Cite as: Lardschneider, E., Topp, A., Kelderer, M., Vonmetz, L. (2026). Undersowing a biofumigation seed mixture as an agroecological solution to soil fatigue in organic apple production. *Proceedings of the 22nd International Conference on Organic Fruit-Growing*, Filderstadt 2026.02.23-25. Ed. FOEKO e.V. 2026: 161-164



# Undersowing a biofumigation seed mixture as an agroecological solution to soil fatigue in organic apple production

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## Abstract

*Continuous apple cultivation often leads to soil fatigue, reducing tree growth and yield. To address this, a six-year field trial (2021–2025) was conducted in an intensively managed orchard at the Laimburg Research Centre (South Tyrol) to evaluate whether undersowing a biofumigation seed mixture at planting could mitigate soil sickness without requiring a fallow year. Sinapis alba, Brassica juncea, and Raphanus sativus var. oleiformis Pers. were sown underneath tree rows and incorporated into the soil in autumn of the planting year; thereafter, all plots received identical management. A soil sickness test assessed M9 rootstock shoot growth in soils from each treatment and thermally treatedsoil. Biofumigation increased cumulative yield from 41.3 to 56.8 kg tree $^{-1}$ (+37.5%; t test, $P = 0.06$) and tree volume from 0.94 to 1.17 m$^3$ (+24.4%; t test, $P = 0.07$). In the soil sickness test, shoot length averaged 27.3 cm (control), 34.5 cm (biofumigation), and 44.2 cm (thermally treated), with biofumigation not differing significantly neither from control nor thermally treatedsoil (ANOVA).*


**Keywords:** apple replant disease, soil fatigue, soil sickness, Brassicaceae, biofumigation

## Introduction

Soil fatigue, also referred to as replant disease, is a widespread phenomenon in intensively managed apple orchards and has also been documented in organically managed systems in South Tyrol (Manici, 2003). Symptoms vary considerably, ranging from growth depression and delayed onset of yield to severe tree decline and dieback (Shashika et al., 2019). The underlying causes of soil sickness are multifactorial and may include pathogenic microorganisms, nematodes (Mazzola, 1997), and phytotoxic plant residues (Neri, 2006). Previous research has demonstrated that modifying the rhizosphere microbiome can mitigate soil fatigue in apple production. Approaches include the incorporation of compost (Thalheimer, 2019) and Brassicaceae seed meal amendments (Mazzola, 2010), which exert biofumigation effects through glucosinolate hydrolysis products.

The present study aimed to evaluate whether undersowing a specific Brassicaceae mixture for biofumigation during the planting year could reduce soil sickness and improve tree growth and yield in the early years following orchard establishment.

## Material and Methods

The trial was conducted from 2020 to 2025 in an apple orchard at the Laimburg Research Centre, South Tyrol, Italy. An intensively managed orchard (cv. Fuji, rootstock M9) was removed in autumn, and a new planting of cv. MC38 – Crimson Snow® on rootstock M9 T337 was established the following spring at a spacing of 0.75 × 3.2 m. The soil was classified as loamy sand with 1.7% organic matter content.

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Table 1: Composition of the Brassicaceae seed mixture: botanical names, variety names, weight percentage in the mixture

| **botanical name** | **variety name** | **weight percentage** |
|---|---|---|
| *Sinapis alba* | Litemberg | 35% |
| *Brassica juncea* | Vitasso | 10% |
| *Raphanus sativus var. oleiformis Pers.* | Regresso | 35% |
| *Raphanus sativus var. oleiformis Pers.* | Apollo | 20% |

The new trees were planted in the same row positions as the previous orchard. The trial was arranged as a complete randomised block design with three replicates. Each block consisted of seven trees, with the first and last trees excluded from data collection.

The seed mixture (Table 1) was sown on 15 July of the planting year and incorporated on 7 September Following soil loosening, manual sowing was conducted at a rate of 25 kg seeds $ha^{-1}$ across a 1 m-wide strip beneath the tree row.

Control plots were left unsown and allowed to be colonised by spontaneous vegetation, which was mulched three times during the first year whenever plant height exceeded 20 cm.

Subsequent soil management was identical across treatments.

Figure 1: Biofumigation seed mixture undersowing beneath the tree row.

Weed control employed crumblers (Krümler) and brush devices.

Fertilisation involved the application of an organic feather meal-based fertiliser (Azocor 105) at 60 kg N $ha^{-1}$, and plant protection measures adhered to integrated production guidelines.

Annual yield (kg tree$^{-1}$) was recorded from the second year onward using a grading machine (Calistar, AWETA, Pijnacker, Belgium).

Tree canopy volume was estimated by modeling the canopy as a cone, with base diameter calculated as the mean of row and cross-row measurements and height measured directly. Volume was computed as:

$$V_{\text{tree}} = \frac{4}{3} \mathbf{a} \times \mathbf{b} \times \mathbf{c} \times \boldsymbol{\pi}$$

where a and b are base diameters and c is height (see Fig. 2).

In 2021, a soil sickness test was conducted by potting M9 rootstocks in soils collected from each field treatment (18 plants per treatment). Total shoot length (cm) was measured 85 days after planting. A thermally treated soil soil (80 °C for 12 h) served as the control.

Yield and tree volume were compared using independent-samples t-tests. Shoot length was analysed by one-way ANOVA with Tukey's post hoc test. Analyses were performed in IBM SPSS Statistics 29.

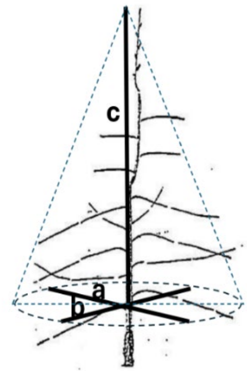

Figure 2: Measurement axes to calculate the tree volume.

## Results

Cumulative yield per tree over five years (2021–2025) amounted to 41.3 kg tree$^{-1}$ in the control treatment and 56.8 kg tree$^{-1}$ in the Brassicaceae seed mixture treatment resulting in a 37.5% increase in cumulative yield over the five-year period (t-test, $P = 0.06$).

In 2025, mean tree volume was 0.94 m³ in the control treatment and 1.17 m³ in the Brassicaceae seed mixture treatment exhibiting a 24.4% greater tree volume compared with the control (t-test, $P = 0.07$).

Table 2: Comparison of biofumigation and control treatments with respect to cumulative yield per tree over the period 2021–2025, tree volume measured in 2025, and shoot length of potted plants measured in 2021.

| **treatment** | **yield** [kg tree$^{-1}$] | ***t*-test** | **tree volume** [m³] | ***t*-test** | **shoot length** [cm] | **ANOVA** |
|---|---|---|---|---|---|---|
| biofumigation | 56.8 ± 8.3 (n=15) | 0.06 | 1.17± 0.12 (n=15) | 0.07 | 34.5± 9.62 (n =17) | ab |
| control | 41.3± 5.48 (n=15) | | 0.94± 0.03 (n=15) | | 27.3± 10.8 (n=17) | a |
| thermally treated soil | | | | | 44.2± 12.3 (n=10) | b |

Shoot growth of M9 rootstocks in the soil sickness test averaged 27.3 cm in the control treatment and 34.5 cm in the seed mixture treatment. Plants grown in thermally treated soil achieved a mean total shoot growth of 44.2 cm. However, this value did not differ statistically from the seed mixture treatment.

## Discussion

The use of amelioration cover crops is a well-established practice in arable and vegetable cropping systems, where they serve to improve soil properties and mitigate replant diseases (El-Sayed Hussein, 2022). However, this approach has rarely been adopted in intensive apple production. The primary reason is the economic drawback. Establishing a one-year cover

crop typically results in a full year without yield, and the agronomic benefits gained through improved soil conditions often fail to compensate for this temporary yield loss.
In South Tyrol, the effects of soil fatigue have intensified over decades of continuous apple cultivation. Even organically managed orchards increasingly exhibit growth reductions and yield decline attributable to soil fatigue. Previous studies have demonstrated that seed meals derived from specific Brassicaceae species can effectively suppress soil fatigue (Mazzola, 2010). Nevertheless, due to high costs and labor-intensive application, these measures have not become widely adopted in the region.
The results of this study provide evidence that undersowing a biofumigation seed mixture at orchard establishment can mitigate soil fatigue and improve early tree performance under continuous apple cultivation. The observed increase in cumulative yield over five years and tree volume indicates a substantial benefit beyond the initial planting year.

Outcomes of the potted plant soil sickness test pointed in the same direction as the field-based observations. Shoot growth in soils from undersown plots was between the control treatment and the thermally treated soil, suggesting some reduction in growth-limiting factors typically associated with soil fatigue.

Despite these promising results several limitations warrant consideration. The trial was conducted at a single site under specific soil and climatic conditions. Thus, extrapolation to other environments should be approached cautiously. Future research should include multi-site trials, mechanistic studies on soil microbial communities and economic analyses to assess cost-benefit ratios for growers.

Overall, this study demonstrates that undersowing a biofumigation seed mixture after planting is a viable strategy to reduce soil fatigue and enhance orchard establishment without disrupting production schedules. These findings provide a foundation for implementing agroecologically sustainable organic management strategies in perennial fruit systems under continuous cultivation.

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