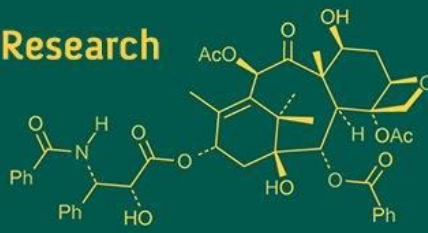


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Regenerative fruit production systems for carbon-smart orchards

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Abstract

Regenerative orchard agriculture combines agroecological practices to enhance soil health, biodiversity and resource efficiency, with a focus on carbon sequestration and greenhouse gas mitigation. This comprehensive report synthesizes current research and case studies on carbon-smart fruit production systems. It covers historical developments and key figures in organic/regenerative farming, then details approaches such as cover cropping, composting, reduced tillage, agroforestry, precision water and nutrient management, integrated pest management and biodiversity enhancement. For each practice, ecological outcomes (soil organic matter, water retention, nutrient cycling, pest regulation, pollination, carbon uptake) and management requirements are examined. Carbon accounting methods and sequestration potentials are discussed, with estimates of carbon storage per hectare for various practices. A life-cycle perspective on greenhouse gas sources (fuel, inputs, soil N₂O) and mitigation strategies is included. Economic analysis compares input costs, labor demands, yields and revenue potential (including carbon markets) across orchard scales.

Keywords: Regenerative agriculture, carbon sequestration orchard management, soil health, cover crops, agroforestry, reduced tillage, integrated pest management, biodiversity, precision irrigation

Introduction

Modern fruit orchards face the twin challenges of meeting rising demand while reducing environmental impact. Traditional intensive orchard systems often rely on high synthetic inputs and practices (frequent tilling, monocultures, chemical pesticides/fertilizers) that degrade soils, reduce biodiversity and emit large amounts of greenhouse gases (GHGs) [29]. In contrast, regenerative agriculture offers an alternative paradigm: it seeks to “restore, renew or revitalize” whole ecosystems in agricultural landscapes, with orchards as prime candidates for such transformation. Regenerative orchards emphasize perennial trees and cover vegetation, minimal soil disturbance and integrated ecological services (such as pollination and natural pest control) to increase system resilience. Crucially, they aim to make orchards carbon-smart, meaning they maximize carbon sequestration in biomass and soil while minimizing emissions from inputs and management [11]. This report defines regenerative fruit production systems as combinations of practices that improve soil health (organic matter, structure, biology), enhance on-farm biodiversity (plants, insects, animals, microbes) and manage resources (water, nutrients, energy) more efficiently and locally. By doing so, regenerative orchards can sequester significant amounts of atmospheric carbon in trees and soils, reduce net GHG emissions (e.g. by cutting synthetic nitrogen or fuel use) and lower reliance on external inputs. The global scope of this report (encompassing temperate and subtropical fruit systems) reflects the fact that most fruit trees are perennials with high biomass, making them especially valuable for carbon storage compared to annual crops [52]. The introduction will first review the historical evolution of sustainable and regenerative practices in agriculture (and orchards specifically) to situate the current movement. It then outlines the *methods and approaches* of modern regenerative orchard management. Subsequent sections delve into detailed aspects of orchard design: soil health, agroforestry designs, cover cropping, composting, tillage reduction, water and nutrient management, integrated pest management (IPM) and biodiversity. We will also cover carbon accounting (measurement of carbon stocks and flows), GHG mitigation strategies, economic

considerations and relevant policy mechanisms (e.g. climate-smart agriculture incentives, carbon markets) ^[53]. Throughout, the focus is on peer-reviewed findings and authoritative reports. Where possible, the global applicability of practices is noted and both temperate (apple, pear, cherry, etc.) and subtropical/tropical fruit systems (citrus, mango, avocado, etc.) are considered. Many examples will draw on temperate orchard research (often apples or citrus), but the principles generally apply across orchard types. The reader is assumed to have some familiarity with agroecological concepts, but key terms and motivations (e.g. what constitutes a carbon-smart practice) are defined as they arise. The narrative emphasizes not only “what” practices are used, but “why” they matter for carbon and resource outcomes and “how” they can be implemented in orchards of different scales ^[30].

Methods and Approaches

Regenerative orchard systems are not governed by a single protocol but by overarching principles and sets of practices adapted to each context. The core methods involve:

- **Soil Health Management:** Focus on building soil organic matter, enhancing microbial life and structure. Techniques include cover cropping organic mulches/compost, reduced tillage and lime/rock dust amendments to replenish minerals. Soils are managed to maintain a continuous plant cover and living roots year-round, feeding soil biota. This often means growing winter cover crops in the tree rows or alleys and minimizing bare fallow periods ^[31].
- **Diverse Planting and Agroforestry:** Instead of monocultures of a single fruit, regenerative orchards may integrate multiple species or varieties, including alley crops (legumes, vegetables), understory pasture or additional tree layers (silvopasture or multistory agroforestry). For example, lines of fruit trees can be interplanted with nitrogen-fixing trees, fodder shrubs or hedgerows of native flowering plants to support beneficial insects. This increases biomass and ecological interactions, smoothing yields and spreads risk ^[12].
- **Water Management:** Efficient irrigation (drip, micro-sprinkler) guided by soil moisture sensors, weather data or plant feedback is crucial. Automated systems can match water supply to needs, cutting waste. Regenerative systems often incorporate water harvesting (ponds, swales, mulch) to improve drought resilience. By maintaining living cover (mulch or cover crops), soil moisture is conserved and infiltration enhanced, which both reduces irrigation needs and improves carbon sequestration ^[54].
- **Nutrient Management:** Fertilizer strategies emphasize natural nutrient cycling. Legume cover crops (e.g. clover, vetch) can fix 50100 kg N/ha (about 4590 lb/acre), reducing or replacing synthetic N inputs. Compost, manure and biochar recycle on-farm biomass and improve soil fertility and water-holding capacity. Mineral inputs (lime, rock dust) are used only to correct proven deficiencies. Soil testing and foliar analysis guide judicious fertilizer use. Nutrient stewardship also involves capturing any nutrient runoff (grass buffers, constructed wetlands) to prevent losses ^[54].
- **Integrated Pest and Disease Management (IPM):** Pest control is based on monitoring and

thresholds, not routine calendar spraying. Orchards are scouted regularly, traps and pheromones are used as needed. Natural enemies (ladybugs, predatory mites, parasitic wasps) are conserved through habitat (flower strips, reduced pesticides) and released if needed. Resistant or less-susceptible varieties may be chosen. This approach follows IPM principles developed in the mid-20th century: use pesticides only when economically justified and combine them with biological methods. The goal is minimal pesticide input while keeping pest populations under control ^[55].

- **Biodiversity Enhancement:** Planting hedgerows, windbreaks and flowering cover cultivars near orchards provides food and nesting for pollinators and predators. In-tree biodiversity (e.g. using perennial groundcovers or allowing natural grasses) is maintained instead of fumigation. Farmer-managed habitats like beetle banks or woodlots increase landscape heterogeneity. Pollinator practices (bee hives, undisturbed nest sites) ensure pollination services, which can increase fruit set and quality. These measures are synergistic with IPM (predators help pests) and water/soil health (roots, litter improve soil) ^[13].
- **Carbon Accounting and Monitoring:** Regenerative orchards measure their climate impact via carbon audits or life-cycle assessments (LCA). This may include on-farm GHG inventory (fuel, fertilizer, emissions) and soil carbon testing (yearly SOC sampling). Many producers work with tools like the USDA's COMET-Farm, University of Cool Farm Tool or custom LCA to quantify carbon footprint. Through carbon accounting, practices that sequester C (e.g. cover cropping) can be verified to generate carbon credits. For instance, CMI Orchards tracks GHGs and expects to earn credits by tipping organic waste to biochar and compost ^[13].
- **Adaptive and Participatory Management:** Regenerative farming requires ongoing learning. Many growers use farmer field-days, precision ag data and collaboration (co-ops, extension networks) to refine practices. Methods may be tested on part of an orchard first and adjustments made. Digital tools (soil sensors, satellite imagery, decision apps) increasingly assist in real-time management. Extension services often blend traditional knowledge (e.g. local varieties, seasonal cues) with modern science to tailor solutions ^[32].
- **Economic and Policy Integration:** In practice, regenerative orchards align with market or policy incentives: organic or regenerative certification can command premiums and carbon markets may pay for verified sequestration. Many government programs (e.g. the USDA's climate-smart commodity grants or EU's eco-schemes) now fund cover crops and soil health practices. Regenerative producers often diversify income with farm tours, direct sales or added-value products ^[14].

Soil Health

Healthy soil is the foundation of regenerative orchards. It stores water and carbon, feeds trees via microbial processes and supports nutrient cycling. Soil health is assessed by measuring properties like organic matter content, soil structure (aggregation), nutrient levels, pH and biology (earthworms, microbial activity). Practices in regenerative orchards aim to increase soil organic matter (SOM) and biological activity over time ^[33].

Cover crops and mulches: Planting cover crops in orchard alleys or under tree canopies is central. Cover species include grasses (e.g. cereal rye, oats), legumes (clover, vetch) and brassicas (mustard) in temperate zones or sunn hemp, cowpea and tropical grasses in warmer climates. These protect against erosion, enhance infiltration and when terminated they add biomass ^[56]. For instance, a mixture of rye and legumes in an apple orchard can capture residual N and prevent nutrient leaching while building organic matter. Mulches (wood chips, straw, prunings) perform similarly: a 5 cm layer of wood mulch under fruit trees can reduce evaporation and slowly feed the soil as it decomposes. USDA guidelines note that cover cropping and mulching help maintain soil cover and organic inputs (minimizing erosion and nurturing soil life). Indeed, one study reports that one pound of soil organic matter can hold 1820 pounds of water, illustrating how adding organic residue improves water retention ^[15].

Reduced tillage: Avoiding deep plowing or shredding the soil prevents the loss of carbon and soil structure. Many regenerative orchards adopt no-till or minimal cultivation practices. For instance, using a roller-crimper to terminate covers (without digging) avoids burying residues deeply. Reduced tillage also protects mycorrhizal fungal networks important for tree roots. Where some soil disturbance is needed (e.g. for herbicide strip or planting), it is kept shallow and infrequent. Studies show that no-till systems generally build soil organic carbon over time, whereas frequent plowing tends to oxidize organic matter to CO₂ ^[16].

Compost and organic amendments: Adding compost or well-aged manure provides immediate nutrients and carbon. High-quality compost (from farm biomass, manure, wood chips) applied at 515 tons/ha in an orchard can raise SOM and feed microbes. One meta-analysis of orchard studies found that long-term organic inputs (manure or compost) increased soil carbon by approx 3.7 Mg C/ha-year, a much faster gain than with no inputs. Compost also improves soil structure and cation exchange capacity, which enhances fertility and resilience. Some orchards rotate animal grazing or green manures (e.g. turning down a cover crop) to recycle biomass ^[34].

Crop rotation and fallowing: While crop rotation is more common in annual farming orchards may alternate orchard blocks with legumes or grain in longer fallow periods. For example, some growers replant old orchards and plant a temporary cereal or clover crop for a year before new trees go in. This helps rebuild soil N and breaks disease cycles. Even leaving some sections fallow with cover vegetation can mimic a “rotation” ^[57].

Monitoring and metrics: Soil health in regenerative orchards is tracked by periodic testing. Key metrics include soil organic carbon, aggregate stability, infiltration rate and earthworm counts. Some projects use more advanced tools like the Haney soil test (which includes microbial respiration) to guide amendments. Over years, an increase in topsoil carbon by a few percent (e.g. from 2% to 4% SOM) can double water retention and greatly improve fertility ^[58].

Agroforestry and Polyculture Designs

Traditional orchards are monocultures of a single fruit tree, but regenerative systems explore more complex designs that

mimic natural forests. Agroforestry in orchards can include interplanting additional tree species, integrating livestock (silvopasture) or cultivating crops between tree rows ^[1]. These designs increase structural and species diversity, which multiplies ecosystem benefits:

- **Mixed-species orchards:** Instead of all one cultivar, plant multiple fruit species (apples, pears, cherries) or varieties. Biodiverse orchards can flower at different times, extending pollinator season and reduce pest build-ups (pests often specialize). For example, a mixed “forest garden” or permaculture orchard in a temperate climate might intersperse nut or berry shrubs between fruit trees. In tropical areas, polyculture fruit orchards (mango, cacao, banana) are common ^[16].
- **Alley cropping:** Plant perennial legumes or cover crops in the alleys between tree rows. These plants can fix nitrogen, add organic matter and provide forage or secondary produce. For instance, rows of olive trees interplanted with beans or vetch have been trialed in Mediterranean agroforestry. In deciduous orchards, permanent grass-legume alleys serve as living mulch ^[59].
- **Silvopasture:** Integrating livestock (sheep, goats, chickens) into orchards can improve ground management and nutrient cycling. In practice, small ruminants graze cover crops or grass under trees, controlling weeds and providing manure. Birds (chickens or ducks) can be let into orchards seasonally to forage on pests and fertilize the soil. Importantly, grazing is carefully managed to avoid soil compaction around young trees. Research and case examples suggest that properly managed sheep or chicken-grazed orchards have lower mowing costs and similar yields, while building soil carbon through manure deposition. For example, some Californian organic vineyards incorporate sheep flocks that cyclically graze between vine rows, reducing herbicide use ^[35].
- **Forest garden (food forest) principles:** In a food forest orchard, multiple vertical layers are utilized: tall fruit/nut trees, smaller tree crops, shrubs, groundcovers and vines, all with overlapping functions. For example, a chestnut tree overstory, with hazelnut mid-layer, blueberry bushes under that and herbaceous flowers at ground level. Pollinators and soil health benefit from this multi-strata design and wood chips from prunings serve as mulch. Though more experimental in orchards, permaculture-inspired designs show high productivity per area and high carbon stocks (through the combined biomass of many species) ^[60].
- **Hedgerows and buffer zones:** Surrounding orchards with native trees and shrubs (hedgerows, riparian buffer strips) are technically agroforestry as well. These linear plantings sequester carbon and harbor wildlife corridors. For example, planting a 5-meter native hedgerow around an orchard edge can accumulate 25 t CO₂/ha-year (roughly 0.51 t C) once mature, while providing pollinator and predator habitat ^[17].

Cover Crops

Cover cropping is a cornerstone of regenerative orchards. In alleys or even under the tree canopy, cover crops offer numerous benefits:

- **Soil protection and water infiltration:** Growing plants year-round keeps soil from eroding under rain or wind.

Deep roots from covers (especially grasses like rye or oats) create channels that improve water infiltration. For example orchard studies find that grass-clover covers can significantly slow surface runoff and increase percolation, reducing nutrient loss ^[36].

- **Nutrient cycling:** Leguminous cover crops (clover, vetch, lupin) can fix substantial nitrogen. In one orchard context, summer legumes added on the order of 50 lb N/acre to the system. This can reduce fertilizer needs by a similar amount. Cereal covers (rye, barley) excel at scavenging residual soil nitrates in winter, which prevents leaching into waterways ^[2].
- **Weed suppression:** A dense cover crop shades out weeds, reducing the need for herbicides or cultivation. For instance, a well-terminated winter rye can reduce spring weed pressure in tree rows. Some orchards run mechanical mowers through cover alleys to mulch down weed flushes ^[61].
- **Soil organic matter:** Each cover crop cycle adds biomass. Even if only a fraction decomposes to humus, repeated years can raise soil organic carbon. Meta-analysis shows that cover cropping in perennial systems can add roughly 2.0 Mg C/ha-year on average (with diminishing returns after initial build-up) ^[36].
- **Pest and disease effects:** Cover crops also influence pests. For example, certain cover crops attract beneficial insects or repel pests. However, there can be trade-offs: legumes may harbor voles or require extra water (the Intermountain Fruit example noted legume water use is approx 2× that of grasses). In a California orchard experiment, a mustard cover in fall reduced nematode populations, benefiting citrus trees ^[36].

Composting and Organic Amendments

Applying compost and organic amendments is another vital regenerative practice. While cover crops feed the soil from the top, compost feeds it from biomass additions, often speeding up soil-building. Key aspects of compost/manure use in orchards include:

- **Compost sources and composition:** Compost can be made from prunings, leaves, fruit waste, manures and farm wastes. For example orchards may produce woody prunings which can be chipped and composted with manure. Some invest in livestock (hens or worms) to process specific wastes (e.g. worm composters digest cider byproducts or kitchen scraps). The CMI Orchards case in Washington has a “Soil Center” facility where orchard waste, manure and plant matter are upcycled into compost, biochar and worm castings ^[18].
- **Nutrient release:** Compost is a slow-release fertilizer. A typical compost analysis might supply 510 kg N/ha for each ton applied (depending on maturity), plus P, K and micronutrients. Unlike soluble fertilizers, compost feeds soil life and plants gradually, reducing nutrient leaching. The 2023 Chinese apple study underscores this: using 200 kg N/ha from organic manure plus 200 kg from urea (instead of 800 kg urea) increased soil carbon and dramatically cut N₂O emissions. Manure compost provides nitrogen in forms that microbes convert slowly, so peak soil nitrogen is lower ^[3].
- **Soil structure improvement:** The humus content and microbial activity from compost leads to better soil aggregation. In sandy soils, compost adds binding organic matter, in clay, it adds pore space. Either way,

root penetration and water infiltration improve. For example, prolonged compost use in California almond orchards has been observed to turn the clayey topsoil into a more friable, nutrient-rich medium ^[37].

- **Disease suppression:** Well-matured composts often contain beneficial microbes (fungi, bacteria) that can outcompete soil pathogens, providing a biofungicide effect. Several studies show lower incidence of soil-borne diseases in compost-amended orchards (though results vary by pathogen and compost type) ^[34].
- **Carbon sequestration:** Organic amendments add carbon directly to soils. The meta-analysis cited earlier noted approx 3.73 Mg C/ha-year from organic fertilization (manure/compost) in perennial systems. Even accounting for some decomposition, this is a large input. Over years, repeated compost application can raise soil C by inches. For perspective, adding 50 t/ha (dry basis) of compost with 30% C adds 15 t C (55 t CO₂) to the soil. While some of this decomposes, a significant fraction (often >50%) can remain as soil humus in the long term [38,45,6].
- **Practical considerations:** Ideally, compost is well-aged (6+ months) to avoid phytotoxicity. Many orchards use compost tea or extracts as foliar sprays or soil drenches for added microbial benefits. Labor/equipment: making or buying compost has costs. However, many farms find that using on-farm residues (prunings, manure) is cheaper and recycles nutrients. One barrier is the volume: large organic acreage may need tons of compost to meet nitrogen needs, so on-farm production or local sourcing is important ^[19].

Reduced Tillage and Soil Disturbance

Conservation of soil structure is a hallmark of regenerative systems. In orchards, tillage can mean any mechanical soil disturbance: plowing, discing, cultivation or root pruners. Excessive tillage oxidizes soil organic matter and kills microbial networks. Regenerative orchards greatly limit such disturbance:

- **No-till or minimal-till orchard floor:** In many organic/regenerative orchards, tree rows are cultivated with minimal tools and alleys are mowed rather than plowed. When planting new trees, a no-till planter (or tree spade) inserts the sapling without tilling the whole row. Once established, the orchard is mostly maintained with groundcovers and occasional spot-cultivation only for immediate weed control or aeration ^[4].
- **Benefits for carbon:** Every pass of a plow or rototiller releases carbon. By contrast, no-till holds carbon in place and lets organic matter accumulate on the surface. Over decades, no-till orchards can build higher carbon than plowed ones. One meta-analysis of perennial cropping (not exclusively fruit) reported that switching from intensive tillage to reduced/no-till can increase carbon sequestration by roughly 0.20.3 Mg C/ha/yr in temperate climates, largely by preserving existing SOC ^[39].
- **Soil biology:** Preserving fungi and roots helps nutrient uptake. For instance, mycorrhizal networks are disrupted by deep cultivation. Regenerative orchards instead may use subsoilers or chisel plows sparingly (only if compaction requires breaking) and keep the topsoil profile intact ^[40].

- **Practical modifications:** If weed control is needed in tree rows, options include flaming (thermal weeding), under-vine drip tape or targeted herbicide in conventional systems. Mechanical approaches include narrow sweep cultivators or bark weeding robots that remove only surface weeds. These methods disturb much less soil than broad tillage. For orchards converting from conventional, sometimes a one-time tillage is used to incorporate organic matter, followed by no-till maintenance ^[40].
- **Evidence:** Several case studies note that no-till orchards have denser earthworm populations and faster infiltration. For example, a Californian citrus orchard trial found that tilling every other row (paired-row cultivation) increased root growth into cover crop areas, compared to plowing every year across all rows. Other on-farm reports indicate that eliminating plowing did not reduce yields but did increase soil life (worm counts doubled after 5 years of no-till in an apple orchard) ^[20].

Water Management

Efficient water use is critical in orchards, especially as climate change brings droughts and as agriculture faces growing competition for water. Regenerative orchards optimize water through both *supply-side* (rainfall harvesting, irrigation) and *demand-side* (soil moisture retention, plant selection) measures.

- **Drip irrigation and precision scheduling:** Most modern regenerative orchards use micro-irrigation (drip or micro-sprinklers) rather than flood irrigation. Drip systems deliver water directly to each tree's root zone, minimizing evaporation. Combined with sensors or scheduling based on evapotranspiration, drip can drastically reduce water use. For example, growers frequently report 3050% savings in irrigation water compared to micro-sprinkler or furrow systems. One analysis notes that automation with soil moisture sensors can significantly cut water consumption while maintaining yields. Regenerative farms often use soil moisture probes or tensiometers to irrigate only when needed and smart systems can shut off during rain ^[41].
- **Mulch and soil cover:** Mulches of wood chips or straw around trees and living mulches (cover crops) retain soil moisture by shading the ground. A mulched orchard can use less frequent irrigation, in Brazil, mango orchards with 5 cm mulch needed only half the irrigation water of bare-ground plots. The USDA notes that added organic matter (from compost or cover crops) increases field capacity the water-holding ability by roughly 1,000,000 liters per hectare per 1% organic matter, which directly translates to drought buffering ^[4].
- **Rainwater capture:** Some regenerative orchards contour land or build swales/ponds to capture runoff. On hilly sites, terraces and micro-basins at tree bases can hold rainwater for infiltration. These features not only water the orchard but also recharge groundwater. In semi-arid regions, planting trees on swales has raised yields by 3050% ^[62].
- **Drought-adapted varieties:** Choosing deep-rooted rootstocks or drought-tolerant cultivars is part of the strategy. For instance, many new almond and apple varieties are bred for lower water use. Grafting fruit varieties onto vigorous rootstocks can explore deeper soil moisture (and sequester more carbon due to larger biomass) ^[42].
- **Efficient fertilization:** Overfertilizing promotes lush foliage that uses more water. Regenerative nutrient management (split applications, slow-release organics) avoids excessive vegetative growth, indirectly saving water ^[21].
- **Integrated canopy management:** Good pruning and tree spacing improve airflow and light, reducing fungal disease (which requires irrigation to treat) and allowing more efficient water use. Dense canopies can create humid microclimates that might waste water, whereas open canopies balance shade with ventilation ^[43].
- **Monitoring and data:** Satellite and drone imagery are increasingly used to track water stress in orchards, enabling targeted watering only in stressed zones. Integrated "irrigation scheduling tools" use crop coefficients and weather forecasts to optimize daily decisions (like the Farmable app described in ^[53]).
- **Water quality:** Some regenerative practices protect water quality by preventing nutrient runoff (critical near waterways). For instance, buffer strips at orchard edges can filter water from any runoff, protecting downstream ecosystems. This is a co-benefit: improving water efficiency while reducing pollution ^[63].

Nutrient Management

Regenerative nutrient management moves away from sole reliance on synthetic fertilizers, instead creating a nutrient cycle that relies on internal and natural sources. The aim is to meet tree needs while minimizing waste and emissions.

- **Organic fertilizers and amendments:** Applying composted manure, green manures (tilled legume covers) and rock minerals (e.g. rock phosphate, greensand) supplies nutrients slowly. For example, as noted, substituting manure for part of the nitrogen fertilizer can boost soil carbon and slash emissions. In practice, many regenerative orchards use yearly compost topdressings (520 t/ha) with known N-P-K content. Because compost releases N over months orchards often also plant legumes (e.g. annual winter peas) that fix additional N ^[5].
- **Precision fertilization:** Soil tests and plant tissue analyses guide exactly what nutrients are needed each year, avoiding blanket application. Fertigation (injecting soluble fertilizers via drip) is used sparingly, when used, it targets critical growth periods (spring flush, fruit set) to minimize excess. Electronic monitoring (EC sensors) can gauge soil nutrient status in real-time for adjustments ^[44].
- **Crop-livestock cycling:** In on-farm examples, poultry raised under young trees eat pests and drop manure, supplying nitrogen. Pigs or cattle may be rotated through harvested orchards to eat fallen fruit and fertilize with their waste. These methods were used historically (e.g. pigs under chestnuts) and modern regenerative farms have revived them in controlled ways. Manure from other farm areas (e.g. dairy slurry, chicken litter) can be composted and applied if managed to prevent nutrient overload ^[22].
- **Reduced synthetic N use:** Encouragingly, research shows orchards need far less synthetic N than many current practices use. The Chinese apple case found that typical rates (3501200 kg N/ha-yr) were excessive and polluting. By cutting N from 800 to 400 kg/ha (and adding organic N), net emissions (CO₂ and N₂O)

dropped dramatically. In practice, many regenerative growers cut N rates by 50% and rely on covers to fill the gap. Excessive N not only wastes money but can lead to soil acidification and nitrous oxide emissions (an extremely potent GHG) ^[64].

- **Phosphorus and micronutrients:** Regenerative orchards often use rock phosphate or bone meal instead of water-soluble P. These release P slowly and feed soil microbes. Foliar sprays of micronutrients (boron, zinc) can correct deficiencies without soil run-off. Soil biology (mycorrhizal fungi) helps make P available. The focus is on slowly building up a rich soil reserve (e.g. raising Mehlich P to a healthy range by years of compost) rather than annual high-dose fertilizer ^[45].
- **Nutrient balance and losses:** Finally, nutrient management acknowledges trade-offs. For example, legume covers give N but need water, too much compost can raise salinity, deciduous orchard soils naturally lose some Ca/Mg from fruit removal, so periodic lime addition might be needed. The goal is balanced nutrition while preventing leaching or runoff (through buffer strips and soil health) ^[46].

Biodiversity and Habitat Enhancement

Biodiversity of plants, insects, soil organisms, birds and other wildlife is a key indicator and driver of regenerative orchard health. Rather than sterile monocultures, regenerative orchards intentionally foster a web of life. Key actions include:

- **Pollinator support:** Many fruit crops are pollinator-dependent, so providing habitat for bees and other pollinators directly increases yield and quality. Practices include maintaining early-flowering plants (e.g. mustards, buckwheat, phacelia) before and after orchard bloom, installing flowering hedgerows and avoiding pesticides harmful to bees. As shown in Pollinator Conservation research orchards integrated with semi-natural habitat see higher pollinator visitation and more reliable fruit set. Apple and cherry orchards often include near-row wildflower strips, citrus blocks may reserve a few rows of cover crops as insectary ^[6].
- **Beneficial insects and fauna:** Beyond pollinators orchards benefit from predators and parasitoids. Planting insectary plants (umbellifers, sunflowers, buckwheat) attracts predatory wasps, ladybugs and hoverflies. Installing bird boxes and bat houses also encourages avian/pipistrelle pest control (birds eat caterpillars and fruit moths, bats eat night-flying pests). Even fungi and nematodes can be beneficial if the soil is healthy. The BioScience review notes that enhancing agroecosystem biodiversity (e.g. flower strips, hedgerows) synergizes pollination and pest control ^[65].
- **Floral and structural diversity:** The physical habitat itself is diversified. For example, leaving some grassy tussocks or clover patches can provide refuge for spiders and ground beetles. Understory mixes with native grasses or shrubs create niches for various organisms. Water features (ponds or wet ditches) can host dragonflies that prey on orchard pests. By contrast, intensively clean or bare orchards typically suffer more invasive pests and fewer natural checks ^[66].
- **Microbial diversity:** Regenerative soil practices (no-till, compost) vastly increase belowground biodiversity. A healthy orchard soil may harbor thousands of

microbial species, which work on nutrient cycling and disease suppression. For example, Rhizophagus mycorrhizal fungi associated with tree roots extend the root's reach, aiding nutrient uptake. Good microbial diversity often correlates with resilience to stress and drought ^[23].

- **Landscape connectivity:** Individual orchards are made part of a larger mosaic. Practices like maintaining adjacent woodlots, riparian vegetation and wildlife corridors help species move through agricultural regions. Migratory pollinators or birds can then service multiple farms. Conversely, fragmented monocultures isolate farms from this regional biodiversity pool. Regenerative orchards tend to integrate seamlessly with surrounding forests or agroforests ^[51].
- **Cultural practices for biodiversity:** Avoidance of prophylactic pesticides is central. Regenerative growers use pesticides only as a last resort, preserving "non-target" species. Even operations using conventional products are increasingly using only spot-treatments or pheromone dispensers. Mowing under trees is done carefully to avoid destroying ground-nesting bees or juvenile beneficials for instance, mowing after midday when bees are less active or leaving un-mowed buffer strips ^[24].

Carbon Accounting and Sequestration Strategies

A defining goal of carbon-smart orchards is to achieve a positive carbon balance. This requires quantifying both carbon inputs (sequestration) and outputs (emissions), then adopting strategies to maximize net storage.

Accounting methods: Many growers and researchers use life cycle assessment (LCA) or farm GHG inventories to quantify emissions (CO₂ from fuel and materials, N₂O from fertilizers, etc.) and sequestration. Tools like COMET-Farm (USDA) or the Cool Farm Tool (University of Aberdeen) allow orchard inputs and outputs to be entered for a carbon footprint analysis. Soil carbon is measured by periodic sampling and tested for organic carbon content ^[47]. Tree carbon is estimated by allometric equations (relating trunk diameter/height to biomass). For example, Ioannidou *et al.* (2024) used six allometric models to estimate tree CO₂ uptake in Mediterranean orchards (Figure 2 illustrates these estimates). One finds typical values of approx 1012 kg CO₂ per mature tree per year (around 34 MgCO₂/ha-year at approx 300 trees/ha) for a mixed orchard ^[7].

Sequestration strategies: Practices that lock more carbon into the system include:

- **Increasing woody biomass:** Planting additional trees (agroforestry hedgerows, multi-layer plantings) raises the amount of long-lived carbon. Each mature fruit tree contains on the order of 0.52 tonnes of carbon (depending on species and size). Maintaining trees longer before rotation also stores more carbon ^[67].
- **Soil carbon accumulation:** By building soil organic matter (SOM), the orchard sequesters C in the ground. Many studies estimate sequestration from SOM accrual at 0.31.0 tC/ha-year with concerted soil-building practices. The Sicilian study found approx 0.46 tC/ha-year net (1.68 tCO₂/ha-year) stored in soil under regenerative management. Table 3 below lists typical sequestration rates for various practices (cover cropping, compost, no-till, agroforestry) ^[48].

- **Biochar:** Converting pruning waste or agricultural residues into biochar and incorporating it into soil creates a stable carbon pool. Biochar's carbon may remain for centuries. If an orchard applies 5 t/ha of biochar (~50% carbon), that adds 2.5 tC/ha immediately (and none of it returns to atmosphere). Biochar also tends to reduce N₂O emissions from soils, amplifying its climate benefits [25].
- **Perennial groundcovers:** Establishing shrubs or perennial grasses instead of tilling annual weeds means carbon continuously flows into the soil via roots [8].

Mitigating emissions: On the output side orchard GHGs comes mainly from:

- **Fossil fuel use:** running tractors, irrigation pumps, dryers (especially citrus and nut drying). Shifting to low-fuel methods (electric tractors, solar pumps) cuts these emissions. Many regenerative growers gradually electrify equipment or use renewable energy for irrigation [49].
- **Nitrous oxide:** applying N fertilizer (synthetic or manure) produces N₂O from soil. By cutting excess N and using inhibitors or urease treatments orchards can reduce N₂O by 40-60%. The Chinese apple study achieved approx 45% lower N₂O by halving synthetic N and adding manure [49].
- **Inputs manufacturing:** Every tonne of synthetic N (urea) costs approx 7.8 tCO₂ to produce. Reducing N use directly avoids these emissions. The Sicilian example showed regenerative practice cut the orchard's carbon footprint by a factor of approx 4 compared to conventional use of agrochemicals [49].

Greenhouse Gas Mitigation

Closely linked to carbon accounting is greenhouse gas (GHG) mitigation. Regenerative orchards aim to reduce their emissions of CO₂ (from energy), N₂O (from nitrogen) and CH₄ (minimal here). Strategies include:

- **Energy efficiency:** Using electric or solar-powered equipment reduces CO₂ from diesel. Some wineries/orchards heat greenhouses or dryers, switching to renewable cuts those emissions. Solar panels on farm buildings and microgrids for irrigation pumps are examples. Even simple practices like reducing unnecessary fuel burns (e.g. no-till lawn mowing, using silage instead of tractor for grass management) add up [9].
- **Reducing synthetic fertilizers:** As noted, cutting synthetic N drastically lowers N₂O. Also, producing synthetic N uses fossil fuel (Haber-Bosch process emits approx 2 tCO₂/tN). By instead using legumes or manure, the orchard's embedded carbon is lowered. Many studies show 30-60% N₂O reductions when organic sources partially replace urea. For example, the Chinese study found N₂O emission factors fell from 0.277 (at 800 kg N) to 0.150 (at 200+200 kg N + organic) a approx 46% reduction [26].
- **Biochar and methane:** Creating biochar off-farm (e.g. pyrolysis) uses energy, but if it replaces biodegradable waste burning, it cuts CH₄. In the orchard, adding biochar does not emit GHG (carbon is stable) and can even reduce N₂O fluxes. It is a frontline mitigation strategy [50].

- **Crop residue management:** Rather than burning prunings or cover crop residues (common in some conventional orchards), regenerative systems mulch or compost them. Burning not only emits CO₂ and particulate CH₄, but wastes organic matter [50].
- **Water and peat:** In some peat-heavy soils (rare in orchards), avoiding peat-based fertilizers protects long-term carbon stores. In irrigation, avoiding flooded methods prevents any methane production (orchards do not typically flood fields, but if rice-farming intercropping existed, it would matter) [68].
- **Transport and logistics:** If orchards integrate locally (e.g. small-scale processing, farmers markets), they cut transport emissions. More broadly, integrating orchard outputs into local economies (e.g. on-farm cider pressing) keeps carbon in the community [68].

Barriers to Adoption and Solutions

Despite the benefits, many orchards remain conventional. Barriers include:

- **Knowledge and Training:** Regenerative practices require understanding ecological processes. Small farmers may lack access to extension education on cover crops or nutrient cycling. This can be addressed by demonstration farms, farmer-to-farmer networks and online resources. Programs like NRCS Technical Assistance grants aim to fill this gap [27].
- **Initial Costs and Risks:** Installing drip irrigation, purchasing cover crop seed or transitioning to organic can be expensive and uncertain. Payments and cost-share programs alleviate this. For example, the USDA's Climate-Smart Agriculture grants fund cover crop seed and equipment. Crop insurance protocols are being adjusted to cover organic/regenerative farms, reducing perceived risk [12].
- **Certification and Market Access:** The organic or regenerative label can be hard to obtain. Harmonizing standards (e.g. for "regenerative certified") would help. Market development (e.g. linking producers with retailers) is key so that premium prices are real rewards [27].
- **Labor Availability:** Regenerative systems can be more labor-intensive, especially in early years (mowing covers, hand-weeding). Mechanization solutions (flail mowers, advanced robotics, roller-crimpers) are evolving. Policy can help by recognizing farm labor as critical and by supporting immigration channels for farm workers [51].
- **Infrastructure and Supply Chains:** Many remote or small-scale orchards lack access to markets or processing. Investing in rural infrastructure (roads, storage, local packinghouses) and cooperative models helps integrate small regenerative growers into supply chains [27].
- **Soil and Climate Constraints:** In very degraded soils or arid climates, regeneration can take years and initial yields may drop. This demands patience and intermediate support (like using drought-hardy fruit varieties, mulching heavily). Researchers are developing optimized cover mixes or drought-tolerant practices for such contexts [10].
- **Institutional Culture:** Some agribusiness or government agencies are still oriented toward high-input models. Overcoming this requires policy

advocacy (e.g. pushing fertilizer tax incentives to favor organics or penalizing high N application) and changing industry standards ^[28].

Conclusion

Regenerative fruit production is a compelling pathway to simultaneously increase orchard productivity, resilience and climate benefits. Drawing on over a century of agronomic innovation (from Carver’s rotations to modern soil carbon science), regenerative orchards reimagine tree cropping as part of a living ecosystem. Practices like cover cropping, compost addition, reduced tillage and biodiversity enhancement rebuild soil organic matter turning orchards into carbon sinks. For instance, studies document that managed citrus and apple orchards can sequester on the order of 0.52 tC/ha-year (while emitting far less CO₂ and N₂O than conventional systems). Over time, this can transform the climate impact of fruit farming. The benefits of regenerative approaches are numerous: improved soil water retention, richer biodiversity (pollinators, predators, microbial), reduced input costs (fertilizers, pesticides) and new income opportunities (organic prices, carbon credits). The trade-offs higher labor or transition costs are being addressed through technological innovation (automation, drones, bioinformatics) and policy incentives. By quantitatively accounting for carbon and economic factors

(as in Tables 14), growers and stakeholders can clearly see that regenerative orchards often match or surpass conventional systems in profitability once fully implemented, especially when ecosystem services are valued. Crucially, the agricultural community must recognize that no single practice suffices. A healthy, carbon-smart orchard is a system: soil health, plant health and even community health are interlinked. For example, soil life and plant diversity together suppress pests, reducing the need for chemicals. Similarly, carbon accounting integrated with farm economics creates feedback loops: as farmers document carbon gains, they gain monetary and reputational incentives to continue and expand regenerative practices. Looking ahead, climate pressures will only intensify the need for sustainable fruit systems. Regenerative orchards not only cut emissions but also buffer against climate shocks (drought, floods, heat waves) through deeper soils and diverse plantings. In essence, they turn orchards into climate allies. Continued research (especially long-term trials) will refine the best species mixtures, cover crop strains and soil amendments for each climate. Meanwhile, sharing knowledge across regions is vital: what succeeds in a Californian vineyard (e.g. winter cover crop cocktails) may inspire Mediterranean or even tropical orchards to adapt the idea.

Table 1: Regenerative practices and expected outcomes in orchards

Regenerative Practice	Key Expected Outcomes
Cover cropping (mixed grasses/legumes)	↑ Soil organic matter & structure, ↑ N supply (legumes approx 50 kg N/ha), ↓ erosion, ↑ water infiltration, ↓ weeds (through ground cover), ↑ pollinator habitat if flowering, modest carbon sequestration (approx 2.0 Mg C/ha-yr).
Composting/Organic manure	↑ Nutrient availability (slow-release N, P, K), ↑ microbial activity, ↑ moisture retention, ↑ SOM and C (approx 3.7 Mg C/ha-yr), ↓ need for synthetic fertilizer, improves soil structure (aggregation).
Mulching (wood chips, straw)	↓ Soil evaporation, ↓ weed growth, ↑ organic matter as mulch decomposes, can moderate soil temperature, provides habitat for beneficial insects on the ground.
Reduced/No-Tillage	↑ Soil carbon retention (prevents oxidation), ↑ earthworm populations & microbes, ↑ infiltration, ↓ machinery fuel use and labor, ↓ erosion, slightly slower early-season soil warming (may require balancing timing).
Agroforestry/Polyculture	↑ Above-and belowground carbon stocks (multiple layers of biomass), ↑ biodiversity (more niches), ↑ ecosystem services (shade, forage, pest control), diversified yield streams, microclimate buffering (less heat/drought stress on trees).
Integrating Livestock	Nutrient recycling via manure, natural weed/pest control (chickens eat grubs), reduced mowing, potential soil compaction if unmanaged, multi-purpose farm output (meat/eggs).
Hedgerows/windbreaks	↑ Habitat for pollinators, birds, beneficials, ↑ carbon storage in woody biomass, ↓ wind damage to trees, ↑ adjacent microclimate stability, source of potential fruits/nuts.
Biodiversity plantings (flowers, native plants)	↑ Pollination and natural enemy populations, ↑ beneficial insect habitat, can suppress pests and diseases indirectly, enhances landscape ecological balance.
Precision irrigation (drip + sensors)	↓ Water use (up to 50% vs. flood), ↑ water-use efficiency, ↓ nutrient leaching, ↑ yield reliability, initial investment in equipment, extended tree life (less water stress).

References

1. Abdul-Salam Y, Hawes C, Roberts D, Young M. The economics of alternative crop production systems in the context of farmer participation in carbon trading markets. *Agroecology and Sustainable Food Systems*. 2019;43(1):67-91. doi:10.1080/21683565.2018.1537986.

2. Alexander P, Paustian K, Smith P, Moran D. The economics of soil C sequestration and agricultural emissions abatement. *SOIL*. 2015;1(1):331-339. doi:10.5194/soil-1-331-2015.

3. Antle JM, Capalbo SM, Mooney S, Elliott ET, Paustian KH. Economic analysis of agricultural soil carbon sequestration: an integrated assessment approach. *Journal of Agricultural Economics*. 2001;26(1):344-367. doi:10.22004/ag.econ.31037.

4. Basso B. Techno-diversity for carbon farming and climate resilience. *Italian Journal of Agronomy*. 2022;17(3):2178. doi:10.4081/ija.2022.2178.

5. Berta N, Roux A. The endless expansion of carbon offsetting: sequestration by agricultural soils in historical perspective. *Cambridge Journal of Economics*. 2024;48(3):451-470. doi:10.1093/cje/beae008.

6. Brandt US, Svendsen GT. A project-based system for including farmers in the EU ETS. *Journal of Environmental Management*. 2011;92(4):1121-1127. doi:10.1016/j.jenvman.2010.11.029.

7. Cammarata M, Timpanaro G, Incardona S, La Via G, Scuderi A. The quantification of carbon footprints in the agri-food sector and future trends for carbon sequestration: a systematic literature review. *Sustainability*. 2023;15(21):15611. doi:10.3390/su152115611.
8. Cammarata M, Tadiello T, Scuderi S, Millar N, Basso B. Regenerative practices can lead to carbon-negative orange groves in Sicily. *Journal of Agriculture and Food Research*. 2025;19:101615. doi:10.1016/j.jafr.2024.101615.
9. Cariappa AAG, Konath NG, Sapkota TB, Krishna VV. Evaluating the potential and eligibility of conservation agriculture practices for carbon credits. *Scientific Reports*. 2024;14(1):9193. doi:10.1038/s41598-024-59262-6.
10. Contasti AL, Firth AG, Baker BH, Brooks JP, Locke MA, Morin DJ. Balancing tradeoffs in climate-smart agriculture: will selling carbon credits offset potential losses in the net yield income of small-scale soybean (*Glycine max* L.) producers in the Mid-Southern United States? *Decision Analysis*. 2023;20(4):252-275. doi:10.1287/deca.2023.0478.
11. Cruz Maceín JL, Gonzalez-Fernandez I, Barrutieta A, Bermejo-Bermejo V, Zamorano Rodríguez JP. Adaptation strategies for dealing with global atmospheric change in Mediterranean agriculture: a triple helix approach to the Spanish case study. *Regional Environmental Change*. 2023;23(4):142. doi:10.1007/s10113-023-02131-1.
12. Dana LP, Dana TE. Expanding the scope of methodologies used in entrepreneurship research. *International Journal of Entrepreneurship and Small Business*. 2005;2(1):79-88. doi:10.1504/IJESB.2005.006071.
13. Das S, Catterjee S, Rajbanshi J. Response of soil organic carbon to conservation practices including climate-smart agriculture in tropical and subtropical regions: a meta-analysis. *Science of The Total Environment*. 2022;805:150428. doi:10.1016/j.scitotenv.2021.150428.
14. de Pinto A, Cenacchi N, Kwon HY, Koo J, Dunston S. Climate smart agriculture and global food-crop production. *PLoS One*. 2020;15(4):e0231764. doi:10.1371/journal.pone.0231764.
15. del Pozo A, Brunel-Saldias N, Engler A, Ortega-Farias S, Acevedo-Opazo C, Lobos GA, *et al.* Climate change impacts and adaptation strategies of agriculture in Mediterranean-Climate regions (MCRs). *Sustainability*. 2019;11(10):2769. doi:10.3390/su11102769.
16. Delate K. Using an agroecological approach to farming systems research. *HortTechnology*. 2002;12(3):345-354. doi:10.21273/HORTTECH.12.3.345.
17. Ecosystem Marketplace. Back to the future: State of the voluntary carbon markets 2011. Washington, DC: Forest Trends; 2011. Available from: https://www.forest-trends.org/wp-content/uploads/imported/svcm-2011_executive-summary_final_rev-pdf.pdf
18. Giller KE, Hijbeek R, Andersson JA, Sumberg J. Regenerative Agriculture: an agronomic perspective. *Outlook on Agriculture*. 2021;50(1):13-25. doi:10.1177/0030727021998063.
19. Gundala RR, Singh A. What motivates consumers to buy organic foods? Results of an empirical study in the United States. *PLoS One*. 2021;16(9):e0257288. doi:10.1371/journal.pone.0257288.
20. Hanson JC, Johnson DM, Peters SE, Janke RR. The profitability of sustainable agriculture on a representative grain farm in the Mid-Atlantic Region, 1981-89. *Northeastern Journal of Agricultural and Resource Economics*. 1990;19(2):90-98. doi:10.1017/S0899367X00002154.
21. Iriarte A, Almeida MG, Villalobos P. Carbon footprint of premium quality export bananas: case study in Ecuador, the world's largest exporter. *Science of The Total Environment*. 2014;472:1082-1088. doi:10.1016/j.scitotenv.2013.11.072.
22. ISMEA-Mercati. Banca dati prezzi Origine [Internet]. Rome: ISMEA; 2024. Available from: <https://www.ismeamercati.it/flex/cm/pages/ServeBLOB.php/L/IT/IDPagina/5391>.
23. Jayaraman T, Aparajay K, Devshali CC, Jaiswal S. Greenhouse gas mitigation and carbon markets in Indian agriculture: An ex ante critical review. *Economic and Political Weekly*. 2023;58(43):45-53.
24. Joskow PL, Schmalensee R, Bailey EM. The market for sulfur dioxide emissions. *The American Economic Review*. 1998;88(4):669-685.
25. Kazimierczuk K, Barrows SE, Olarte MV, Qafoku N. Decarbonization of agriculture: the greenhouse gas impacts and economics of existing and emerging climate-smart practices. *ACS Engineering Au*. 2023;3(6):426-442. doi:10.1021/acsengineeringau.3c00031.
26. Khangura R, Ferris D, Wagg C, Bowyer J. Regenerative Agriculture-A literature review on the practices and mechanisms used to improve soil health. *Sustainability*. 2023;15(3):2338. doi:10.3390/su15032338.
27. Kooten GC, Zanello R. Carbon offsets and agriculture: options, obstacles, and opinions. *Canadian Journal of Agricultural Economics*. 2023;71(3):375-391. doi:10.1111/cjag.12340.
28. LaCanne CE, Lundgren JG. Regenerative agriculture: merging farming and natural resource conservation profitably. *PeerJ*. 2018;6:e4428. doi:10.7717/peerj.4428.
29. Lancaster KJ. A new approach to consumer theory. *Journal of Political Economy*. 1966;74(2):132-157. doi:10.1086/259131.
30. Langeveld JWA, van Keulen A, de Haan JJ, Kroonen-Backbier BMA, Oenema J. The nucleus and pilot farm research approach: experiences from The Netherlands. *Agricultural Systems*. 2005;84(3):227-252. doi:10.1016/j.agsy.2004.06.016.
31. Lankford B, Orr S. Exploring the critical role of water in regenerative agriculture: building promises and avoiding pitfalls. *Frontiers in Sustainable Food Systems*. 2022;6:891709. doi:10.3389/fsufs.2022.891709.
32. Lazarus WF. Machinery Cost Estimates. St. Paul: University of Minnesota; 2012. Available from: https://aede.osu.edu/sites/aede/files/publication_files/Machinery%20Cost%20Estimates%20-%20University%20of%20Minnesota.pdf

33. Lewandowski J, Peters M, Jones CA, House RM, Sperow M, Eve M, *et al.* Economics of sequestering carbon in the U.S. agricultural sector. Washington, DC: USDA Economic Research Service; 2004. Technical Bulletin No. TB-1909.
34. Li S, Kallas Z. Meta-analysis of consumers' willingness to pay for sustainable food products. *Appetite*. 2021;163:105239. doi:10.1016/j.appet.2021.105239.
35. MacRae RJ, Hill SB, Mehuys GR, Henning J. Farm-scale agronomic and economic conversion from conventional to sustainable agriculture. *Advances in Agronomy*. 1990;43:155-198. doi:10.1016/S0065-2113(08)60478-2.
36. Miltenberger O, Jospe C, Pittman J. The good is never perfect: why the current flaws of voluntary carbon markets are services, not barriers to successful climate change action. *Frontiers in Climate*. 2021;3:686516. doi:10.3389/fclim.2021.686516.
37. Minasny B, Malone BP, McBratney AB, Angers DA, Arrouays D, Chambers A, *et al.* Soil carbon 4 per mille. *Geoderma*. 2017;292:59-86. doi:10.1016/j.geoderma.2017.01.002.
38. National Academies of Sciences, Engineering, and Medicine. Negative emissions technologies and reliable sequestration: A research agenda. Washington, DC: The National Academies Press; 2018. doi:10.17226/25259.
39. Ngwira AR, Aune JB, Mkwinda S. On-farm evaluation of yield and economic benefit of short-term maize legume intercropping systems under conservation agriculture in Malawi. *Field Crops Research*. 2012;132:149-157.
40. Oldfield EE, Lavallee JM, Blesh J, Bradford MA, Cameron-Harp M, Cotrufo MF, *et al.* Greenhouse gas mitigation on croplands: clarifying the debate on knowns, unknowns and risks to move forward with effective management interventions. *Carbon Management*. 2024;15(1):2365896.
41. Peng X, Wang Y, Ma Y, Liu X, Gu X, Cai H. Seasonal variation and controlling factors of carbon balance over dry semi-humid cropland in Guanzhong Plain. *European Journal of Agronomy*. 2023;149:126912. doi:10.1016/j.eja.2023.126912.
42. Pergola M, D'Amico M, Celano G, Palese AM, Scuderi A, Di Vita G, *et al.* Sustainability evaluation of Sicily's lemon and orange production: an energy, economic and environmental analysis. *Journal of Environmental Management*. 2013;128:674-682. doi:10.1016/j.jenvman.2013.06.007.
43. Pudasaini K, Rolfe J, Bhattarai T, Walsh K. Comparison of major carbon offset standards for soil carbon projects in Australian grazing lands. *Carbon Management*. 2024;15(1):2298725. doi:10.1080/17583004.2023.2298725.
44. Rapisarda P, Parisi P, Mazzamuto F. An operative model for regional interventions supporting the citrus sector in Sicily. *Quality-Access to Success*. 2015;16(149):165-171.
45. Rehberger E, West PC, Spillane C, McKeown PC. What climate and environmental benefits of regenerative agriculture practices? An evidence review. *Environmental Research Communications*. 2023;5(5):052001. doi:10.1088/2515-7620/acd6dc.
46. Rhodes CJ. The imperative for regenerative agriculture. *Science Progress*. 2017;100(1):80-129. doi:10.3184/003685017X14876775256165.
47. Roberts M, Hawes C, Young M. Environmental management on agricultural land: cost benefit analysis of an integrated cropping system for provision of environmental public goods. *Journal of Environmental Management*. 2023;331:117306.
48. Schreefel L, de Boer IJM, Timler CJ, Groot JCJ, Zwetsloot MJ, Creamer RE, *et al.* How to make regenerative practices work on the farm: a modelling framework. *Agricultural Systems*. 2022;198:103371. doi:10.1016/j.agry.2022.103371.
49. Scuderi A, Cammarata M, Branca F, Timpanaro G. Agricultural production trends towards carbon neutrality in response to the EU 2030 Green Deal: economic and environmental analysis in horticulture. *Agricultural Economics-Czech*. 2021;67(11):435-444. doi:10.17221/145/2021-AGRICECON.
50. Scuderi A, Cammarata M, La Via G, Pecorino B, Timpanaro G. Life-cycle assessment of biofortified productions: the case of Selenium Potato. *Applied System Innovation*. 2021;4(1):1. doi:10.3390/asi4010001.
51. Scuderi A, Matarazzo A, La Via G, Cammarata M, Timpanaro G. Multicriteria analysis of investment choices following flood damage: the case study of sustainable citrus farming in Sicily. *Agriculture*. 2022;12(8):1122.
52. Scuderi A, Timpanaro G, Cammarata M. Analysis of global warming potential: organic vs. conventional tomatoes. *Agricultural Economics-Czech*. 2023;69(7):267-275. doi:10.17221/104/2023-AGRICECON.
53. Sinnett A, Behrendt R, Ho C, Malcolm B. The carbon credits and economic return of environmental plantings on a prime lamb property in south eastern Australia. *Land Use Policy*. 2016;52:374-381. doi:10.1016/j.landusepol.2015.12.023.
54. Snorek J, Freidberg S, Smith G. Relationships of regeneration in Great Plains commodity agriculture. *Agriculture and Human Values*. 2024;41(1):1-16. doi:10.1007/s10460-024-10558-3.
55. Soloviev ER, Landua G. Levels of regenerative agriculture. Version 1.0. Terra Genesis International; 2016.
56. Sommerfeld HB. Types, rates and methods of depreciation of farm buildings. *Journal of the American Society of Farm Managers and Rural Appraisers*. 1939;3(1):11-17.
57. Soussana JF, Lutfalla S, Ehrhardt F, Rosenstock T, Lamanna C, Havlík P, *et al.* Matching soil carbon sequestration or reducing agricultural greenhouse gas emissions with the soil carbon '4 per 1000' goal. *Frontiers in Sustainable Food Systems*. 2019;3:7.
58. The World Bank. Carbon Pricing Dashboard [Internet]. Washington, DC: World Bank; 2024. Available from: <https://carbonpricingdashboard.worldbank.org/compliance/price>
59. Timpanaro G, Cammarata M, Urso A. Analysis of trade flows of ornamental citrus fruits and other Rutaceae in the Mediterranean basin and potential for *Xanthomonas citri* introduction. *Agriculture*. 2020;10(11):517.
60. Verain M, Dagevos H, Antonides G. Sustainable food consumption. Product choice or curtailment? *Appetite*. 2015;91:375-384. doi:10.1016/j.appet.2015.04.055.

61. Villat J, Nicholas K. Quantifying soil carbon sequestration from regenerative agricultural practices in crops and vineyards. 2023.
62. Wang Z, Li K. Can environmentally themed music increase consumers' willingness to pay for low-carbon food? A discrete choice experiment method. *Frontiers in Sustainable Food Systems*. 2023;7:1302511. doi:10.3389/fsufs.2023.1302511.
63. Wertz-Kanounnikoff S. Estimating the costs of reducing forest emissions: a review of methods. Bogor, Indonesia: CIFOR; 2008. CIFOR Working Paper No. 42.
64. Xia W, Zeng Y. Consumer's willingness to pay for organic food in the perspective of meta-analysis. *International Conference on Applied Economics (ICOAE)*. 2008:933-943.
65. Yoder L, Ward AS, Dalrymple K, *et al.* An analysis of conservation practice adoption studies in agricultural human-natural systems. *Journal of Environmental Management*. 2019;236:490-498. doi:10.1016/j.jenvman.2019.02.009.
66. Zerres C, Zerres M, Tsorakidis N, Papadoulos S. Break-even analysis. Denmark: BusinessSumUp; 2014. ISBN 978-87-7681-290-4.