm. At most 7% of root length was found at depths 875-1125mm (de la Mora, 2007). A separate Brazilian study found that (within rows of lime) by far most root area was in the top 250mm of soil, with no more than 10% of root area at depths of 750-1000mm (Neves et al., 2004).

A well-developed root system may be important to the ecological benefits of *C. arabica* and/or *A. pintoi*. Glasshouse experiments have shown that *Cajanus cajan* (but not *Sesbania sesban*) redistribute deuterated water to adjacent *Zea mays* plants through hydraulic lifting. It was further found that shading the *Cajanus cajan* increased the water redistribution (Sekiya and Yano, 2004). If this mechanism exists in the *C. latifolia - C. arabica - A. pintoi* system it is possible that as the *C. latifolia* grows and creates shade, the *A. pintoi* will provide it with more water which it and the *C. arabica* can access from deeper soil layers. Much apparently depends on the root associations that form between the three species.

Soil aggregate sizes

Arbuscular mycorrhizae, such as that which colonize *C. latifolia, C. arabica, and A. pintoi*, produce glomalin-related soil proteins that stabilize carbon, moisture, and soil aggregates (clods) (Rillig 2004). Soil aggregate sizes are an indicator of soil properties and health, and can change with land use. They are also related to soil type and content of fine roots and other remnants, and other soil microbial components. Cover crops can increase the proportion of larger-size aggregates, related to increased SOC.(Dai et al., 2024)

Hypotheses

We proposed that:

H1 Plots cover-cropped with *A. pintoi* will have lower temperature and higher humidity.

H2 The *A. pintoi* plots should have a higher rate of *C. latifolia* survival compared to bare soil.

Method & Results

We planted *C. latifolia* (with sour orange rootstock)(Franco Valderrama et al., 2021) at 4m between trees and 5m between rows, starting 1/2024 (dates follow (DD/)MM/YYYY), resulting in a density of 500 trees/ha. Between rows of *C. latifolia*, we planted double-rows of *C. arabica*, Marsellesa variety, at 1.5m x 1.5m, starting in 7/2024. The overall density of coffee was 2667 trees/ha. Starting in 7/2024, the we planted *A. pintoi* in a 0.3x0.3m grid. The *A. pintoi* fully closed by 5/2025. During this period the plots were rainfed.

We divided the farm into experimental plots to test elements of the system, shown in Fig. 1 and Fig. 2. The reference system was implemented in plot 1A. Plot 6 was the last to be planted, and this was done near the start of winter when germination becomes difficult; as a result this plot has a mix of *A. pintoi* and weeds. Most plots were too small to monitor by remote sensing, so we created groupings in Table 1.

Table 1
Treatment groups for remote sensing. Plots other than 7,8 were too small to be analyzed separately. Heterogeneity refers to minor differences within the treatment group, see text. There is a large boulder in plots 1C,1D which may influence remote sensing results, so we excluded those plots from ARA. Remote sensing measurements were relative to MAIZE in order to compensate differences in scene brightness.

Acronym	**Plots**	**Main treatment. (Remote sensing area, m^2)**	**Heterogeneity**
ARA	1A,1B, 2,3	*A. pintoi* cover cropped. (1190 m^2)	Plot 3 has *C. latifolia* but no *C.arabica.* Plots 2,3 have no mycorrhizal inoculant. Plot 1B was amended with anthill soil when planting *C. arabica*.
BSU	4,5	Bare soil, unshaded (400 m^2)	Plot 4 has *C. arabica* planted with no mycorrhizal inoculant.
BSSh	1	Bare soil, partial tree shade	None
MIX	6	*A. pintoi* and native weeds	None
WEEDS	7	Native weed cover (8100 m^2)	None
MAIZE	8	Maize (7100 m^2)	None

C. latifolia leaf transpiration

We used an SC-1 leaf porometer (Meter Group, Munich, Germany) to measure *C. latifolia* stomatal conductance. The goal was to compare the treatments, so for strongest signal we chose one dark, healthy leaf, growing as close to the ground as possible, from each tree. Dessicator beads were changed after every 10 measurements.

Soil aggregate size measurement

Soil samples were taken along the sample line, bagged, and marked with the collection location. The samples were then spread out and allowed to dry on white office paper. They were then photographed along with a ruler. We measured the size of the aggregates using ImageJ software, and recorded along with the sample's site of collection and treatment. The ImageJ processing was similar to that of (J. Kumara, 2012). We used the ruler in the image to set the scale. We converted the images to binary, and finally computed the area of each aggregate.

Transient effect of *A. pintoi* and mycorrhizal inoculant on *C. arabica* in autumn after planting

In the autumn after planting, the *C. arabica* under + COVER/+INOC treatment had good (dark, green) leaf color and its typical shiny cuticle. -COVER/+INOC showed leaf yellowing, suggesting that *A. pintoi* provided nitrogen as desired. *C. arabica* under + COVER/-INOC had dull leaf cuticle (Fig. 3, 16/10/2024 panel). The effect disappeared over the winter (Fig. 3, 14/01/2025 panel), to the point that the staff evaluated the -COVER condition as better for plant health. The conditions shown in the 16/10/2024 panel did not return in 10/2025.

C. arabica infection and change in *A. pintoi* management

Two problems arose during *A. pintoi* establishment, we here present their corrective action. First, the trees appeared to be growing faster and have better leaf color in the WEEDS plot, compared to ARA, which we ascribed to competition between *C. arabica* and *A. pintoi*, rather than the desired fixation of soil nitrogen by the latter. Second, we observed a (possibly fungal) discolored growth on the stalks and leaves of the coffee trees. We attributed this to excess moisture due to shading by the *A. pintoi*. To address both, we: 1. mowed the *A. pintoi*. 2. edged around the trees (Figure G).

After these two interventions the discoloration on stalks and leaves disappeared (Fig. 4.B,C). We ascribed this to a reduction in moisture. We also noted an improvement in *C. arabica* leaf color. The *A. pintoi* was in flower at the time, so the mowing should have interrupted the fruiting process. The mowing litter was left in place to provide fertilizer – popularly called “chop-and-drop.” *A. pintoi* looks brown after mowing, but regrows within 2 weeks.

Cover cropping and soil temperature

In unshaded conditions, ARA soil is 4.5°C cooler than BSU, with high statistical significance. BSSh was shaded by trees, and had a similar temperature to ARA (Fig. 5). Thus *A. pintoi* reduces soil temperature, and the effect is due to shading. When we took soil samples from BSU, moisture from the soil condensed on the inner wall of the 50mL falcon tubes, suggesting high soil evaporation. This higher temperature was palpable to us while taking measurements.

C. latifolia leaf transpiration

On 03/05/2025, one day after a rain broke otherwise dry conditions [Figure 6], we took leaf porometer measurements on *C. latifolia* trees along the blue line in Fig. 1. We detected a greater leaf transpiration in the BSU compared to the plots [Figure 7].

C. latifolia drought survival

BSU was planted with 27 *C. latifolia* trees of which 6 died (Fig. 1). Plots 2 and 3 were planted with 30 and 1A,B with 75 trees; of these 105 trees (comprising ARA), 1 died (row 3 tree 1, felled by wind). If we apply the cumulative hypergeometric distribution, with a population of 105 including 7 successes, sample of 28, and 6 successes in the sample, we obtain a significance of $p = .001$.

C. arabica tree deaths were not counted, but we noted that those in BSU had high drought-related mortality as well. Some *C. arabica* seedlings also died in ARA, apparently from competition with *A. pintoi.*, albeit at lower rates.

Soil moisture and vegetation index by remote sensing

Soil moisture was measured by NDMI (Normalized Difference Moisture Index). NDMI is computed from Sentinel2 multispectral images, namely the NIR (Near Infrared, at 10m resolution) and SWIR (Short Wave Infrared, 20m resolution) bands. It is correlated with surface moisture content. GNDVI (Green Normalized Difference Vegetation Index) is computed from the NIR and green (visual, 10m resolution) bands. GNDVI is correlated with chlorophyll content.

The effect of the cover crop on NDMI and GNDVI was most significant in the DS (dry season). During this period we noticed a drying out of the soil which soon led to a die-off of several lime (Fig. 1) and coffee trees in BSU. The DS traditionally runs March-June (de la Mora, 2007). For our remote sensing measurements, we considered the DS to run 1 March to 30 June. In 2025 the DS arguably ended by 15 June [Figure 6], however changing the end of the DS did not change the conclusions.

BSU had no *A. pintoi*, and conscientious mowing had made the weeds too weak to survive the conditions as the 2025 DS started, so these dried out leaving bare soil. During the 2025 DS, NDMI was lower in BSU than in ARA. In the 2024 DS (before the A. pintoi was established) there was no significant difference in NDMI between these two areas. An overhead view of BSU, ARA, MAIZE, and WEEDS is shown in Fig. 8.

1. A) Red trace: temperature, 10-day rolling average. Thin blue bars: precipitation. Both from visualcrossing.com. Grey boxes: cloudy days (no GNDVI or NDMI measurement), detected by average RGB intensity > 1650. The DS is indicated with horizontal black bars.
2. B) GNDVI for ARA (A. pintoi), BSU (bare soil), and WEEDS, relative to the MAIZE plot. Vertical error bars reflect ± 1 standard deviation. Quantities are averaged over the DS, indicated with pink vertical bars. In 2025, ARA has higher GNDVI than BSU ($p = .009$, by z-test), or MAIZE ($p = .0009$). For the difference between ARA and WEEDS, $p = 0.07$. ARA GNDVI is higher in 2025 (when the plot had established *A. pintoi*) than 2024 (when it was bare soil, $p = 0.02$) and in 2023 (when it had maize, $p = 0.03$).
3. C) ARA has higher NDMI than BSU ($p = .03$).

Effect of *A. pintoi* on soil aggregate size

The photos of soil samples were separated into four groups, +/-COVER and +/-INOC. INOC did not appear to have an effect on the aggregate area distribution, but as the mycorrhiza was only applied to the *C. arabica roots*, we further subdivided the + COVER/+INOC based on where the sample was taken (under a *C. latifolia* vs under a *C. arabica* tree), however this was not discernibly different from the overall + COVER/+INOC (data not shown). The *A. pintoi* cover crop, however, did have a significant effect on the aggregate size distribution (Fig. 10).

Discussion

The goal of this work was to evaluate the drought protective effect of *A. pintoi* on *C. latifolia*. There were zero *C. latifolia* tree deaths due to drought in the *A. pintoi* cover cropped plots, whereas the bare-soil plots had a significant fraction of trees die.

The full-sun, *A. pintoi* plots (ARA) had soil temperature 4.5°C cooler than the ASU. There was also significantly higher NDMI, a remote measurement of moisture, in ARA than in BSU in 2025 (Fig. 9). This appears to be primarily due to soil shading by the dense *A. pintoi* canopy, as the tree-shaded, bare-soil (BSSh) plots had temperature indistinguishable from that of ARA. However we do not rule out hydraulic lifting as a contributing factor.(Sekiya and Yano, 2004)

GNDVI, a measure of chlorophyll, was higher for ARA than BSU in 2025 (Fig. 9). The GNDVI was also higher for ARA in 2025 (when the *A. pintoi* had closed) than for ARA in 2024 (when there was no *A. pintoi*) or 2023 (when there was maize). Thus *A. pintoi* cover cropping leads to more photosynthesis per ha. Photosynthesis leads to production of plant biomass, and also produces carbohydrates that can be traded with mycorrhiza for nutrients, leading to increased soil microbial biomass. All of this may ultimately increase soil carbon.

Indeed the *A. pintoi* is affecting soil properties, namely the distribution of soil aggregate sizes is wider (more aggregates in the > 100mm^2 size range, Fig. 10). Cover crop roots and organic matter can affect the distribution of size of soil pores (Al-Shammary et al. 2025). Mycorrhizae such those associated with *A. pintoi* increase aggregate stability (Rillig 2004). On the other hand INOC, the mycorrhizal inoculant treatment, had no clear effect on soil aggregate size distribution. Since the +/-INOC samples were taken from different locations, these had the effect of validating our conclusions regarding the soil aggregate size distribution in relation to *A. pintoi*.

INOC did appear to give the *C. arabica* its expected waxy sheen in the autumn after planting, without it the leaves took on a matte finish. The difference in finish disappeared soon after (Fig. 3). As mentioned, INOC had no clear effect on soil aggregate sizes a year after planting. This could be related to the experimental fields' history, as a once-mature *C. arabica* plantation, with soil still in good condition. The mycorrhizal inoculant similarly has its origin in mature *C. arabica* plantations. It could be that in good *C. arabica* plantation soils, the inoculant has only a short-term effect, after which the existing soil microbiome outcompetes the inoculant.

C. latifolia in BSU had higher post-rain leaf transpiration than that in ARA. The soil was still wet but the canopy and air were dry. The BSU trees were already suffering from earlier water stress, and the warmer (compared to ARA) soil may have led the trees to use transpiration to cool their leaves. Faster soil drying is a clear risk of this strategy.

Although this work is about drought survival, the test system and method have consequences well beyond that. This is the first report of a *C. latifolia / C. arabica* intercropping system. It is also the first report of *A. pintoi* as a cover crop with either of these trees. This remote sensing results show that for sufficiently strong signals and appropriate references (here all measurements were relative to MAIZE) and time-averaging (over the entire DS), moisture and vegetation can be measured for small plots previously considered too small for Sentinel2 (Novák and Křížová, 2020).

In conclusion, the *A. pintoi* cover crop had a strong effect on soil moisture (by remote sensing), temperature (measured on-site), and structure, compared to bare soil in full sun. As a result, 100% of *C. latifolia* survived the DS in the former. Bare soil in shade had similarly good results in soil temperature and tree condition, indicating that shading provides a similar protective effect. We conclude that *A. pintoi* does indeed provide drought protection for young trees, and the effect is likely due mainly to soil shading. Differences in vegetation index and soil structure suggest future benefits in soil carbon sequestration.

Abbreviations

NDMI
Normalized Difference Moisture Index
NDVI
Normalized Difference Vegetation Index
SOC
Soil Organic Carbon
A. pintoi
Arachis pintoi
C. latifolia
Citrus latifolia
C. arabica
Coffea arabica

Declarations

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Availability

Code is available at github.com/samuelflores/earth-observation .

Competing interests

S. Flores intends to sell coffee and lime grown on the experimental plots. D. Trejo sells mycorrhizal inoculant through Universidad Veracruzana.

Author contributions

D. Trejo suggested the use of *A. pintoi* and her mycorrhizal inoculant. J. Bañuelos measured soil temperatures and aggregate sizes. Both consulted throughout the project. S. Flores conceived and implemented the agroforestry system, supervised agricultural staff, wrote the code, processed the data, and wrote the paper.

References

1. Alele JO, Ding Q, Sayed HAA (2023) A combined ridging and cover crop tillage system for sustainable coffee plantation in Kenya. Agron (Basel) 13:655
2. Blanco-Canqui H, Ruis SJ (2020) Cover crop impacts on soil physical properties: A review. Soil Sci Soc Am J 84:1527–1576
3. Castillo-Martínez SI, Díaz-José J, Leyva-Ovalle OR, Ramírez-Rivera E, de Díaz-José J, Murguía-González O, Ramírez JG, Cruz-Castillo JF, J.G (2022) Urgently needed transition pathways toward sustainability in agriculture: the case of Persian lime (Citrus latifolia Tanaka) production in Veracruz, Mexico. Environ Dev Sustain. https://doi.org/10.1007/s10668-022-02806-5
4. Dai W, Feng G, Huang Y, Adeli A, Jenkins JN (2024) Influence of cover crops on soil aggregate stability, size distribution and related factors in a no-till field. Soil Tillage Res 244:106197
5. de Carvalho FF, Barreto-Garcia PAB, Pérez-Maluf R, Monroe PHM, Pereira FR, Almeida TC, Nunes MR (2024) Effects of Coffee arabica cultivation systems on tropical soil microbial biomass and activity in the northeast region of Brazil. Agrofor Syst 98:2397–2410
6. de la Mora MA (2007) Respuesta productiva de una pastura de gramas nativas bajo pastoreo rotacional intensivo en clima cálido húmedo 2007. AIA Av en Investigación Agropecuaria 11:35–55
7. Dornelles P, Perin A, GuimarÃ F, Melo GB (2016) Water content and soil nutrient in consortium of native fruit trees with cover crops. Afr J Agric Res 11:4100–4108
8. Ferreira T, Shuler J, Guimarães R, Farah A (2019) Introduction to Coffee Plant and Genetics, in: Coffee: Production, Quality and Chemistry. The Royal Society of Chemistry, p 01
9. Franco Valderrama AM, Caamal Cauich I, Pat Fernández VG, Pérez Soto F (2021) Characterization of Persian lime production (Citrus x latifolia; Tanaka ex Q. Jiménez). https://doi.org/10.32854/agrop.v14i11.1883. Agro Productividad
10. Kumara J, G.H.A.J (2012) Image analysis techniques on evaluation of particle size distribution of gravel. Int J GEOMATE. https://doi.org/10.21660/2012.5.1261

11. Johns GG (1994) Effect of Arachis pintoi groundcover on performance of bananas in northern New South Wales. Aust J Exp Agric 34:1197
12. Liu H, Gao X, Li C, Cai Y, Song X, Zhao X (2025) Intercropping increases plant water availability and water use efficiency: A synthesis. Agric Ecosyst Environ 379:109360
13. Massrie KD (2025) Why is the price of coffee rising globally? Future prospects for Ethiopian coffee. Front Sustain Food Syst 9. https://doi.org/10.3389/fsufs.2025.1545168
14. Merga D, Beksisa L (2023) Mechanisms of drought tolerance in coffee (Coffea arabica L.): Implication for genetic improvement program: Review. Am J BioScience. https://doi.org/10.11648/j.ajbio.20231103.12
15. Mulinge J, Saha H, Mounde L, Wasilwa L (2018) Effects of legume cover crops on orange (citrus sinensis) fruit weight and Brix. Int J Plant Soil Sci 21:1–9
16. Neves CSVJ, Murata IM, Stenzel NMC, Medina C, de Borges C, Okumoto AV, Lee SH, Kanai RHC, H.T (2004) Root distribution of rootstocks for Tahiti lime. Sci Agric 61:94–99
17. Niguse G, Iticha B, Kebede G, Chimdi A (2022) Contribution of coffee plants to carbon sequestration in agroforestry systems of Southwestern Ethiopia. J Agric Sci 160:440–447
18. Noponen MRA, Healey JR, Soto G, Haggar JP (2013) Sink or source—The potential of coffee agroforestry systems to sequester atmospheric CO2 into soil organic carbon. Agric Ecosyst Environ 175:60–68
19. Novák V, Křížová K (2020) Sentinel-2 imagery utilization for small-plot agricultural studies. IOP Conf Ser Mater Sci Eng 725:012078
20. Partelli FL, Cavalcanti AC, Menegardo C, Covre AM, Gontijo I, Braun H (2020) Spatial distribution of the root system of Conilon and Arabica coffee plants. Pesquisa Agropecuária Brasileira 55, e01333
21. Pavan MA, Chaves JCD, Siqueira R, Androcioli Filho A, Colozzi Filho A, Balota EL (1999) High coffee population density to improve fertility of an oxisol. Pesqui Agropecu Bras 34:459–465
22. Perdoná MJ, Soratto RP (2015) Higher yield and economic benefits are achieved in the macadamia crop by irrigation and intercropping with coffee. Sci Hortic (Amsterdam) 185:59–67
23. Rivera-Hernández B, González-Jiménez V, Carrillo-Ávila E, Garruña-Hernández R, Andrade JL, Quej-Chi VH, Arreola-Enríquez J (2022) Yield, physiology, fruit quality and water footprint in Persian lime (citrus latifolia tan.) in response to soil moisture tension in two phenological stages in Campeche, México. Water (Basel) 14:1011
24. Sekiya N, Yano K (2004) Do pigeon pea and sesbania supply groundwater to intercropped maize through hydraulic lift?—Hydrogen stable isotope investigation of xylem waters. Field Crops Res 86:167–173
25. Sumiahadi A, Chozin M, Guntoro D (2018) 10 Effectiveness of Arachis pintoi Karp. & Greg. as Biomulch to Reduce Soil Erosion and Increase Soil Fertility on Maize Cultivation
26. Tao S, Chave J, Frison P-L, Le Toan T, Ciais P, Fang J, Wigneron J-P, Santoro M, Yang H, Li X, Labrière N, Saatchi S (2022) Increasing and widespread vulnerability of intact tropical rainforests to repeated

droughts. Proc Natl Acad Sci U S A 119:e2116626119

27. Tropical, Grasslands (1995)
28. Unger PW, Vigil MF (1998) Cover crop effects on soil water relationships. J Soil Water Conserv 53:200–207
29. Valdés-Rodríguez OA, Salas-Martínez F, Palacios-Wassenaar OM (2023) Hydrometeorological hazards on crop production in the State of Veracruz, Mexico. Atmos (Basel) 14:287
30. Vidhya V, Jyothibabu R, Alok KT, Rashid CP, Arunpandi N, Devi CRA, Gupta GVM, Thirumurugan R (2024) Ecophysiological status of copepods in the oxygen minimum zone of Eastern Arabian Sea. Mar Pollut Bull 211:117370
31. Akchaya K, Parasuraman P, Pandian K et al (2025) Boosting resource use efficiency, soil fertility, food security, ecosystem services, and climate resilience with legume intercropping: a review. Front Sustain Food Syst 9. https://doi.org/10.3389/fsufs.2025.1527256
32. Al-Shammary AAG, Al-Shihmani LSS, Fernández-Gálvez J, Caballero-Calvo A (2025) A comprehensive review of impacts of soil management practices and climate adaptation strategies on soil thermal conductivity in agricultural soils. Rev Environ Sci Biotechnol 24:513–543
33. Jarrah M, Mayel S, Franko U, Kuka K (2022) Effects of agricultural management practices on the temporal variability of soil temperature under different crop rotations in Bad Lauchstaedt-Germany. Agron (Basel) 12:1199
34. Rillig MC (2004) Arbuscular mycorrhizae, glomalin, and soil aggregation. Can J Soil Sci 84:355–363
35. Tian Y, Schindlbacher A, Malo CU et al (2023) Long-term warming of a forest soil reduces microbial biomass and its carbon and nitrogen use efficiencies. Soil Biol Biochem 184:109109

Figures

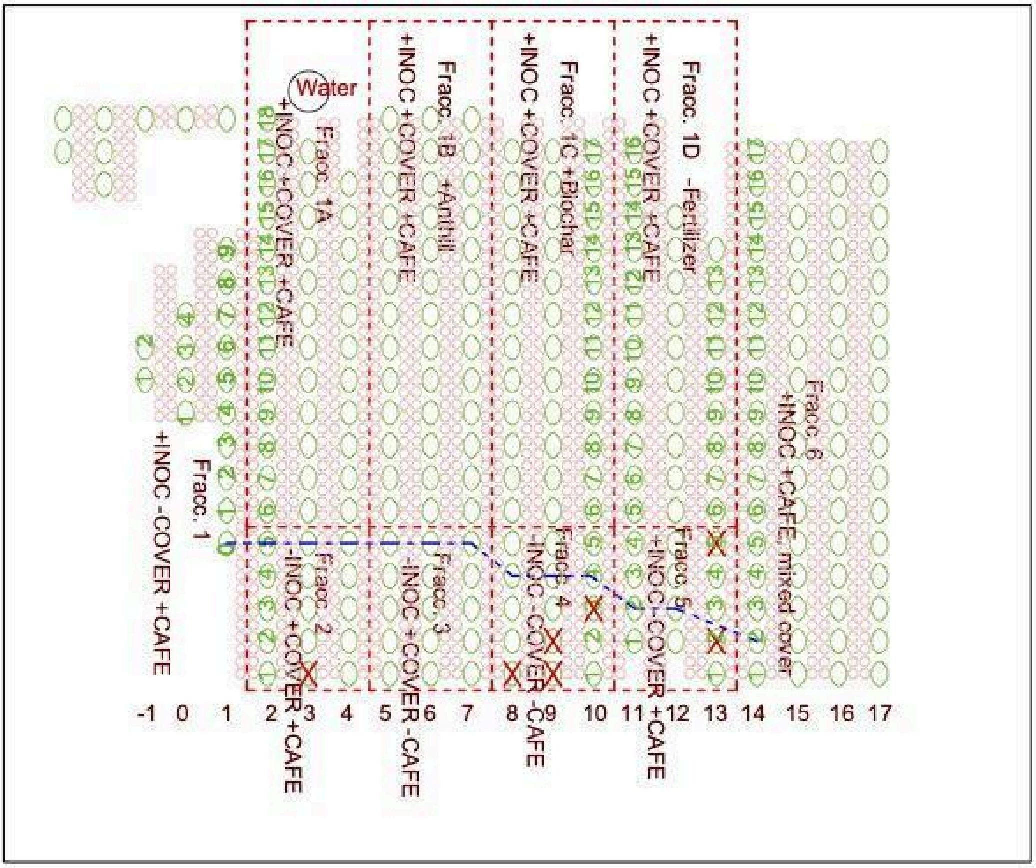

Figure 1

Planting map of plots 1-6. Boundaries shown by red dashed lines. CAF = coffee trees planted in alleys between rows of lime (as opposed to empty alleys). INOC = mycorrhizal and bacterial inoculant added to coffee seedlings prior to planting. COV = *A. pintoi* planted as a cover crop. Green ovals: *C. latifolia* trees. Red X: dead lime trees. Pink circles: *C. arabica* trees. Horizontal numbers: *C. latifolia* row numbers. Vertical green numbers: *C. latifolia* tree numbers. “Water” indicates location of spring-fed water tank. Measurements were made of leaves and soil along the blue dashed line. Blue line condition is sunny except for plot 1.

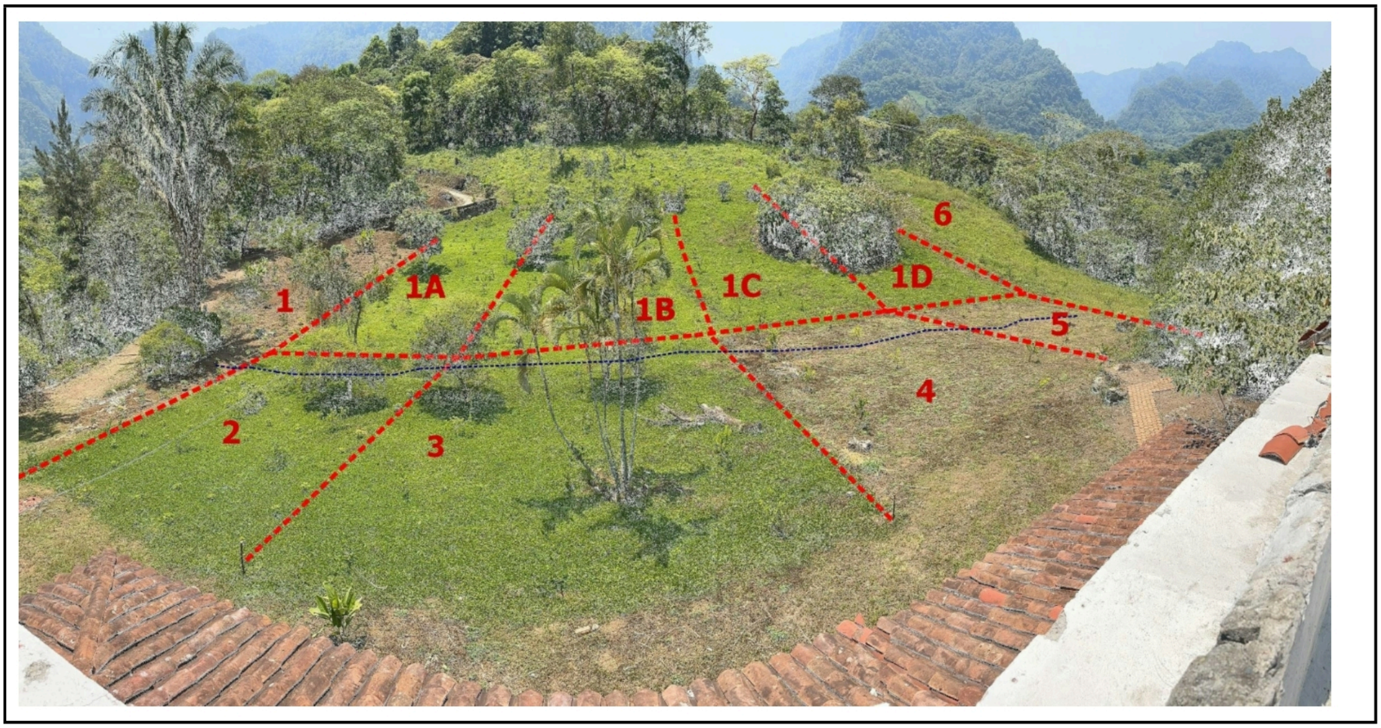

Figure 2

Panorama view looking south. Plot numbers in red. Note bare soil in plots 1, 4, 5.

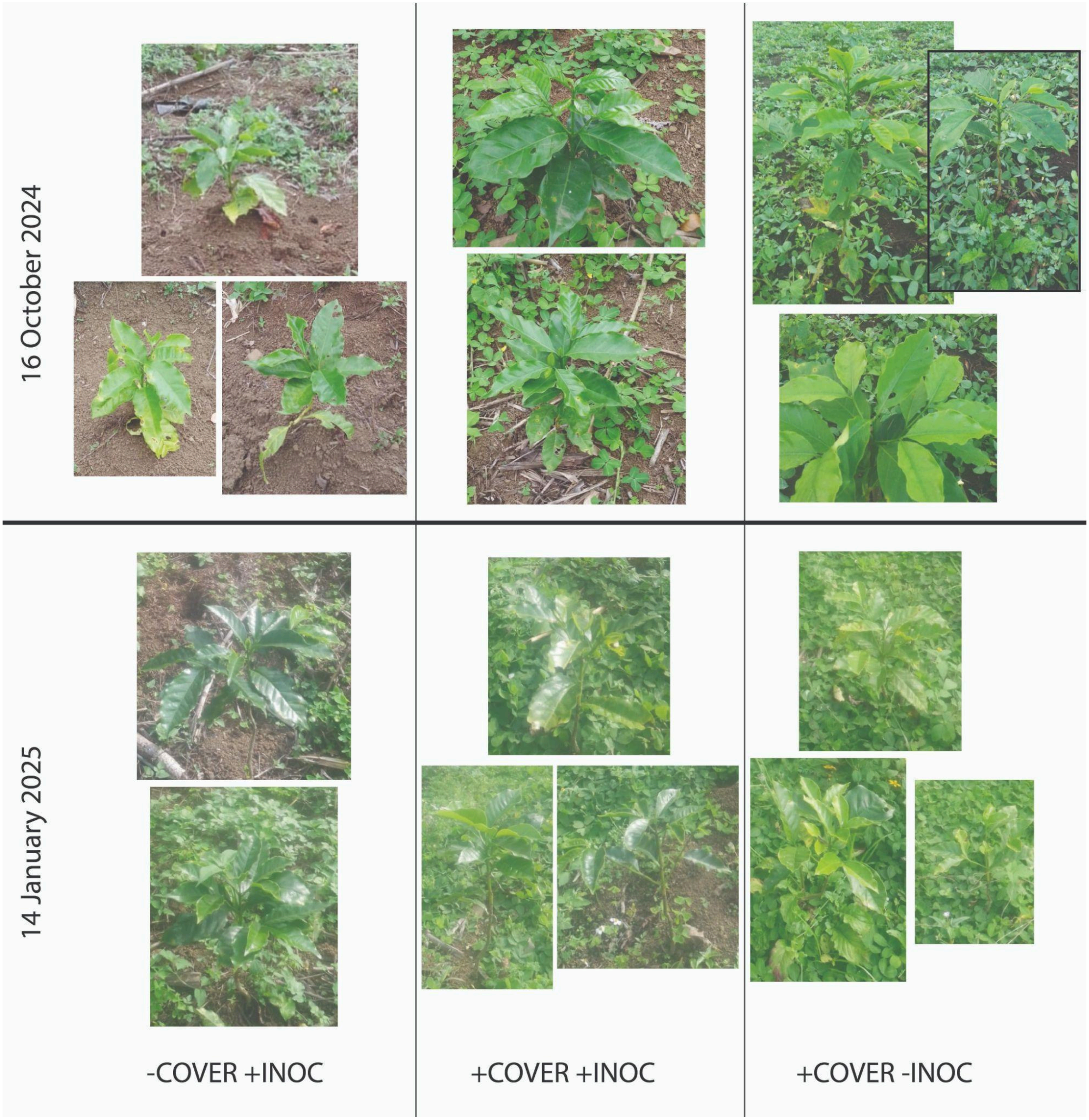

Figure 3

Transient effect of A. pintoi and mycorrhizal inoculant on C. arabica. Upper panels: Note leaf yellowing in -COVER/+INOC, and dull leaf cuticle in +COVER/-INOC. Lower panels: -COVER/+INOC color and +COVER/-INOC cuticle luster improved greatly over winter.

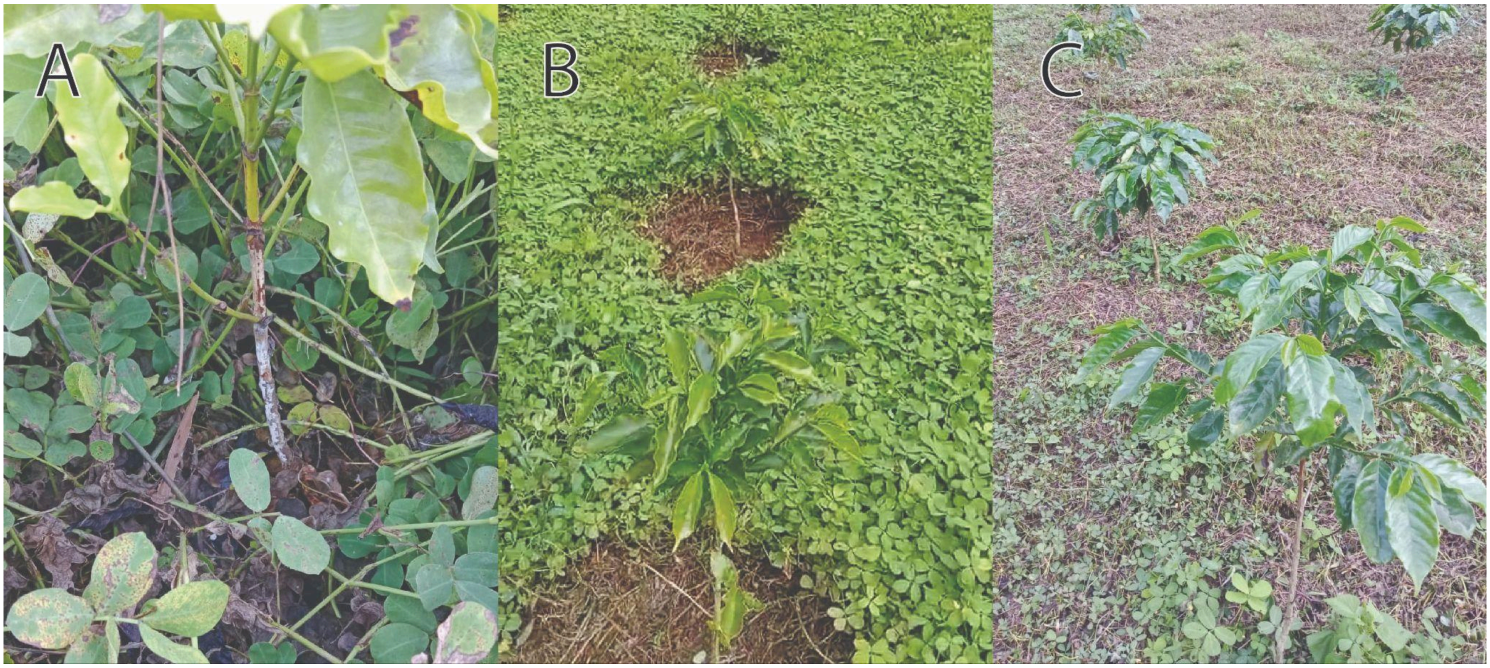

Figure 4

Arachis pintoi management. A: *C. arabica*seedling showing unidentified infection growing on stem, as well as poor leaf coloration, 3-7-2025. *A. pintoi* is shown surrounding the *C. arabica.* B: Edging around *C. arabica*, 06/08/2025 . Note fully closed *A. pintoi*mat, and improved leaf color on *C. arabica*. C: After mowing, 01/10/2025. Mown litter is left on ground, and *A. pintoi* later regrows.

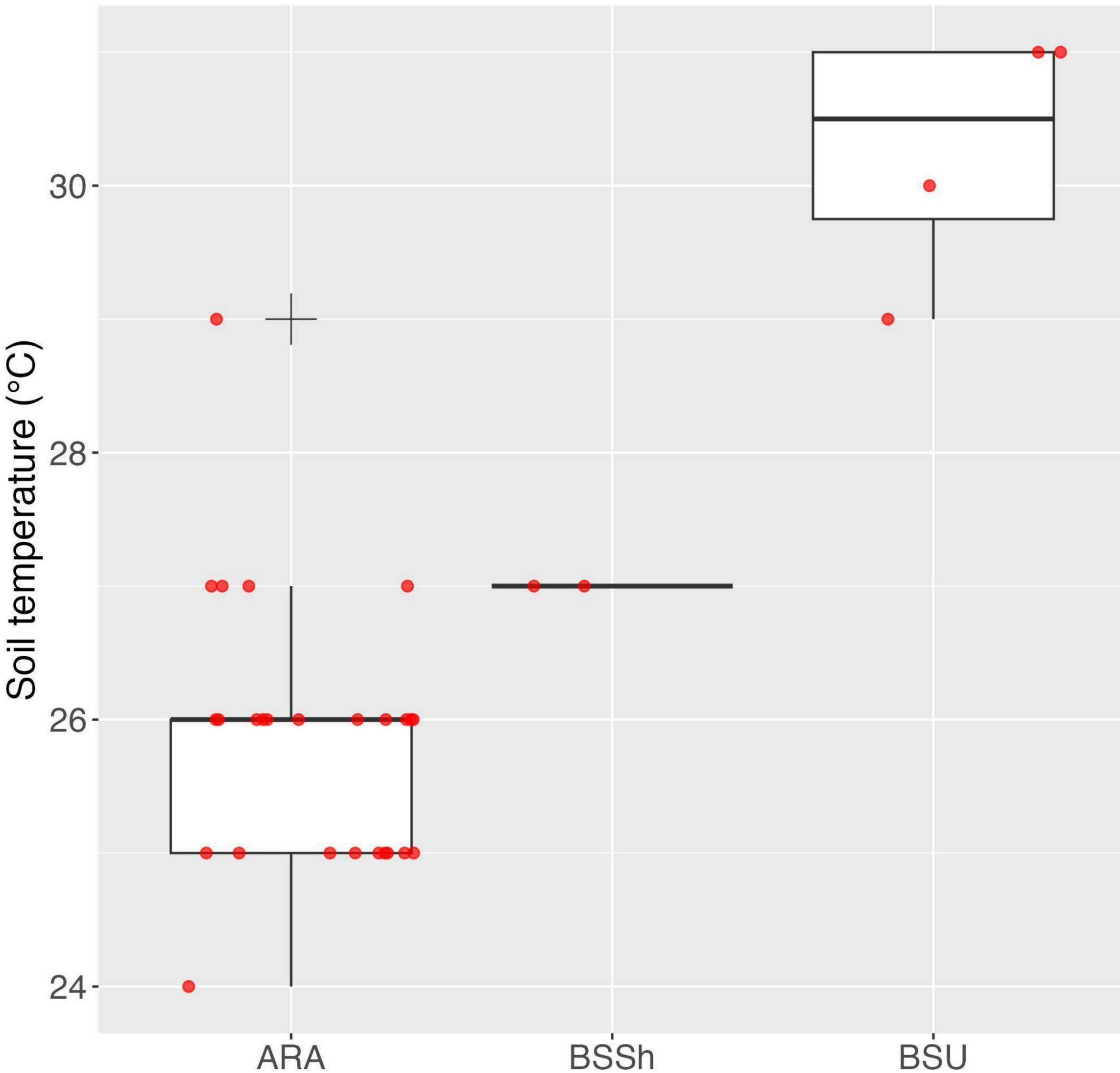

Figure 5

Soil surface temperature. The difference between ARA and BSU soil temperature is significant ($p=0.0009$, by two-sample unpaired Student's t with unequal variances, $t = -8.5$). Ambient temperature (2-5-2025) was minimum 17.2, average 21.5, and maximum 26.4°C.

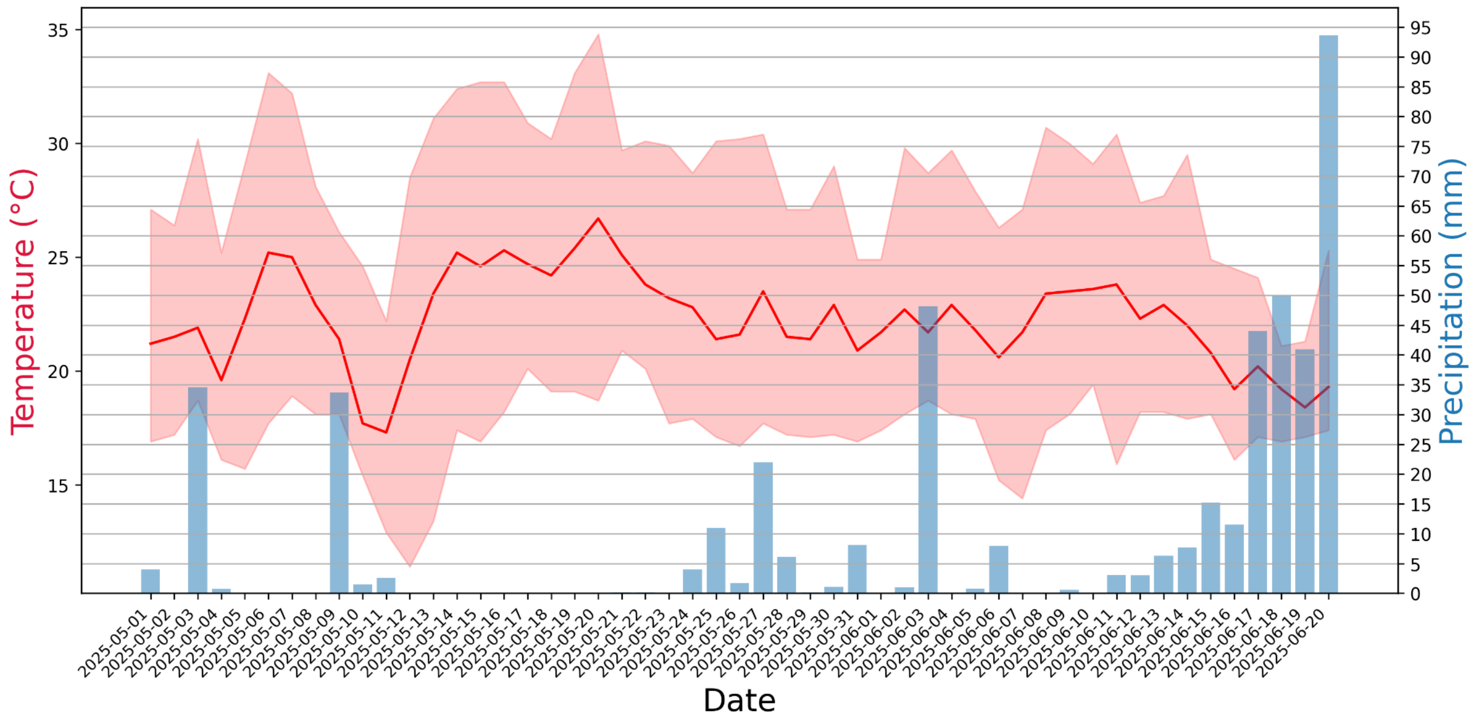

Figure 6

Rainfall and temperature at experiment site, including leaf porometer measurement date and end of DS. Red trace indicates mean, shaded red area indicates day's minimum to maximum temperature range. Data from visualcrossing.com. 35mm rain fell on 03/05/2025, one day before our leaf porometer measurements of 04/05/2025. This was preceded by 10 days of little rain. DS appears to end by 15/07/2025.

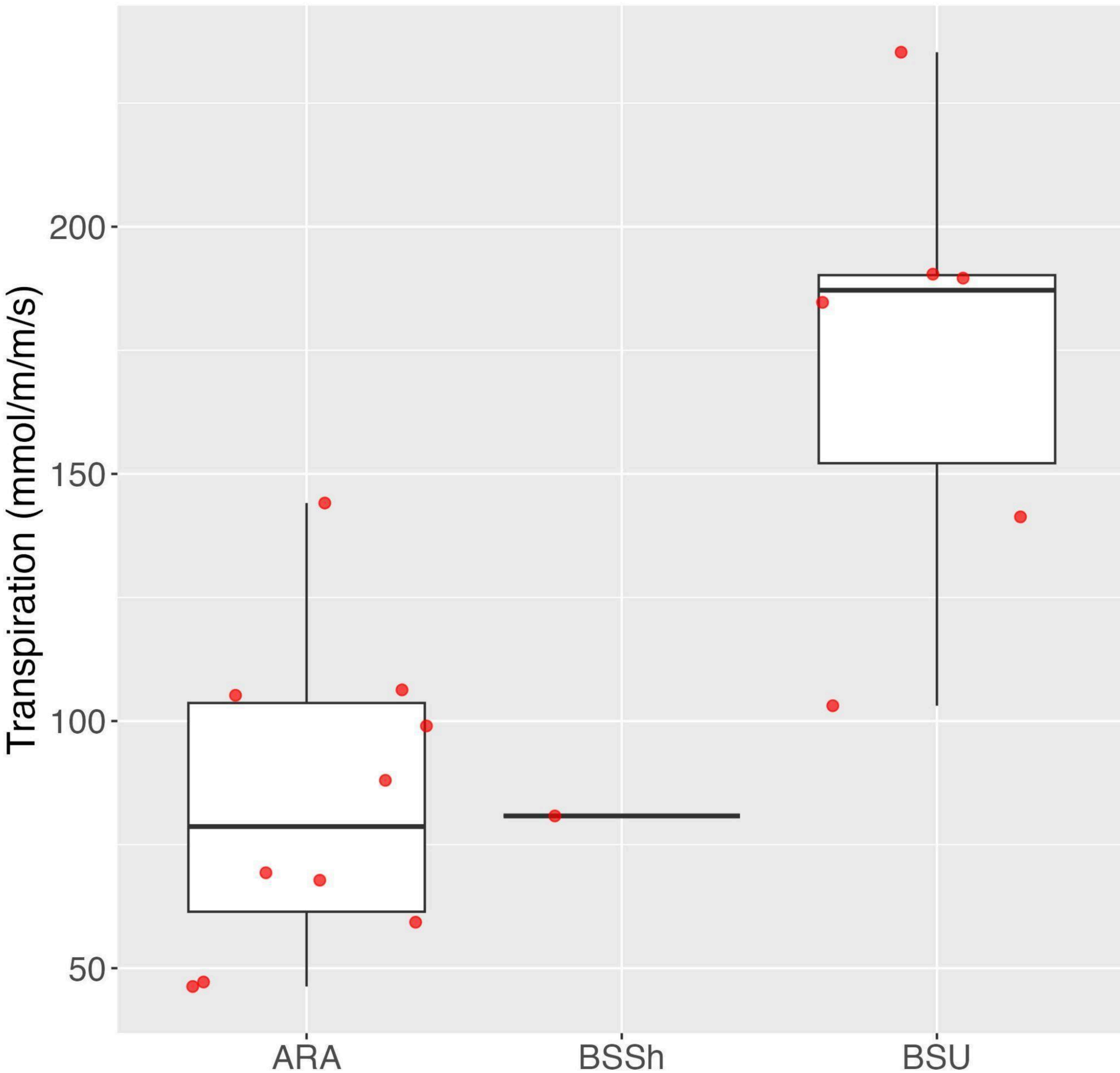

Figure 7

Foliar transpiration on *C. latifolia*, 1 day post-rain. Measured on 04/05/2025 . Red dots: individual measurements. BSU and ARA have significantly different mean transpiration (Two-sample unpaired Student's t with unequal variances, t = -4.3, p=0.003). The BSSh tree is row 1 tree 0, transpiration reading 80.8 mmol/m/m/s.

Figure 8

Treatment groups for remote sensing. Image from ESRI, plots marked using GeoDataFrames (GDFs) and LeafMap. WEEDS plot marked onsite using a GPS cellphone. ARA and BSU mapped using a combination of GPS and the planting map of Figure 1. MAIZE GDF placed using ESRI image only.

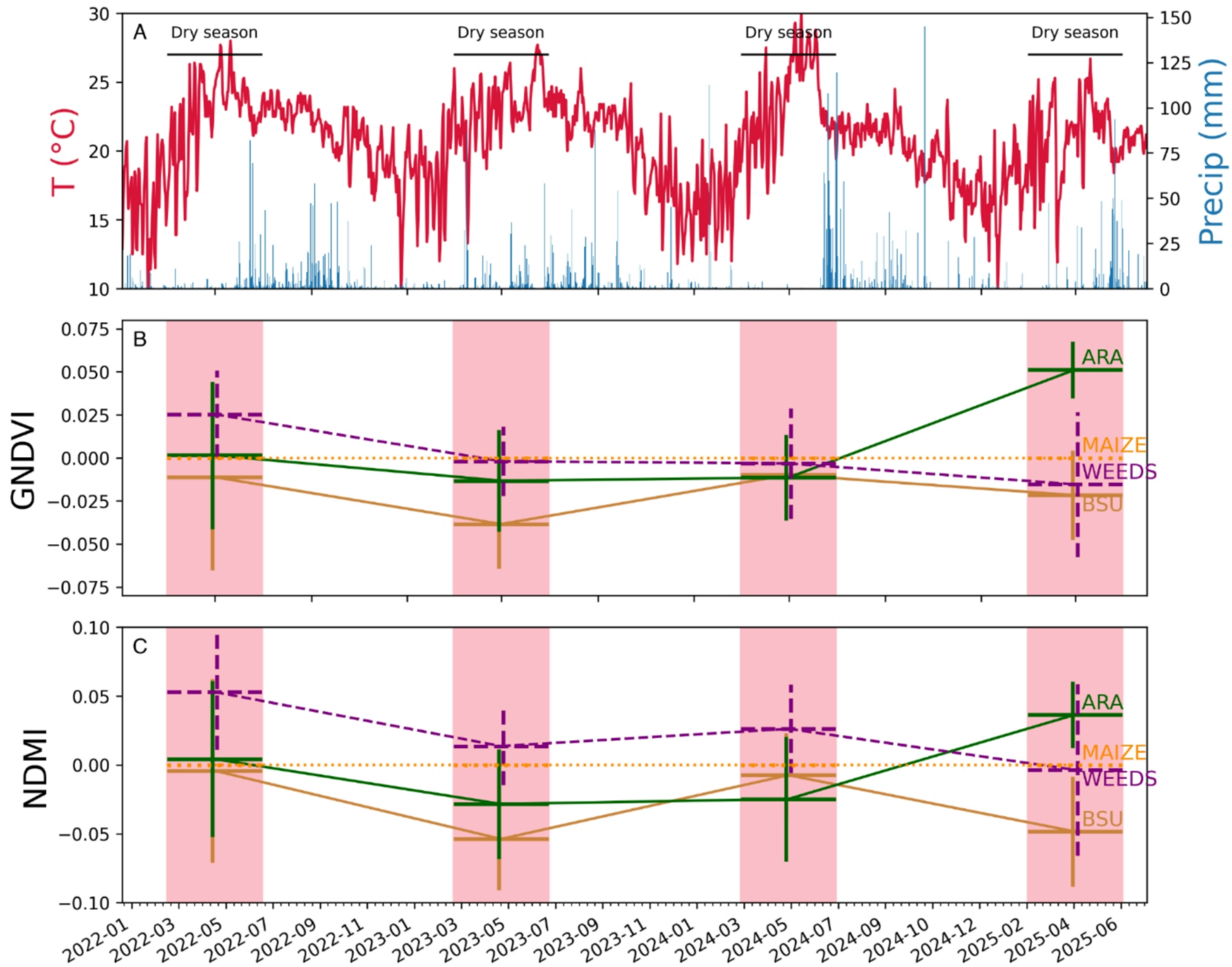

Figure 9

Weather, GNDVI, and NDMI over three treatments, against MAIZE as a reference.

A) Red trace: temperature, 10-day rolling average. Thin blue bars: precipitation. Both from visualcrossing.com. Grey boxes: cloudy days (no GNDVI or NDMI measurement), detected by average RGB intensity > 1650. The DS is indicated with horizontal black bars.

B) GNDVI for ARA (A. pintoi), BSU (bare soil), and WEEDS, relative to the MAIZE plot. Vertical error bars reflect ±1 standard deviation. Quantities are averaged over the DS, indicated with pink vertical bars. In 2025, ARA has higher GNDVI than BSU (p=.009, by z-test), or MAIZE (p=.0009). For the difference between ARA and WEEDS, p=0.07. ARA GNDVI is higher in 2025 (when the plot had established *A. pintoi*) than 2024 (when it was bare soil, p=0.02) and in 2023 (when it had maize, p=0.03).

C) ARA has higher NDMI than BSU (p=.03).

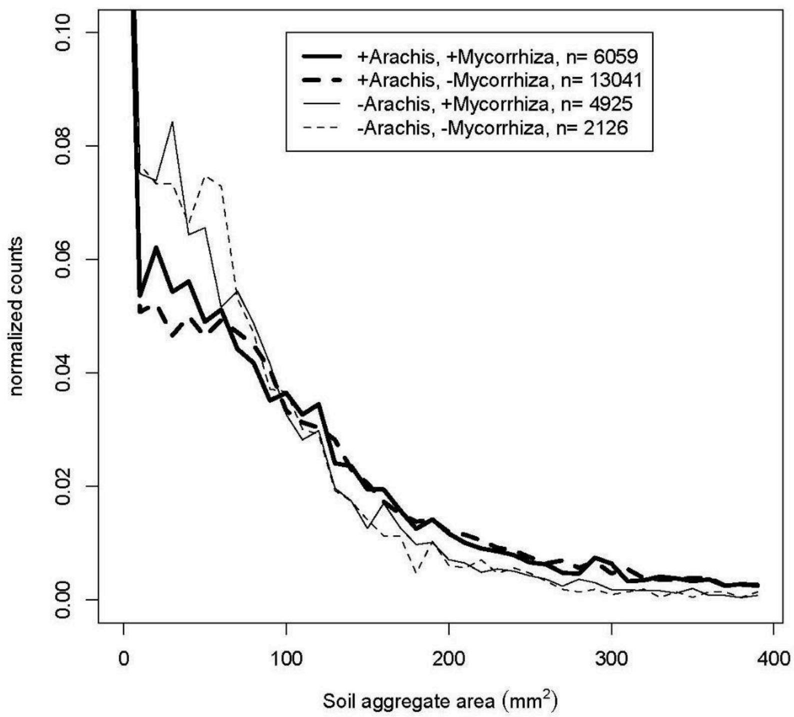

Figure 10

Histogram of soil aggregate area (measured from photographs of soil samples) under four treatments. Bin size is 10 mm^2. Sample size n refers to the number of aggregates detected in the photographs.