

Carbon Sequestration in Pistachio Systems: Evidence from Cultivated *Pistacia Vera* L. Orchards and Natural *Pistacia* Woodlands

O.J. Nazarova, PhD

Research Institute of Forestry under the Central Asian University of Environmental and Climate Change Studies (Green University), Uzbekistan



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Highlights

- Direct pistachio evidence supports measurable woody-biomass and soil-carbon pools, but not a universal annual sequestration rate.
- Carbon stock, sequestration rate and product GHG footprint are distinct metrics and should be reported separately.
- Natural *Pistacia* woodlands and cultivated *P. vera* orchards cannot be ranked reliably without harmonized sampling and clear species identification.
- Repeated biomass and SOC measurements, combined with management inventories and remote sensing, are the priority for dryland carbon accounting.
- Tree health is relevant to carbon permanence; regional pathology evidence from Uzbekistan should inform long-term monitoring rather than be treated as a carbon estimate.

Abstract

Pistachio production is concentrated in dry and semi-dry regions where long-lived woody vegetation can contribute to climate-change mitigation while supporting farm income and landscape stability. Yet the carbon-sequestration literature for pistachio is much thinner than the language often used to describe the crop as a carbon sink. This critical review separates three related but distinct evidence streams: direct measurements of biomass or soil carbon in pistachio systems, life-cycle and greenhouse-gas assessments of pistachio production, and indirect evidence from other perennial tree crops. The available studies show that pistachio orchards and natural *Pistacia* woodlands contain meaningful carbon pools in woody biomass and soil, but they do not support a universal sequestration rate for the species. Carbon outcomes depend on stand age and structure, soil depth and texture, water availability, ground-cover management, residue handling, irrigation energy, fertilizer use and the persistence of healthy trees. The evidence also highlights a methodological problem: carbon stock, annual sequestration and product carbon footprint are frequently treated as interchangeable, although they answer different questions. Direct pistachio studies on soil organic carbon, canopy-based biomass estimation and seasonal carbon allocation are therefore interpreted separately from life-cycle studies that quantify management emissions. Evidence from olive, hazelnut and mixed orchard systems is used only to inform methodology and plausible management responses, not as a substitute for pistachio-specific data. For Central Asian drylands, the highest research priority is repeated, paired measurement of tree biomass and soil organic carbon in cultivated orchards and well-characterized natural stands, combined with management inventories, remote sensing and explicit uncertainty analysis. A standardized framework of this kind would allow pistachio to be evaluated credibly as part of regional carbon-farming and land-restoration strategies.

Keywords: *Pistacia vera*; pistachio orchard; carbon sequestration; soil organic carbon; woody biomass; dryland forestry; life-cycle assessment; carbon farming; Central Asia.

1. INTRODUCTION

Pistachio is often presented as an environmentally attractive crop because it is perennial, drought-adapted and capable of remaining productive in climates that are difficult for many other fruit trees. Those characteristics make the crop relevant to discussions of climate-smart agriculture and dryland restoration. They do not, however, establish that every pistachio orchard is a net carbon sink. A credible assessment requires evidence about the amount of carbon stored in living biomass and soil, how those stocks change through time, and how management-related greenhouse-gas (GHG) emissions alter the net climate balance.

Carbon sequestration is the net transfer of atmospheric carbon into relatively persistent ecosystem pools. In woody agricultural systems, the main pools are above- and belowground biomass and soil organic carbon (SOC). The distinction between a carbon stock and a sequestration rate is fundamental: a stock is the amount of carbon present at a given time, whereas sequestration is a change in that stock over a defined interval. Life-cycle assessment (LCA) addresses a different question by accounting for emissions associated with inputs, field operations, processing or other stages of production. These metrics can be combined in a broader climate assessment, but they should not be substituted for one another (IPCC, 2014; Lal, 2004; Waqas et al., 2025).

The original pistachio literature contains several useful but non-equivalent lines of evidence. Bagheri et al. (2021) examined canopy-based estimation of aboveground biomass and carbon in wild pistachio trees; Budak et al. (2025) assessed SOC stocks in semi-arid pistachio orchards in Siirt Province, Türkiye; and Marino et al. (2022) described seasonal branch carbon dynamics in bearing pistachio. In parallel, Bartzas and Komnitsas (2017), Bartzas et al. (2017), Gökdoğan et al. (2022) and Babaeian et al. (2025) evaluated environmental burdens or GHG emissions associated with pistachio production. Together these studies justify serious interest in the carbon role of pistachio systems, but they do not support a single universal figure for carbon sequestration per hectare per year.

This review therefore asks a narrower and more useful question: what can the current evidence actually support about carbon storage and climate performance in cultivated pistachio orchards and natural *Pistacia* woodlands, and what measurements are still required before robust comparisons can be made?

2. REVIEW APPROACH AND EVIDENTIAL BOUNDARIES

This article is a critical narrative review rather than a systematic meta-analysis. Evidence was organized into three levels. The first level comprises studies that directly measure a carbon pool, carbon allocation or closely related variable in pistachio systems. The second includes pistachio-specific LCA, energy-use or sustainability studies that inform the emissions side of the climate balance but do not directly quantify ecosystem carbon accumulation. The third consists of studies in other perennial woody systems that are useful for methods or management hypotheses but cannot be treated as pistachio-specific evidence.

This separation is important because several common claims become overstated when evidence is transferred across levels. For example, a lower product carbon footprint does not necessarily mean that an orchard stores more carbon in soil. Likewise, a high one-time biomass stock does not establish a high annual sequestration rate. Estimates from olive, hazelnut, walnut or mixed orchards can help identify appropriate sampling designs and management variables, but species, root architecture, pruning regimes, planting density and irrigation history differ enough that their numerical values should not be imported directly into pistachio.

The review also distinguishes cultivated *P. vera* orchards from natural *Pistacia* woodlands. The term 'wild pistachio' is used in the literature for more than one *Pistacia* species. Species identity, stand origin and management history should therefore be reported explicitly before natural-stand estimates are compared with commercial *P. vera* orchards.

Table 1. Evidence hierarchy used in this review

Evidence level	Representative source(s)	System / metric	Interpretation
Direct pistachio / <i>Pistacia</i> carbon evidence	Bagheri et al. (2021)	Wild pistachio trees; canopy-based aboveground biomass/carbon	Supports remote-sensing-assisted AGB/carbon estimation; not SOC or annual sequestration.
Direct pistachio carbon evidence	Budak et al. (2025)	Pistachio orchards; soil organic carbon stock	Supports SOC stock assessment in semi-arid orchards; not an annual sequestration rate unless repeated through time.

Direct pistachio physiological carbon evidence	Marino et al. (2022)	P. vera branch carbon dynamics	Supports seasonal allocation and crop-load effects; not whole-ecosystem carbon stock.
Pistachio GHG / LCA evidence	Bartzas & Komnitsas (2017); Bartzas et al. (2017); Gökdoğan et al. (2022); Babaeian et al. (2025)	Production systems and environmental burden	Supports identification of emission hotspots and management trade-offs; does not directly measure ecosystem sequestration.
Supporting perennial-orchard evidence	Proietti et al. (2016); Pacchiarelli et al. (2022); Ioannidou et al. (2025); Ruiz-Carrasco et al. (2026)	Olive, hazelnut, mixed and other woody systems	Useful for methods and management hypotheses; numerical values should not be transferred directly to pistachio.
Regional tree-health evidence	Nazarova et al. (2023)	Pistachio disease in Uzbekistan	Supports the relevance of tree-health monitoring to carbon permanence; not a carbon-sequestration estimate.

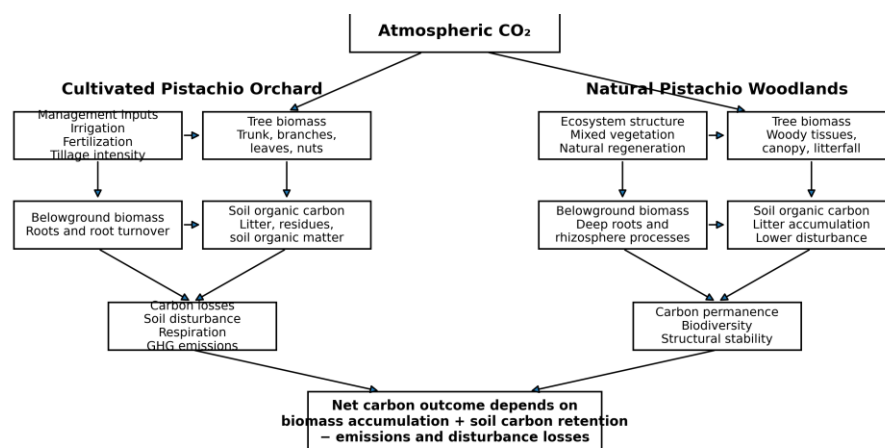
3. CARBON POOLS AND THE MEANING OF A 'CARBON SINK'

Long-lived tree crops store carbon in multiple compartments. Aboveground woody biomass is the most visible pool, but roots and soil often represent a large share of total ecosystem carbon. Annual leaves, fine roots and pruning residues move carbon rapidly between living biomass, litter and soil, while harvest removes carbon from the orchard. Whether exported carbon remains stored for days, months or years depends on its subsequent use and is normally outside the standing orchard stock unless a broader product-system boundary is defined.

SOC is particularly important in dryland systems because it can persist beyond individual crop cycles, yet it is also difficult to measure correctly. Carbon concentration alone is insufficient; stock calculations require soil depth, bulk density and, where relevant, correction for coarse fragments. Comparisons through time are more defensible when the same sampling depths and an equivalent-soil-mass approach are used, especially where irrigation, tillage or organic amendments change bulk density. Budak et al. (2025) provide pistachio-specific evidence that SOC can be quantified meaningfully in semi-arid orchards, but such measurements should not be converted into annual sequestration rates unless repeated observations or defensible chronosequences are available.

Aboveground carbon presents a parallel challenge. Allometric equations can estimate tree biomass from trunk, canopy or other structural measurements, but orchard trees are pruned and often multi-branched, while natural *Pistacia* stands may differ in architecture and species composition. Bagheri et al. (2021) demonstrate the value of canopy information and high-resolution imagery for estimating aboveground biomass and carbon in wild pistachio trees. The broader lesson is methodological: remote sensing is most useful when calibrated against field measurements and should not be expected to estimate SOC directly.

Figure 1 summarizes the accounting boundary. It also clarifies why a system can have a substantial carbon stock while still carrying a significant GHG burden from pumping irrigation water, manufacturing fertilizers, field operations or nitrous-oxide emissions. The term 'carbon sink' is most defensible when a positive change in ecosystem carbon stocks is demonstrated over time and interpreted alongside relevant emissions.



Conceptual figure: cultivated systems may store substantial carbon, but soil management and greenhouse-gas emissions affect net outcomes; natural pistachio woodlands often favor carbon permanence through lower disturbance and stronger ecological complexity.

Figure 1. Carbon sequestration pathways in cultivated pistachio orchards and natural pistachio woodlands. The conceptual framework distinguishes carbon stored in above- and belowground biomass and soil from management-related greenhouse-gas losses and emphasizes that net outcomes depend on both stock change and emissions.

4. CULTIVATED PISTACIA VERA ORCHARDS: WHAT THE EVIDENCE SUPPORTS

Commercial pistachio orchards accumulate woody biomass as trees establish and mature, but the magnitude and duration of that accumulation vary with planting density, cultivar-rootstock combination, pruning, crop load and water supply. Marino et al. (2022) showed that carbon allocation within pistachio branches changes seasonally and responds to crop load. This does not provide a hectare-scale sequestration rate, but it is important because it demonstrates that carbon movement within the tree is dynamic rather than a simple function of tree age.

Soil is potentially the more persistent pool. Budak et al. (2025) assessed SOC stocks in pistachio orchards established under semi-arid conditions in Türkiye. Their work is directly relevant to orchard carbon accounting, but it should be cited for measured SOC stock rather than for an annual sequestration rate or a comparison with natural stands unless those outcomes were explicitly measured. This distinction removes a major source of overstatement in the pistachio-carbon literature.

Management can increase or decrease carbon retention. Maintaining ground cover, returning suitable organic residues and minimizing unnecessary soil disturbance are plausible routes to higher SOC, consistent with broader soil-carbon literature (Lal, 2004; Paustian et al., 2016). In pistachio, however, the net benefit also depends on water competition, salinity, orchard traffic, residue handling and local disease management. Evidence from other perennial orchards supports testing these practices, but it does not justify assuming a fixed percentage increase in pistachio SOC.

The orchard GHG balance must be considered separately. Gökdoğan et al. (2022) quantified energy use efficiency and GHG emissions in pistachio production in Adıyaman, Türkiye. Bartzas and Komnitsas (2017) and Bartzas et al. (2017) used life-cycle approaches to characterize environmental impacts of pistachio production, while Babaeian et al. (2025) compared conventional and more bio-friendly production systems. These studies are useful for identifying emission hotspots such as energy and input use. They do not, by themselves, measure the increase in orchard biomass or SOC. A full climate assessment should therefore report stock change and management emissions as separate components before calculating any net balance.

5. NATURAL PISTACIA WOODLANDS AND THE PROBLEM OF COMPARABILITY

Natural pistachio woodlands are ecologically different from commercial orchards. They are usually irregular in age and spacing, receive little or no irrigation or fertilizer, contain a more heterogeneous understory, and may include several *Pistacia* species or associated shrubs and trees. These attributes can favor long-term carbon retention and biodiversity, but they also make simple per-hectare comparisons difficult.

Bagheri et al. (2021) provide an important example of biomass and carbon estimation in wild pistachio trees using high-resolution imagery. Their study supports the use of canopy-based remote sensing for spatial assessment of aboveground carbon in open dryland woodland. It should not be generalized automatically to *P. vera* orchards, to SOC, or to annual carbon sequestration. Natural-stand carbon estimates also need explicit information on species identity, crown form, stem structure, stand density and the area definition used to extrapolate from trees to hectares.

The intuitive expectation that natural stands always store more carbon than orchards is not a universal rule. Mature

natural woodlands may contain older trees, greater structural diversity and less soil disturbance, while irrigated orchards can achieve high productivity and woody biomass. Conversely, orchard pruning, harvest exports and management emissions may reduce the net climate benefit. The correct comparison is therefore empirical: matched sites should be evaluated using the same carbon pools, soil depths, spatial units and uncertainty procedures.

6. WHAT CAN BE COMPARED NOW - AND WHAT CANNOT

At present, the pistachio literature is strong enough to support three conclusions. First, both cultivated orchards and natural Pistacia systems contain measurable carbon in woody biomass and soil. Second, management influences the climate balance through both carbon storage and GHG emissions. Third, available studies use different boundaries and metrics, so direct ranking of natural versus cultivated systems is premature without harmonized measurements. Several numerical claims commonly repeated in informal summaries should therefore be avoided. A one-time SOC stock should not be reported as tonnes of CO2 sequestered per hectare per year. Likewise, converting biomass carbon to CO2-equivalent does not create a sequestration rate unless the time interval over which that carbon accumulated is known. Differences among studies may reflect soil depth, tree age, stand density, analytical method or system boundary rather than a biological difference between cultivated and natural pistachio.

Evidence from other tree crops is valuable when used carefully. Proietti et al. (2016) compared carbon balances in intensive and extensive woody cultivation systems, Pacchiarelli et al. (2022) quantified carbon sequestration in hazelnut orchards, Ioannidou et al. (2025) examined carbon sequestration in mixed Mediterranean orchards, and Ruiz-Carrasco et al. (2026) evaluated field-based carbon-farming practices in olive groves. These studies strengthen the case for integrated biomass, soil and management accounting. Their numerical results should remain indirect evidence for pistachio.

Figure 2 provides a qualitative synthesis of the principal contrasts discussed above; it should not be interpreted as a universal quantitative ranking of carbon stocks between managed orchards and natural woodlands.

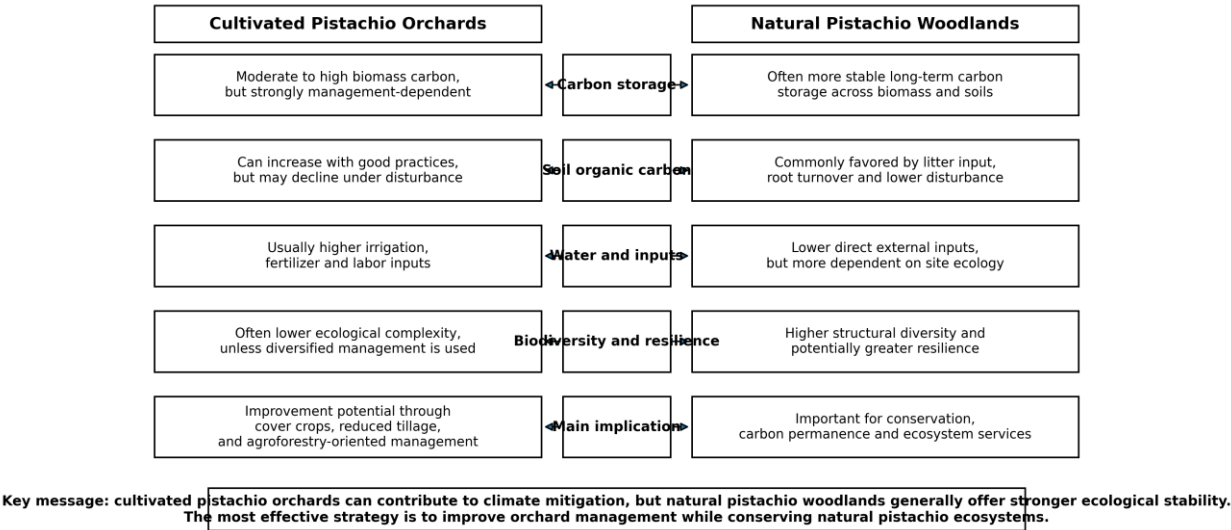


Figure 2. Cultivated versus natural pistachio systems: carbon storage, management and sustainability. This qualitative synthesis highlights management-dependent carbon storage in orchards and the role of lower disturbance, structural complexity and ecosystem resilience in natural woodlands; site-specific measurements remain necessary for quantitative comparison.

7. MANAGEMENT CONTROLS ON ORCHARD CARBON PERFORMANCE

Water management is central in pistachio because irrigation can increase growth while also creating an energy cost. The climate outcome depends on the source and efficiency of irrigation water, pumping head, electricity mix and the degree to which additional water increases durable biomass or soil carbon. Reporting irrigation volume without the associated energy and yield context is therefore incomplete. Nitrogen management presents a similar trade-off. Adequate nutrition supports canopy function and yield, but excessive nitrogen can increase upstream fertilizer emissions and field N2O losses. Carbon-farming recommendations should not promote additional fertilization simply because it increases short-term biomass. Nutrient-use efficiency, soil testing and realistic yield targets are more defensible indicators of climate-smart management.

Ground cover, reduced soil disturbance and organic amendments are promising because they can increase carbon inputs to soil and protect soil structure. Their effectiveness is site-specific in semi-arid orchards, where competition for water and the decomposition response to irrigation are important. Long-term field trials should report SOC change

by depth, bulk density, ground-cover biomass, irrigation and residue fate rather than relying on a single soil-carbon concentration.

Planting density and pruning affect both standing biomass and orchard function. High density can increase carbon per hectare early in orchard development, but crowding, mechanization and eventual tree removal complicate long-term accounting. Pruned biomass should be tracked explicitly: on-site mulching can return carbon and nutrients to soil, whereas burning or removal changes the system boundary.

8. MEASURING CARBON SEQUESTRATION IN PISTACHIO SYSTEMS

A rigorous field protocol should combine repeated measurements of tree structure, roots where feasible, dead organic matter, SOC and management activity. For orchards, tree inventories should record age, rootstock and scion, spacing, trunk dimensions, canopy dimensions, pruning intensity and yield. Locally calibrated allometric equations are preferable because pruning produces crown forms that may differ substantially from forest trees.

For SOC, sampling should be stratified by depth and position relative to tree rows, irrigation emitters and inter-row areas. Bulk density and coarse fragments must be measured alongside carbon concentration. Resampling after a meaningful interval is necessary to estimate sequestration directly. When land-use history is known, chronosequences can be informative, but they require careful matching of soil and landscape conditions.

Remote sensing can extend field observations spatially. High-resolution optical imagery, LiDAR or structure-from-motion methods can characterize canopy volume and cover, and repeated observations can track structural change. Waqas et al. (2025) discuss broader methods for incorporating tree biomass sequestration into LCA. For pistachio, remote sensing should be calibrated against field biomass and used as a scaling tool rather than as a replacement for ground measurements.

Uncertainty should be reported explicitly. Errors arise from plot sampling, tree allometry, carbon fractions, bulk-density measurements, spatial heterogeneity and remote-sensing models. Internationally useful datasets should provide confidence intervals or uncertainty ranges rather than a single point estimate with false precision.

Table 2. Minimum measurement framework for pistachio carbon studies

Component	Minimum data	Preferred reporting unit	Key caution
Aboveground biomass	Tree age, spacing, trunk/canopy dimensions; locally calibrated allometry; carbon fraction	Mg C ha ⁻¹	Forest allometry may be biased by orchard pruning or multi-stem form.
Belowground biomass	Root sampling or validated root:shoot model	Mg C ha ⁻¹	Generic root ratios can add large uncertainty.
Soil organic carbon	Carbon concentration, bulk density, coarse fragments, fixed depth/equivalent soil mass	Mg C ha ⁻¹ by depth	Concentration (%) alone is not a stock.
Carbon sequestration rate	Repeated stock measurements or defensible chronosequence	Mg C ha ⁻¹ yr ⁻¹	A single-date stock cannot be divided arbitrarily by stand age.
Management GHG emissions	Irrigation energy, fertilizer, N ₂ O, fuel and operations	Mg CO ₂ e ha ⁻¹ yr ⁻¹ or kg CO ₂ e kg ⁻¹ product	Do not mix product footprint with land-based sequestration.
Remote sensing	Ground-calibrated canopy/biomass models; repeated imagery	Spatial biomass/carbon estimate	Does not replace field SOC measurement.
Permanence / tree health	Mortality, canopy loss, major diseases and drought injury	Survival, severity, canopy metrics	Important for interpretation of long-term carbon retention.

9. CARBON STOCK, GHG FOOTPRINT AND CARBON FARMING

Carbon farming is sometimes used as an umbrella term for practices intended to increase carbon storage or reduce GHG emissions. In perennial horticulture, these goals overlap but are not identical. A pistachio orchard may accumulate biomass while consuming energy for irrigation and producing N₂O from fertilized soil. Conversely, a low-input orchard may have a small annual increase in biomass but a low operational footprint. Both dimensions matter.

Life-cycle studies in pistachio are therefore complementary to field carbon inventories. Bartzas and Komnitsas (2017), Bartzas et al. (2017), Gökdoğan et al. (2022) and Babaeian et al. (2025) help identify management-related environmental burdens. A robust carbon-farming claim should combine such emission accounting with repeated stock measurements. Product-based results (for example, kg CO₂e per kg of nuts) and land-based results (Mg C ha⁻¹ or Mg CO₂e ha⁻¹ yr⁻¹) should be presented separately because they answer different management questions.

Evidence from Mediterranean perennial systems suggests that mixed vegetation, soil-cover management and reduced disturbance can contribute to carbon retention, but the strongest pistachio recommendations will come from replicated local trials. The aim should be to identify practices that improve both orchard resilience and verified climate performance rather than to maximize one carbon pool in isolation.

10. TREE HEALTH, PERMANENCE AND THE CENTRAL ASIAN CONTEXT

Carbon storage in perennial systems has a permanence dimension: carbon retained in living biomass depends on tree survival and continued canopy function. Drought, salinity, pests and diseases can reduce growth, cause branch dieback or shorten stand life, thereby affecting both biomass carbon and the flow of litter and roots to soil. Tree health should therefore be treated as a supporting variable in long-term carbon studies rather than as a separate issue.

This point is especially relevant in Central Asia, where pistachio is important both as a crop and as a component of dryland forestry and restoration. Nazarova et al. (2023) documented *Septoria pistaciae* affecting pistachio in Uzbekistan and described its biological characteristics. That study does not estimate carbon sequestration and should not be cited as evidence for a carbon sink. Its relevance here is different: it demonstrates that locally important disease pressure exists and may influence stand persistence, canopy condition and ultimately the reliability of long-term carbon storage. Integrating tree-health observations into carbon-monitoring plots would therefore improve interpretation without conflating pathology with carbon measurement.

For Uzbekistan and neighboring drylands, research should prioritize paired comparisons among managed orchards, restoration plantings and well-characterized natural *Pistacia* stands. Such designs should document species and genotype, stand age, soil properties, water regime, management history and tree health. The same plots can then support biomass inventories, SOC sampling, remote-sensing calibration and long-term ecological monitoring.

11. RESEARCH PRIORITIES

Five priorities would substantially strengthen the evidence base. First, pistachio-specific allometric equations should be developed for both orchard and natural stand architectures, with destructive sampling where ethically and legally feasible. Second, SOC monitoring should use harmonized depths, bulk-density measurements and repeated sampling, ideally with equivalent-soil-mass calculations. Third, management inventories should quantify irrigation energy, fertilizers, fuel, pruning-residue fate and harvest exports so that stock change can be interpreted alongside GHG emissions.

Fourth, long-term designs should include tree survival, canopy condition and major biotic and abiotic stresses. This is particularly important where restoration or carbon-farming claims depend on decades of persistence. Fifth, remote sensing should be used to scale verified field relationships across landscapes, with transparent calibration and uncertainty rather than unsupported stand-level extrapolation.

A regional network of permanent monitoring plots would be especially valuable in Central Asia. Even a modest number of well-characterized sites measured consistently for five to ten years would be more informative than many one-time estimates using incompatible methods. Such a network could also test whether carbon benefits coincide with improved soil condition, biodiversity, water-use efficiency and farm resilience.

12. CONCLUSIONS

Pistachio systems are plausible contributors to climate mitigation in dryland regions, but the current evidence does not justify a single sequestration rate or a categorical claim that cultivated orchards or natural stands are universally superior. The strongest pistachio-specific evidence concerns measurable SOC stocks, aboveground biomass estimation, seasonal carbon allocation and production-related GHG burdens. These are complementary pieces of the carbon balance, not interchangeable measurements.

For international reporting, the next step is methodological discipline: repeated biomass and SOC inventories, clearly

defined system boundaries, separate reporting of carbon stock change and GHG emissions, and explicit uncertainty. Natural Pistacia stands and cultivated P. vera orchards should be compared only when species identity, age, soil, climate and measurement methods are sufficiently matched.

Within Central Asia, pistachio offers a useful model for linking carbon accounting with dryland forestry, orchard management and ecosystem restoration. A research program that combines field inventories, remote sensing, soil measurements and tree-health monitoring would provide a defensible basis for future carbon-farming claims and policy decisions.

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