Redesign of dryland apple orchards by intercropping the bioenergy crop canola (**Brassica napus** L.): Achieving sustainable intensification

**Xiaodong Gao** | **Nana He** | **Ruhao Jia** | **Pan Hu** | **Xining Zhao**

1Institute of Soil and Water Conservation, Northwest A&F University, Yangling, Shaanxi Province, China
2Institute of Soil and Water Conservation, Chinese Academy of Science & Ministry of Water Resources, Yangling, Shaanxi Province, China
3National Engineering Research Center of Water Saving and Irrigation Technology at Yangling, Yangling, Shaanxi Province, China
4College of Water Resources and Architectural Engineering, Northwest A&F University, Yangling, Shannxi Province, China

**Abstract**

China’s Loess Plateau (LOP) contains around 22% of all the world’s apple trees, mainly on smallholdings run by farmers. However, business-as-usual (BAU) intensification has reduced the ecological resilience of orchards. Agroforestry is considered to be an important method of realizing sustainable intensification of agroecosystems. However, the design of practical agroforestry systems in drylands remains poorly researched. We hypothesized that crop density is a key factor in designing dryland apple tree-based agroforestry systems. We carried out an experiment in apple orchards in the semi-arid LOP, where the bioenergy crop canola (**Brassica napus** L.) was intercropped at low, medium, and high densities with row spacings of 25, 50, and 100 cm, respectively, to study its effects on water, carbon, and production. We found that intercropping of canola at different densities clearly decreased soil water content (SWC) in the top 60 cm soil layer at all sampling locations, reduced midday leaf water potential (**Ψ**<sub>m</sub>) and leaf water content (LWC), and caused apple trees to produce more fine roots at greater depths. However, intercropping did not affect SWC in soil layers below 60 cm. The SWC profiles, **Ψ**<sub>m</sub> and LWC, progressively recovered over the mulching period. Introduction of canola also significantly (**p** < 0.05) increased SOC content in the surface layer, an effect less visible in deeper layers, and increased the quality of apple fruit to varying degrees while not affecting apple yield measurably. Overall, higher intercropping density does not lead to severer water deficit but have better carbon sequestration benefit than lower density, and therefore seems more appropriate in our study site. Our findings provide solid evidence that agroforestry helps achieve sustainable intensification of dryland orchards.

**Keywords**

bioenergy crop, C sequestration, intercropping, soil water, sustainability
1 | INTRODUCTION

Smallholder-run orchards in drylands are often managed using clear cultivation, that is, removing grass cover to remove competition for water and nutrient with fruit trees (Gao et al., 2021). This is especially true on the dryland Loess Plateau (LOP) in China where 1.3 million ha of apple orchards, accounting for 22% of the world’s total apple-growing area, are mainly cultivated by smallholder farmers. The dry and infertile soils mean that these farmers try to clear natural grass cover away (Figure S1) to keep enough water and nutrients for fruit trees. However, this does not always work. This business-as-usual (BAU) intensification has caused severe ecological and environmental issues relating to soil desiccation, soil erosion, low soil organic C (SOC) sequestration, and excessive use of chemical fertilizers (Gao et al., 2021). Therefore, an alternative method is needed to meet the requirement of Sustainable Development Goals and China’s carbon neutrality goal by 2060.

Agroforestry, a general concept involving multiple forms of interactions between trees and crops, has been described as practical agroecology because it successfully adapts ecological concepts and principles to the design and management of agroecosystems (Altieri et al., 2015). It has been increasingly recognized as a promising intensification pathway to sustainable agriculture (Kuyah et al., 2019; Pretty, 2018). For dryland orchards, establishment of agroforestry through intercropping has been suggested as a way of realizing sustainable intensification (Gao et al., 2021), based on the benefits of agroforestry for multiple ecosystem services in terms of yield and soil fertility improvement (Gao, Liu, et al., 2018), microclimate enhancement (Blaser et al., 2018; Lin, 2007), water regulation (Harper et al., 2014; Ling et al., 2017; Wu et al., 2016), C sequestration (Cardinael et al., 2017; Shi et al., 2018), erosion control (Kinama et al., 2007; Spencer et al., 2020), and increased income for smallholder farmers (Akinnifesi et al., 2010). Although meta-analysis studies generally show that agroforestry gives improved infiltration and soil water availability when compared to monocultures (Kuyah et al., 2019), tree crop water competition remains a major concern when establishing agroforestry systems in drylands because unsuitable combinations of trees and crops can suffer significant ecosystem service tradeoffs (Muthuri et al., 2005; Ndoli et al., 2017; Rao et al., 1997; Sudmeyer & Hall, 2015). A recent example, described by Abdulai et al. (2018), showed that extreme drought in western Africa caused more severe cocoa mortality in the *Albizia ferruginea*-based agroforestry than growing cocoa in full sun, due to strong competition for soil water. This indicated that the ecosystem services that are delivered in agroforestry are context specific, and can depend on the climate, tree species, and crops, and how the components of agroforestry are managed in the landscape (Kuyah et al., 2019). Therefore, despite the great potential of agroforestry as an alternative method to replace monoculture orchards on drylands, a practical design seems more important when establishing a sustainable agroforestry system.

On the LOP, the bioenergy crop canola (*Brassica napus* L.) is one of the most popular cover crops grown when building agroforestry systems in orchards because it has the potential to provide multiple ecosystem services as stated above (Gao et al., 2021). It has been extensively intercropped in apple orchards with assistance from local governments. Several recent studies have indicated that intercropping canola fodder helped increase the soil water content (SWC) under fruit trees in sloping jujube plantations and showed that it rarely competed for water with jujube trees in droughts on the semiarid LOP (Gao, Liu, et al., 2018). However, a scientific design for such systems is lacking. The efficacy of canola fodder crops has never been measured in dryland apple orchards. How might crop density affect water status and C sequestration? Excessively dense cropping may exacerbate water stress in orchards and hence result in excessive competition with the apple trees, reducing apple yield and quality.

We assumed that crop density is a key factor when designing an apple tree-based agroforestry system using intercropping in drylands. Therefore, this study aimed to discover how intercropping of the bioenergy crop canola at different densities affected water and carbon allocation in terms of belowground and aboveground biomass, soil water availability, tree water status, and SOC sequestration, to develop an optimal intercropping strategy for dryland apple orchards based on agroecological principles. Our hypotheses are as follows. First, intercropping will result in the apple trees creating more fine roots in deeper soils so as to occupy a separate resource niche to the cover crops and hence avoid competition. Second, intercropping can improve soil water availability by increasing infiltration and water retention and reducing soil evaporation, and thus improve tree water status. However, high-density intercropping can result in water deficit due to enhanced inter-row transpiration. Third, intercropping at all densities can increase SOC sequestration due to the input of organic materials, and is expected to be more pronounced in the higher density treatments.

2 | MATERIALS AND METHODS

2.1 | Study site

The study site was located in Yujiagou village (109°20’E, 36°41’N) within the Zhangtian river basin, Yan’an City,
Shaanxi province (Figure S2). This site has a semiarid climate with a mean annual precipitation (MAP) of 535 mm, a mean annual temperature of 9.4°C, and an average frost-free period of 179 days (Gao et al., 2018). The dominant Asian monsoon (Liu & Ding, 1998) means that the peak precipitation in this region occurs between the middle of summer and early autumn (July, August, and September), accounting for approximately 73% of annual precipitation. The catchment is covered by thick loess soils (silt loam; Gao et al., 2016). The basic soil properties of the study site are shown in Table S1.

This research experiment was set up in a rain-fed orchard on local dry farming land, which was a typical loess hilly area. The orchard terrain was flat highland. The tested apple trees (Malus domestica Borkh. cv. Red Fuji) were planted 3.5 m apart within rows with 4 m between rows. The trees were 13 years old at the start of the experiment. Their average height was 2.5 m, and the average crown radius was 2.1 m. The same management measures, such as pruning and branching, fertilization, and tillage, were applied every year. The canola used was Yanyou #2 (Brassica campestris L.) with good drought and frost resistance. The maximum height of this canola was approximately 120–140 cm, and the root system was mainly in the 0–50 cm soil layer.

2.2 | Experimental plot layout

The intercropping experiment used four treatments: high-density (HCI, row spacing was 25 cm), medium-density (MCI, row spacing was 50 cm), and low-density (LCI, row spacing was 100 cm) canola intercropping between rows of apple trees. A clear tillage orchard was used as the control (CK). Each treatment had three replicates, that is, three plots with an area of 112 m² (14 m in length and 8 m in width) for each of them, comprising eight apple trees. The intercropping width was 2 m, and the edge was 1 m away from the row of fruit trees (Figure 1c). The intercropping direction was consistent with that of the apple tree row.

Since 2013, local fruit farmers have been starting to grow canola for oilseed harvesting in orchards, with the intercropping time from late April to mid-October each year. As the water demand for fruit trees peaks from mid-May to early July when there is often severe drought, we changed the traditional intercropping time (Figure 1a) to early August each year, with the canola cut and mulched as green manure the next April during the study period (Figure 1b). Therefore, the time from early August to the next April is termed the intercropping period, and the rest of the time is termed the mulching period. The altered intercropping time was adopted in August 2017, with in situ monitoring carried out from 2018 to 2020.

2.3 | Data collection

2.3.1 | Soil water content

SWC was monitored using a portable Time Domain Reflectometry (TDR) system (TRIME-PICO IPH/T3; IMKO) with a measurement accuracy of ±2% (volumetric content). Three 200 cm long tubes were installed under the apple tree canopy (UTC, 30 cm from tree trunk), at the interface of trees and crops (ITC, 100 cm from tree trunk), and in the middle of the intercropped area (MIA, 200 cm from tree trunk) of each plot to monitor SWC (Figure 1c). Each treatment used three plots, so there were 36 tubes in total, and SWC was measured at depths from 20 cm down to 200 cm in 20 cm increments, twice a week during the frost-free period (April–November) in 2018 and 2019.

2.3.2 | Fine root

At the end of the apple tree growth period (November 2019), a root auger (Φ = 6 cm) was used to sample soils from the UTC, ITC, and MIA locations in each plot for fine root analysis. Fine root samples were collected from each 20 cm layer down to 200 cm. All the samples were gently rinsed in a 0.4 mm sieve, and the roots left in the sieve were removed with tweezers. As the roots were different colors (those of canola were white and those of apple tree were brown), they were easy to sort using software. The roots were scanned with a 600 dpi scanner (CanoScan LiDE 110) to obtain TIFF format images. The WinRHIZO root system image analysis software (Regent Instruments, Canada) was used to obtain the fine root length (Φ < 2 mm). The ratio of the fine root length from each soil layer to the soil volume of the corresponding soil layer was used as the fine root length density (FRLD) in the soil layer.

2.3.3 | Apple yield and quality, and biomass of intercropping canola

The yield of each apple tree was determined by randomly selecting three trees in each plot, then harvesting and weighing all the fruit from these trees to derive the average yield. In each plot, 10 apples were randomly selected from the harvested trees to be used for quality testing, in terms of soluble solid, sugar-acid ratio, and vitamin C content.

From each plot, five canola individuals were taken from the intersection of the two diagonals of the experimental plot, that is, the center of the experimental plot, and the intersection to the midpoint of the four corners.
at the different growth stages of canola. The stem thicknesses and the heights of the plants were measured using a vernier caliper and tape measure, respectively. The weight of the material from the five canola plants (converted to a per square meter figure) was determined on the day before overwintering and mowing.
Quantification of soil water availability

We used a relative SWC index, the soil moisture relative difference (SMRD), to analyze the effects of intercropping on soil water availability. According to Gao, Liu, et al. (2018), it can be assumed that there is no significant difference in SWC under apple trees (θ) between different treatments prior to intercropping, and that any significant reduction (or increase) in θ for an intercropping treatment indicates the occurrence of competition (facilitation) for water by canola, with the magnitude of change in θ corresponding to the strength of the interaction. The SMRD was defined as follows:

$$\text{SMRD}_{ij} = \frac{\theta_{ij} - \theta_{0j}}{\theta_{0j}},$$

(1)

where $\theta_{ij}$ and $\theta_{0j}$ represent the soil water content on the $j$th sampling date for the $i$th intercropping treatment and in the
control, respectively. When SMRD is negative and significantly $(p < 0.05)$ different from zero, it means that canola competes with apple trees for water; more negative values indicate a greater degree of competition. Conversely, a positive SMRD value indicates that soil water uptake by apple trees was facilitated by canola.

### 2.5 Statistical analysis

A linear mixed model (LMM) was used to analyze the SWC. The data were first verified in SPSS 18.0 for normal distribution, and they overall followed normal or log-normal distribution. The different treatments and sampling periods were used as fixed effects, and each treatment was randomly sampled three times as a random effect, to evaluate the change of SWC in the different sampling periods. The calculation used the \textit{nlme} function in the \textit{nlme} package of the R language (v.3.5.3; R Core Team, 2020). The data were analyzed with a one-way ANOVA. The effects of intercropping density on soil hydraulic properties, SWC, tree water status, and aboveground and belowground biomass were tested using Duncan’s multiple range test with $p < 0.05$ as implemented in spss 18.0 version (SPSS Inc.). The graphs were drawn using OriginPro 2018.

### 3 RESULTS

#### 3.1 Meteorology and soil properties

The annual precipitation in 2018 and 2019 was 492 and 608 mm, respectively (Figure S3). Compared to MAP, 2019 was drier and 2020 was wetter. The precipitation in July, August, and September accounted for 60.2%, on average, of the annual total for both years. Both the daily maximum and minimum temperatures peaked in June and July, and were lowest in December and January (Figure S3).

Saturated hydraulic conductivity (Ks) is shown in Table 1. Canola intercropping significantly $(p < 0.05)$ improved Ks of all layers, with the effect increasing with canola density. Intercropping also greatly affected the macropore area, the macropore perimeter, the roundness, and the macroporosity (Figure 2). All intercropping treatments, particularly the medium and high density ones, significantly $(p < 0.05)$ increased these macropore parameters in the top 20 cm soil layer.

#### 3.2 Aboveground and belowground biomass

The growth data for canola at different densities in terms of plant height (PH), taproot length (TL), taproot thickness (TT), ground fresh weight (GFW), and taproot fresh weight (TFW) are shown in Table 2. At an individual plant scale, PH and TL showed no clear differences between various treatments in different sampling periods, except in November 2019 when HCl had a much lower PH than the other two densities. However, the differences between TT, GFW and TFW for the various densities seem much more apparent. For TT, the higher density treatments had significantly $(p < 0.05)$ higher values than the LCI. For GFW and TFW, the values of the three variables decreased with canola densities. At the quadrat scale, GFW and TFW showed significant $(p < 0.05)$ differences between different densities, irrespective of sampling periods. In contrast to the individual plant scale, both of these parameters increased with the increase in canola density, except for the TFW in November 2018.

The distribution of FRLD in canola and apple trees is shown in Figure 3. On the surface, the FRLD generally increased with the increase in canola densities; however, no clear difference was observed between different densities at subsurface layers. The presence of canola clearly shifted the fine root distribution of apple trees into the deeper soil layers. At the UTC location, the FRLD of apple trees in the intercropping treatments was clearly higher than that for monoculture trees, except in the 40–60 cm soil layer. This phenomenon seemed more apparent for the higher density treatments. At the ITC and MIA locations, similar phenomena existed but mainly below the 100 cm soil layer. The results here confirmed our first hypothesis.

#### 3.3 Soil water, SOC, and nutrient effects

The LMM showed that SWC was significantly impacted by canola density, sampling date, soil layer, sampling position, and their combinations (Table 3). The variations in SMRD at different positions and depths are shown in Figure 4. Over the intercropping period, negative SMRD existed in the whole surface layer at different positions. This was especially true for the MIA location, where negative values were greatest; less negative values were observed in the ITC location, and the least negative values existed in the UTC location. Nonetheless, SMRD became less negative at deeper depths. Generally, negative values were not observed in the 60–100 cm soil layer at locations UTC and ITC, and it also disappeared below 100 cm at the MIA location. During the mulching period, the SMRD progressively became more positive, which was especially true in the UTC location. This transition showed visible lags in subsurface layers at all positions, with the peak of positive values occurring in the next intercropping period in the 100–200 cm soil layer. Furthermore, in the ITC and MIA locations, the SMRD values were more positive in subsurface layers, particularly below 60 cm, than in the
surface layer. In addition, the variations and degrees of SMRD for different densities were similar. Therefore, the findings here did not support our second hypothesis during intercropping period.

The vertical distribution of SOC content and storage in 2018 and 2019 are shown in Figure 5. As expected, no visible difference was observed in these 2 years. After 7 years of growing canola, the SOC content and storage in the intercropping treatment were significantly higher than in the monoculture orchards. Significantly higher values were also observed in the 20–40 and 40–60 cm soil layers. In this way, the results here confirmed the third hypothesis.

### 3.4 | Tree water status

The variation of midday leaf water potential ($\Psi_m$) is shown in Figure 6. Overall, the $\Psi_m$ was lower in dry seasons (May...
30 and July 5, 2019) and higher in wet seasons (other sampling dates). Nonetheless, the variations at different sampling dates were relatively small, ranging from −1.71 to −2.40 Mpa, showing clear isohydric characteristics. Moreover, in the intercropping period, the apple trees in the agroforestry systems had lower $\Psi_m$ than monoculture trees but the difference between various treatments was not significant. However, in the mulching period, the apple trees showed significantly ($p < 0.05$) higher $\Psi_m$ than the monoculture trees.

The variation in leaf water content (LWC) over the study period is shown in Figure 7. Generally, LWC behaved similarly to $\Psi_m$. In the intercropping period, monoculture apple trees had higher LWC than those in agroforestry whereas, in the mulching period, the opposite relationship was observed. The differences among different treatments were significant ($p < 0.05$) on 11 August 2019 and 5 July 2020. In addition, the variation in fruit water content in apples was very small. The findings here partly supported the second hypothesis.
FIGURE 5 Distribution of soil organic carbon (SOC) and soil carbon storage for different treatments (low-density intercropping [LCI], medium-density intercropping [MCI], high-density intercropping [HCI], and Control [CK]). (a) and (b) show the soil organic carbon (SOC) in 2018 and 2019, (c) shows the soil organic carbon (SOC) storage in 2019. * indicates significant difference ($p < 0.05$) between treatments and ns indicates no significant difference; ** indicates significant difference ($p < 0.01$) between treatments.

FIGURE 6 The difference in midday leaf water potential of apple trees for different intercropping densities (low-density intercropping [LCI], medium-density intercropping [MCI], high-density intercropping [HCI], and Control [CK]) with lowercase letters indicating significant difference ($p < 0.05$). ** indicates significant difference ($p < 0.01$) between treatments.
3.5 | Apple yields and quality

Overall, canola intercropping did not noticeably affect apple yield in both years, whereas the quality of apple fruit was improved to varying degrees (Figure 8). Specifically, compared with the monoculture trees, intercropping significantly ($p < 0.05$) improved the soluble solids in apples in both years, and significantly ($p < 0.05$) increased the sugar–acid ratio in 2019. However, there was no clear increase in Vitamin C content. In addition, the three intercropping densities showed no significant differences between them for either yield or quality of apples.

4 | DISCUSSION

4.1 | Water regulation: From competition to facilitation

Intercropping canola in dryland apple orchards clearly affected SWC (Figure 4), $\Psi_m$ (Figure 6), and LWC (Figure 7). Overall, this effect on water availability can be divided into two contributing factors: the water demand of the canola itself in the situation of monoculture, and the interaction between apple trees and canola, particularly between their belowground roots. This latter factor is much more complex than the former. In general, plants can identify neighbors through a series of signaling methods, such as light, VOCs (volatile organic compounds), and root exudates among others, and then determine the best strategy—competition or facilitation—to use (Bilas et al., 2021; Chen et al., 2015; Wang et al., 2021). Recent studies demonstrated that plants can distinguish between kin and non-kin (Crepy & Casal, 2016) or determine neighbor species identity (Madsen et al., 2020). Such kin or species recognition helps plants to reshape their shoot and root architecture to reduce competition (Palmer et al., 2016; Proust et al., 2011; Takigahira & Yamawo, 2019). However, there is a great deal of evidence showing that facilitation is strong between heterospecific neighboring plants (Gao, Liu, et al., 2018; Li et al., 2014; Schob et al., 2018). A famous example is that of the trees and grasses on savannas, which coexist through the use of different resource niches (Huntley, 1982).

In this study, we found that the roots of apple trees and canola clearly overlapped within the top 60 cm soil layer at the MIA and ITC locations (Figure 3). Therefore, the trees and canola may recognize the identity of each other through root exudate and, through this, non-kin recognition might cause them to compete for soil resources, resulting in rapid soil water consumption in the 0–60 cm soil layer (Figure 4). As the canola had a higher FRLD than apple trees in the shallow layers (Figure 3), it could exhibit greater competitiveness over those trees. The strong

**FIGURE 7** Differences in water content of leaves and fruits for different intercropping densities (low-density intercropping [LCI], medium-density intercropping [MCI], high-density intercropping [HCI], and Control) with lowercase letters indicating significant difference ($p < 0.05$). ** indicates significant difference ($p < 0.01$) between treatments; *** indicates significant difference ($p < 0.001$) between treatments
competition in the shallow soils forced apple trees to grow more fine roots in the deeper soil below 60 cm, which is more evident in the higher-density canola plots (Figure 3). In this way, the trees can exploit different resource niches to the canola to reduce their competition for water and other resources. From the previous analysis, it can be seen that the relationship between apple trees and canola shifted from competition at the early stage to subsequent facilitation, which can be a result of compromise to avoid strong competition. Moreover, we found that at the UTC location, where there was no root overlap, the SWC in the top 40 cm of soil also clearly reduced relative to the monoculture (Figure 4). This is possibly because the decrease in soil water availability between the apple trees due to competition forced them to modify their water use strategy. A practical modification might be to increase soil water use under the tree canopy to meet water demand. In addition, we also found that the density of canola had a weak effect on SWC (Figure 4), $\Psi_m$ (Figure 6), and leaf and fruit water content (Figure 7). A possible explanation is that the aboveground and belowground biomass was restricted in middle- and high-density plots (Table 2), resulting in a decrease in soil water use by individual plants.

In the mowing and mulching periods, soil water use by canola dramatically declined. The mown canola was mulched between tree rows to reduce soil temperature and evaporation. Moreover, an increase in macropores (Figure 2) would greatly increase infiltration to deeper soils, benefiting soil water recovery in the soil.

4.2 | Mechanism of carbon sequestration benefits

The accumulation of SOC in the orchard increased significantly after several years of intercropping canola (Figure 5), as a result of diverse biotic and abiotic factors. The accumulation of aboveground and belowground biomass and rhizosphere sediments of canola may have provided sufficient substrate for microbes, which improved the diversity, activity, and degree of intricacy of community structure of soil microbes (Pei et al., 2021; Zheng et al., 2016). Consequently, the more active microbial communities acted as “processors,” transporting plant-derived residues to the soil by secreting extracellular enzymes to decompose or transform macromolecular plant-source carbon, thereby increasing SOC content (Liang & Zhu, 2021). At the same time, microorganisms acted as “regulators” of the rate of soil carbon fixing and the dynamic changes in the SOC pool (Liang et al., 2017), because they converted plant-derived organic carbon into their own biomass through assimilation, and then transported microbial-derived organic carbon to the soil through individual proliferation, growth, and death.

In addition, the secretions and humus of canola root bound fine soil particles together to form a larger aggregate structure (Sheehy et al., 2015). Therefore, the increase in soil carbon sequestration capacity may be due to the fact that these aggregates encased SOC, protecting it from decomposition and utilization of microorganisms through its physical isolation (Lehmann & Kleber, 2015).
4.3 | Implications

Traditional apple orchards on LOP are managed using clear cultivation and depend greatly on chemical fertilizers (Gao et al., 2021). This BAU intensification hinders sustainable development of dryland orchards. A redesign of dryland orchards by incorporating ecological principles is expected to provide better ecosystem services and help realize sustainable intensification (Figure 9). Agroforestry is deemed to be one of the main methods of realizing sustainable intensification (Smith et al., 2012). This is because agroforestry techniques can increase biodiversity (Torralba et al., 2016; Warren-Thomas et al., 2019), diversify income sources for farmers (Ehrenbergerova et al., 2019), reduce the input of chemical fertilizers (Musokwa et al., 2019), and strengthen resource recycling and soil health (Bhargavi & Behera, 2020). Therefore, scientists have suggested the use of intercropping in dryland orchards on the LOP to achieve sustainable intensification (Gao et al., 2021).

Our study showed that soil water competition between apple trees and cover crops mainly occurred in shallow soils, with that competition shifting to facilitation after the trees grew more fine roots in the deeper soil. During the mulching period, SWC, Ψm, and LWC of the apple trees were largely improved. Therefore, overall, canola intercropping had no clear negative effect on water availability and production of apple orchards. Furthermore, the 7-year intercropping period greatly increased SOC sequestration (Figure 5). In this way, this study has provided new and solid evidence for the feasibility of agroforestry in dryland orchards. Furthermore, we also found that although the density of canola had a weak effect on SWC and SOC, higher-density plots showed clearly greater belowground and aboveground biomass at the quadrat scale (Table 2), suggesting that higher intercropping density has better carbon sequestration benefit than lower density. Nonetheless, it is worth noting that only three density gradients were included in this experiment; and if the intensity is increased or decreased further, or if the intercropping duration is longer, there may be different results. Moreover, considering the uneven precipitation in the growing season and the narrow spacing between the apple trees, a critical research area needing in-depth studies is when and where to intercrop and mow (Figure 9).

5 | CONCLUSIONS

Here, we redesigned dryland apple orchards by intercropping the bioenergy crop canola at different densities, aiming to improve soil water availability and SOC sequestration. We found that the introduction of canola clearly decreased soil water availability in the top 60 cm soil layer at all sampling locations during the intercropping period, which reduced Ψm and LWC and made apple trees grow more fine roots in deeper soils to exploit different resource niches to the cover crops, to avoid undue competition. However, the canola did not affect SWC in deeper soil layers below 60 cm. The soil water profiles, Ψm and

![Diagram](image-url)
LWC progressively recovered over the mulching period with clear lags in deeper layers. Moreover, introduction of canola clearly increased SOC content in the shallow layer and improved the quality of fruit apple to varying degrees. Although this benefit did not increase linearly with intercropping densities, higher density showed better carbon sequestration benefit than lower density through increasing belowground and aboveground biomass at quadrat scale. In this way, the high-density intercropping of canola seems more appropriate in our study site. Our study has provided solid evidence that agroforestry helps realize sustainable intensification in dryland apple orchards.

ACKNOWLEDGMENTS
This work was jointly supported by the National Key Research and Development Program of China (2021YFD1900700), National Natural Science Foundation of China (42125705, 41771316), Natural Science Basic Research Program of Shaanxi (2021JC-19), CAS “Youth Scholar of West China” Program (XAB2018A04), the Cyrus Tang Foundation, and the ‘111’ Project (B12007).

CONFLICT OF INTEREST
The authors state that they have no conflict of interest.

AUTHOR’S CONTRIBUTION
Xiaodong Gao and Xining Zhao conceptualized the study. Xiaodong Gao, Xining Zhao, and Ruhao Jia designed the experiment. Ruhao Jia and Pan Hu conducted the experiments. Xiaodong Gao, Ruhao Jia, and Nana He performed the data analysis. Xiaodong Gao, Xining Zhao, Nana He, and Ruhao Jia wrote the paper.

DATA AVAILABILITY STATEMENT
Data are available on request from the corresponding author.

ORCID
Xiaodong Gao https://orcid.org/0000-0002-4954-8830
Xining Zhao https://orcid.org/0000-0002-2546-7112

REFERENCES
Abdulai, I., Vaast, P., Hoffmann, M. P., Asare, R., Jassogne, L., Van Asten, P., Rotter, R. P., & Graefe, S. (2018). Cocoa agroforestry is less resilient to sub-optimal and extreme climate than cocoa in full sun. Global Change Biology, 24(1), 273–286. https://doi.org/10.1111/gcb.13885
Akillinisfi, F. K., Ajayi, O. C., Sileshi, G., Chirwa, P. W., & Chianu, J. (2010). Fertiliser trees for sustainable food security in the maize-based production systems of East and Southern Africa. A review. Agronomy for Sustainable Development, 30(3), 615–629. https://doi.org/10.1051/agro/2009058
Altieri, M. A., Nicholls, C. I., Henao, A., & Lana, M. A. (2015). Agroecology and the design of climate change-resilient farming systems. Agronomy for Sustainable Development, 35(3), 869–890. https://doi.org/10.1007/s13593-015-0285-2
Bhargavi, B., & Behera, U. (2020). Securing the livelihood of small and marginal farmers by diversifying farming systems. Current Science, 119(5), 854–860. https://doi.org/10.18520/cs/v119/5/854-860
Bilas, R. D., Bretman, A., & Bennett, T. (2021). Friends, neighbours and enemies: An overview of the communal and social biology of plants. Plant, Cell & Environment, 44(4), 997–1013. https://doi.org/10.1111/pce.13965
Blaser, W. J., Oppong, J., Hart, S. P., Landolt, J., Yeboah, E., & Six, J. (2018). Climate-smart sustainable agriculture in low-to-intermediate shade agroforests. Nature Sustainability, 1(5), 234–239. https://doi.org/10.1038/s41893-018-0062-8
Cardinael, R., Cardinael, R., Chevallier, T., Cambou, A., Beral, C., Barthes, B. G., Dupraz, C., Durand, C., Kouakoua, E., & Chenu, C. (2017). Increased soil organic carbon stocks under agroforestry: A survey of six different sites in France. Agriculture, Ecosystems & Environment, 236, 243–255. https://doi.org/10.1016/j.agee.2016.12.011
Chen, B. J. W., Chen, B. J. W., During, H. J., Vermeulen, P. J., de Kroon, H., Poorter, H., & Anten, N. P. R. (2015). Corrections for rooting volume and plant size reveal negative effects of neighbour presence on root allocation in pea. Functional Ecology, 29(11), 1383–1391. https://doi.org/10.1111/1365-2435.12450
Crepy, M. A., & Casal, J. J. (2016). Kin recognition by self-referent phenotype matching in plants. New Phytologist, 209(1), 15–16. https://doi.org/10.1111/nph.13638
Ehrenbergerova, L., Septunova, Z., Habra, H., Puerta Tuesta, R. H., & Matula, R. (2019). Shade tree timber as a source of income diversification in agroforestry coffee plantations, Perú. Bois & Forêts Des Troptiques, 342, 93–103. https://doi.org/10.19182/bft2019.342.a31812
Gao, X. D., Li, H. C., Zhao, X. N., Wu, P. T., & Ma, W. (2018). Identifying a suitable revegetation technique for soil restoration on water-limited and degraded land: Considering both deep soil moisture deficit and soil organic carbon sequestration. Geoderma, 319, 61–69. https://doi.org/10.1016/j.geoderma.2018.01.003
Gao, X. D., Liu, Z. P., Zhao, X. N., Ling, Q., Hoo, G. P., & Wu, P. T. (2018). Extreme natural drought enhances interspecific facilitation in semiarid agroforestry systems. Agriculture, Ecosystems & Environment, 265, 444–453. https://doi.org/10.1016/j.agee.2018.07.001
Gao, X. D., Zhao, X. N., Wu, P. T., Brocca, L., & Zhang, B. Q. (2016). Effects of large gullies on catchment-scale soil moisture spatial behaviors: A case study on the Loess Plateau of China. Geoderma, 261, 1–10. https://doi.org/10.1016/j.geoderma.2015.07.001
Gao, X. D., Zhao, X. N., Wu, P. T., Yang, M., Ye, M. T., Tian, L., Zou, Y. F., Wu, Y., Zhang, F. S., & Siddique, K. H. M. (2021). The economic–environmental trade-off of growing apple trees in the drylands of China: A conceptual framework for sustainable intensification. Journal of Cleaner Production, 296, 126497. https://doi.org/10.1016/j.jclepro.2021.126497
Harper, R. J., Sochacki, S. J., Smettem, K. R. J., & Robinson, N. (2014). Managing water in agricultural landscapes with short-rotation biomass plantations. Global Change Biology Bioenergy, 6, 544–555. https://doi.org/10.1111/gcbb.12090
Huntley, B. J. (1982). Ecology of tropical savannas. B. H. Walker (Eds.). Springer Verlag, 669 pp.
Tongkaemkaew, U., Edwards, D. P., & Dolman, P. M. (2019). Rubber agroforestry in Thailand provides some biodiversity benefits without reducing yields. *Journal of Applied Ecology, 57*(1), 17–30. https://doi.org/10.1111/1365-2664.13530

Wu, J., Liu, W., & Chen, C. (2016). Can intercropping with the world’s three major beverage plants help improve the water use of rubber trees? *Journal of Applied Ecology, 53*(6), 1787–1799. https://doi.org/10.1111/1365-2664.12730

Zheng, J. F., Chen, J. H., Pan, G. X., Liu, X. Y., Zhang, X. H., Li, L. Q., Bian, R. J., Cheng, K., & Zheng, J. W. (2016). Biochar decreased microbial metabolic quotient and shifted community composition four years after a single incorporation in a slightly acid rice paddy from southwest China. *Science of the Total Environment, 571*, 206–217. https://doi.org/10.1016/j.scitotenv.2016.07.135

**SUPPORTING INFORMATION**

Additional supporting information may be found in the online version of the article at the publisher’s website.

**How to cite this article:** Gao, X., He, N., Jia, R., Hu, P., & Zhao, X. (2022). Redesign of dryland apple orchards by intercropping the bioenergy crop canola (*Brassica napus* L.): Achieving sustainable intensification. *GCB Bioenergy, 14*, 378–392. [https://doi.org/10.1111/gcbb.12916](https://doi.org/10.1111/gcbb.12916)