Plant Gene and Trait 2026, Vol.17, No.5, 332-351
http://genbreedpublisher.com/index.php/pgt

Feature Review Open Access

# Effects of Training, Pruning, and Crop Load Regulation on Stable-Yield Cultivation of Pear

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Plant Gene and Trait, 2026, Vol.17, No.5 doi: 10.5376/pgt.2026.17.0024
Received: 16 Aug., 2026
Accepted: 19 Sep., 2026
Published: 27 Sep., 2026

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**Preferred citation for this article**:
Lu M.Y., 2026, Effects of training, pruning, and crop load regulation on stable-yield cultivation of pear, Plant Gene and Trait, 17(5): 332-351 (doi: 10.5376/pgt.2026.17.0024)

**Abstract** Stable pear production depends on coordinating vegetative and reproductive growth to maintain a dynamic balance among tree architecture, fruiting wood renewal, crop load, and resource supply. This review examines the roles of tree training, pruning, and crop-load regulation in stable pear production. It summarizes the biological basis of shoot growth, flower bud formation, and alternate bearing; evaluates the effects of different training systems on canopy structure, ventilation and light distribution, fruiting position, and yield formation; and discusses the effects of winter pruning, summer pruning, and pruning intensity on fruiting wood renewal and tree vigor. Particular attention is given to the effects of flower and fruit load on source-sink relationships, nutrient allocation, fruit quality, and return bloom, as well as to the synergistic interactions among tree training, pruning, and crop-load regulation in relation to tree carrying capacity, fruiting wood arrangement, and the balance between vegetative and reproductive growth. Excessive tree vigor, overly severe pruning, and excessive crop load can disrupt the balance between growth and fruiting, whereas appropriate training systems, moderate pruning, timely flower and fruit thinning, and coordinated irrigation and fertilization can improve the canopy light environment, fruit quality, and yield stability while reducing alternate bearing. In the future, pear orchard management should integrate three-dimensional phenotyping, machine vision, intelligent modeling, and precision water and nutrient management, gradually shifting from experience-based practices toward quantitative, dynamic, and precision regulation based on tree vigor, canopy structure, and carrying capacity, thereby providing technical support for long-term stable and efficient pear production.

**Keywords** Pear; Tree training and pruning; Crop-load regulation; Alternate bearing; Stable production

## 1 Introduction

Pear is one of the most important temperate deciduous fruit crops in China and worldwide, playing an important role in fresh fruit supply, the development of specialty fruit industries, and increasing growers' income, while also possessing substantial economic value in both traditional production regions and newly expanding cultivation areas (Kaçal, 2018; Sousa et al., 2022; Dias et al., 2025; Zhang et al., 2026). As perennial woody fruit trees with long production cycles, pear trees exhibit complex interactions between vegetative and reproductive growth. Yield formation is influenced not only by cultivar, tree age, and ecological conditions, but also by tree architecture, shoot composition, flower bud formation, fruit set, and orchard management practices (Sharma et al., 2019; Pio et al., 2023). In commercial production, some pear orchards are prone to canopy overcrowding, excessive shoot growth, outward displacement of fruiting sites, poor flower bud formation, and alternate bearing, resulting in substantial year-to-year fluctuations in both yield and fruit quality. In perennial fruit crops in particular, a high-cropping "on-year" is often followed by a low-cropping "off-year". Such alternation not only reduces production stability and economic returns but also increases the difficulty of orchard management (Jangid et al., 2023). Studies have shown that alternate bearing in pear is closely associated with cyclical imbalances between vegetative and reproductive growth. During high-crop-load years, changes in carbohydrate allocation and hormonal signaling can suppress floral induction for the following season, while tree vigor, water relations, and carbohydrate storage capacity are also associated with susceptibility to alternate bearing (Jupa et al., 2021; Carraro et al., 2026). Therefore, coordinating vegetative and reproductive growth while maintaining appropriate tree vigor, crop load, and stable fruit quality is a major objective of efficient pear orchard management.

Stable production does not simply mean achieving the highest possible yield in a particular year; rather, it emphasizes the coordinated maintenance of long-term tree productivity, annual yield stability, and marketable fruit quality (Pio et al., 2023). When crop load is excessively high, developing fruits become strong competing sinks for assimilates, and large amounts of photosynthates and mineral nutrients are preferentially allocated to fruit development. This can restrict shoot growth, flower bud formation, and the accumulation of tree reserves, thereby increasing the risk of reduced yield and alternate bearing in the following year. Conversely, excessively low crop loads may stimulate vigorous vegetative growth, resulting in excessive shoots and canopy overcrowding, which are likewise unfavorable for establishing a stable fruiting structure. Modern pear orchards therefore increasingly emphasize the efficient use of space, solar radiation, water, labor, and other production inputs, while maintaining an appropriate source-sink balance through suitable tree architecture and crop-load management (Sousa et al., 2022; Dias et al., 2025). Training systems can also affect yield and fruit quality by altering canopy structure, internal light conditions, and the spatial distribution of fruiting wood. For example, in 'Korla Fragrant' pear, canopy thinning improved light interception and yield in high-density orchards, but additional fruit thinning was required to maintain fruit quality, demonstrating a clear synergistic relationship between canopy structural regulation and crop-load management.

Tree training and pruning, together with crop-load regulation, are two key categories of orchard practices for achieving stable pear production. Tree training establishes an appropriate canopy structure by defining tree form, scaffold branch arrangement, and the spatial distribution of branches, thereby improving canopy ventilation, light penetration, and the distribution of fruiting sites. Different training systems can also significantly influence tree vigor, production efficiency, and the severity of alternate bearing. For example, the Tall Spindle system improved productivity and production efficiency in 'Santa Maria' pear, whereas the Bi-axis system provided better vigor control and reduced alternate bearing in 'Rocha' pear (Dias et al., 2025). Pruning regulates shoot number, shoot-type composition, and vigor through techniques such as heading, thinning, renewal pruning, branch bending, and pinching, thereby promoting the establishment and renewal of fruiting branches while improving the canopy light environment. Excessive vegetative growth reduces light penetration into the canopy, fruit yield, and fruit quality, while also increasing pruning costs and labor inputs. Maintaining a compact canopy and effective fruiting wood through pruning and related vigor-control practices is therefore an important basis for stable production (Jupa et al., 2021; Sharma et al., 2026). Crop-load regulation, in contrast, mainly controls the number of fruits per tree or per fruiting branch through flower thinning, fruit thinning, and appropriate fruit retention, thereby promoting more balanced allocation of limited resources between vegetative growth and fruit development. Early fruit thinning can reduce competition among developing fruits, improve the growth and quality of retained fruit, and, to some extent, enhance return bloom in the following year. In recent years, leaf number, leaf area-to-fruit ratio, and canopy structural traits obtained through machine learning and three-dimensional point-cloud techniques have also been used to estimate reasonable crop loads, showing potential to improve individual fruit weight and fruit size without reducing total yield (Zhang et al., 2024; Zhang et al., 2026).

This review examines the roles of tree training, pruning, and crop-load regulation in stable pear production, treating tree architecture, pruning, and crop-load management as an interconnected regulatory system rather than as independent cultural practices. First, the biological basis of stable production is discussed in terms of shoot growth, flower bud formation, and yield formation. The effects of different training systems and pruning practices on canopy structure, fruiting wood, and tree vigor are then summarized, followed by an examination of how flower and fruit load influences nutrient allocation, fruit quality, and subsequent-year fruiting. On this basis, particular attention is given to the synergistic relationships among tree training, pruning, and crop-load regulation, as well as appropriate management strategies for different cultivars, tree ages, and vigor levels. Emerging technologies, including chemical fruit thinning, mechanical blossom thinning, canopy phenotyping, and quantitative estimation of appropriate crop load, are also considered. Overall, this review aims to systematically clarify the management mechanisms underlying stable pear production from the perspective of interactions among tree architecture, vegetative vigor, and reproductive load, and to provide a theoretical basis and practical reference for rational tree training and pruning, precise fruit retention, and integrated orchard management.

## 2 Growth and Fruiting Characteristics of Pear Trees and the Basis for Stable Production

### 2.1 Shoot growth and fruiting habits

Shoot growth in pear trees shows clear seasonal and hierarchical characteristics, and tree architecture is generally composed of extension shoots, vegetative shoots, fruiting shoots, and fruiting branch systems of different ages. Different shoot types perform distinct functions. Extension and vegetative shoots mainly contribute to canopy expansion, leaf area development, and nutrient accumulation, whereas short fruiting shoots, medium fruiting shoots, and some long fruiting shoots are directly involved in flowering and fruiting. Pear cultivars differ markedly in apical dominance, branch architecture, and spur-forming ability; therefore, fruiting habits do not follow a single fixed pattern. Cook and Du Plooy (2004) showed that pear cultivars exhibit a continuum from spur-type and strongly acrotonic architectures to more open tree forms with weaker apical dominance. Fruiting wood renewal also varies among cultivars: some cultivars renew spurs primarily through bourse shoots, whereas others rely more heavily on one-year-old shoots. In tropical pear production systems, reproductive spurs are closely associated with higher yield, while vegetative brindles also serve as important sources of future fruiting wood renewal. Therefore, pruning should preserve productive spurs while avoiding excessive removal of shoots with renewal potential (Pio et al., 2018).

Shoot vigor is an important factor determining whether a branch remains predominantly vegetative or shifts toward reproductive development. Studies on Japanese pear have shown that excessively vigorous long shoots generally form relatively few flower buds, with most buds concentrated near the shoot apex. In contrast, moderately vigorous shoots that cease elongation earlier tend to form more flower buds at multiple nodes (Asami and Ito, 1937). Banno et al. (1985) further reported that pear cultivars with earlier shoot-growth cessation produced significantly more flower buds on extension shoots than cultivars with prolonged vigorous growth. This suggests that continuously vigorous shoot growth directs more assimilates toward vegetative organ development, thereby reducing the potential for flower bud formation. As trees age, insufficient pruning and poor renewal of fruiting wood can also lead to excessive growth in the outer canopy, weakening of interior fruiting branches, and gradual outward displacement of fruiting sites, ultimately reducing the effective fruiting area of the canopy.

In addition to shoot vigor, branch angle and spatial arrangement also influence fruiting capacity. Branch angle can alter apical dominance, leaf light exposure, and source-sink relationships, thereby affecting the composition of fruiting shoots and assimilate transport. Niyaz et al. (2026) found that adjusting branch angle to 80° in ‘Korla Fragrant’ pear increased fruit set, leaf area, chlorophyll levels, and the proportion of medium-sized fruiting spurs, while also improving fruit quality. Therefore, orchard training and pruning should not aim merely to reduce branch number. Instead, branch number, angle, vigor, and renewal rate should be regulated in an integrated manner so that vegetative, fruiting, and renewal shoots remain in appropriate proportions, providing a suitable structural basis for subsequent flower bud formation and crop-load regulation.

### 2.2 Flower bud formation and changes in tree vigor

Flower bud formation in pear is a key biological process determining fruiting potential in the following year. It is not controlled solely by tree vigor, but rather by the combined effects of shoot-growth cessation, tree nutritional status, canopy light conditions, and endogenous hormones. In temperate fruit trees, floral induction generally begins during the summer to autumn of the previous year and is regulated by external factors such as temperature, light, water, and mineral nutrition, as well as by internal factors including hormone levels and tree nutritional status (Carraro et al., 2026). Studies on Japanese pear have shown that flower bud formation on extension shoots begins shortly after shoot growth ceases, and cultivars with earlier shoot-growth cessation generally form more flower buds. At the hormonal level, cultivars with lower flower bud formation tend to have higher levels of IAA and gibberellins in shoot apices during vigorous growth, whereas cultivars with higher flower bud formation show lower gibberellin and ABA levels and higher cytokinin levels in axillary buds (Banno et al., 1985). These findings indicate that moderate suppression of excessive shoot growth can facilitate the transition from vegetative to reproductive development.

Tree nutritional status also plays an important role in flower bud formation, although this relationship cannot be simply explained by the assumption that a higher carbon-to-nitrogen ratio is always beneficial. Banno et al. (1984)

found that, within an appropriate range, increased nitrogen supply promoted both tree growth and flower bud formation in Japanese pear, with nitrogen application during June and July being particularly beneficial. Earlier work by Asami and Ito (1937) also suggested that soluble nitrogen level was more consistently associated with flower bud formation than carbohydrate accumulation alone. At the same time, flower bud development requires adequate stored reserves within shoots. Jaumień (1983) reported that growth-inhibited shoots that formed flower buds accumulated more reducing sugars, starch, nitrogenous compounds, and several mineral elements than continuously vigorous shoots that failed to form flower buds. Jupa et al. (2021) further indicated that limited carbohydrate storage capacity in the scion was associated with greater susceptibility to alternate bearing.

Accordingly, both excessive and insufficient vigor are unfavorable for stable flower bud formation. Under excessive vigor, shoots continue to grow for prolonged periods, vigorous water shoots and competing shoots increase, canopy light penetration declines, and a larger proportion of assimilates continues to be allocated to vegetative expansion. Under weak vigor, leaf area and photosynthetic capacity decline, reducing nutrient accumulation and potentially compromising flower bud quality and subsequent fruit set. Moderate pruning can improve the canopy light environment and reduce ineffective and competing shoots, while appropriate crop-load management can prevent excessive depletion of nutrients by fruit. Therefore, maintaining moderate tree vigor, suitable shoot growth, and sufficient stored reserves is essential for the formation of high-quality flower buds and the maintenance of fruiting potential in the following year.

### 2.3 Yield formation and alternate bearing

Pear yield formation is determined by multiple successive processes, including flower bud number and quality, flowering, fruit set, fruit retention, and individual fruit weight. In essence, yield formation reflects the continuous allocation of resources between vegetative and reproductive growth (Sousa et al., 2022). An appropriate crop load maintains suitable sink strength, allowing the tree to support normal fruit development while retaining sufficient carbohydrates and mineral nutrients for shoot growth, root activity, and flower bud formation for the following year. In contrast, when crop load is excessive, developing fruit act as strong sinks and intensify competition for assimilates and mineral nutrients, resulting in smaller fruit, reduced fruit quality, weaker shoot and trunk growth, and lower flowering potential in the subsequent year (Plavcová et al., 2022).

Alternate bearing is one of the most typical manifestations of annual yield instability in pear, characterized by a high-yielding “on-year” followed by a low-yielding “off-year”. This phenomenon is closely associated with the suppression of floral induction in high-crop-load years (Jangid et al., 2023). In ‘Deveci’ pear, which shows a strong tendency toward alternate bearing, failure to thin fruit during an on-year may result in almost complete absence of flowering in the following season. Mechanistically, alternate bearing is mainly driven by two interacting processes. First, developing fruit create intense competition for carbohydrates and mineral nutrients. Second, hormonal signals produced or regulated by developing fruit may directly suppress floral induction and bud development (Sharma et al., 2019). Tree age, rootstock, environmental stress, and orchard management can further modify these effects, indicating that alternate bearing is not caused by a single factor.

Long-term studies of tree growth further demonstrate that excessive fruiting not only affects current-season fruit quality but can also influence structural growth in the following year. These findings suggest that heavy cropping may adversely affect secondary growth in the following season, potentially through competition for assimilates and changes in stored reserves. Therefore, the key to stable pear production is not to maximize yield in a single year, but to maintain annual crop load within the carrying capacity of the tree. In practice, fruiting shoot number and renewal ratio should be regulated through appropriate pruning, while actual fruit retention should be controlled through flower and fruit thinning. These measures should be dynamically adjusted according to tree age, vigor, water and nutrient conditions, and cultivar susceptibility to alternate bearing (Kaçal, 2018). In recent years, indicators such as leaf number, leaf area-to-fruit ratio, and three-dimensional canopy parameters have also been used to evaluate canopy assimilate supply capacity and appropriate crop load, providing a new technical basis for shifting pear crop-load management from experience-based judgment toward quantitative regulation (Zhang et al., 2024; Zhang et al., 2026).

## 3 Effects of Training Systems on Tree Structure and Fruiting Capacity

### 3.1 Common pear training systems and their structural characteristics

The main objective of pear tree training is to establish a canopy within limited orchard space that has a rational structure, clear hierarchical organization, convenient management, and sustained fruiting capacity. With the increasing use of dwarfing rootstocks, high-density planting, and mechanized orchard management, pear training systems have gradually shifted from traditional large-canopy forms toward simpler, more planar, and narrower canopies. Common training systems currently include the open-center system, central leader system, spindle system, Tall Spindle system, V-shaped system, Bi-axis system, and trellis systems. Different regions adopt different structures according to cultivar characteristics, planting density, and ecological conditions (Zhao et al., 2022; Dias et al., 2025). In European pear production, the central leader remains a common basic training system, whereas high-density orchards increasingly adopt narrow-canopy systems such as Tall Spindle and Bi-axis. In China, central leader, spindle, and modified spindle systems are widely used in northern production regions, whereas Y-shaped, single-arm, double-arm, and horizontal trellis systems are more commonly adopted in some southern regions and in orchards with a higher degree of production intensification.

Different training systems vary markedly in the number of central leaders, orientation of scaffold branches, tree height, canopy thickness, and arrangement of fruiting wood, and therefore differ in canopy development and management requirements. Traditional large-canopy systems usually have strong structural frameworks and long fruiting longevity, but as trees age they are more prone to excessive canopy thickness, interior shading, and reduced management efficiency. Compact and planar systems are more favorable for improving space-use efficiency, reducing tree height, and facilitating mechanized operations, but they impose greater requirements on branch angle management, renewal of fruiting wood, and crop-load control (Zhao et al., 2024). For example, in ‘Wonhwang’ pear, the traditional free-standing upright system retains one vertical central leader and 3-5 primary branches, whereas the planar trellis system develops two permanent main arms forming a Y-shaped structure, with temporary fruiting laterals trained along horizontal wires. This transforms the canopy from a three-dimensional structure into a relatively thin planar fruiting wall (Liu et al., 2024).

Training systems also exert clear effects on shoot composition and canopy volume. In ‘Korla Fragrant’ pear, crown-reduction and heading-back training restricted canopy expansion and increased the proportion of medium-length shoots, whereas thinning-based training increased the proportion of long shoots, total branch length, and canopy volume (Yan et al., 2025). Studies on ‘Zaosu’ pear showed that single-arm and double-arm systems produced more open canopies, lower leaf area indices, and more uniform internal light distribution, whereas central leader trees developed denser canopies with more severe interior shading. Therefore, from the perspective of stable production, an ideal training system should not simply aim to minimize canopy size or branch number. Instead, it should coordinate the relationships among structural support, fruiting space, canopy light environment, and renewal of fruiting wood, while also taking cultivar vigor, rootstock, planting density, and management level into account.

### 3.2 Effects of training systems on canopy ventilation and light distribution

Canopy ventilation and light distribution are important links between tree architecture and photosynthetic productivity. Branch density, canopy thickness, tree height, and branch angle jointly determine the extent to which solar radiation and air penetrate from the canopy exterior toward the interior and lower canopy layers. Pear studies consistently show that light intensity generally declines from the canopy exterior toward the interior and from the upper to the lower canopy, with denser canopies showing larger and more persistent low-light zones. When trees are excessively tall, canopy layers are too thick, or interior branches overlap and cross, outer leaves may intercept a large proportion of incoming radiation, while leaves in the middle and lower canopy remain under prolonged low-light conditions. This reduces net photosynthetic efficiency, weakens fruiting wood, and compromises fruit quality.

Appropriate training systems can improve internal canopy light distribution by controlling canopy thickness, branch number, and spatial arrangement. In high-density ‘Korla Fragrant’ pear orchards, low-light zones were

mainly concentrated in the lower canopy, interior canopy, and inter-tree spaces, while canopy height was one of the major structural factors determining the spatial distribution of light. Structural treatments such as crown reduction, branch thinning, and heading-back improved the light environment at different canopy levels. Crown reduction increased average light interception by approximately 15%, branch thinning increased it by approximately 11%, and heading-back more effectively improved light conditions in the middle and lower canopy layers (Yan et al., 2025; Yan et al., 2026). These findings indicate that canopy optimization should not focus solely on increasing total light interception; improving the uniformity of light distribution among canopy layers and positions is equally important.

Planar training systems show particular advantages in improving the internal canopy light environment. In 'Wonhwang' pear, compared with the traditional free-standing upright system, the planar trellis system increased net photosynthetic rates of leaves within the canopy, particularly in interior regions on the sun-exposed side (Liu et al., 2020; Liu et al., 2024). The pear-specific studies cited above indicate that the benefits of planar canopies depend on improving light distribution within productive canopy zones, not merely increasing total light interception. Therefore, pear orchard training systems should be integrated with annual pruning, with continuous adjustment of branch number, branch angle, and canopy thickness to maintain stable long-term ventilation and light penetration.

### 3.3 Effects of training systems on fruiting distribution and yield formation

Tree architecture influences flower bud formation, fruit set, and fruit development by determining the location of fruiting wood, canopy light conditions, and shoot vigor. Under a well-organized canopy structure, fruiting branches can be distributed relatively evenly across scaffold branches, lateral branches, and fruiting wood, allowing both interior and exterior canopy zones to retain productive capacity. By contrast, when canopies remain overcrowded for prolonged periods, interior fruiting branches gradually weaken or die because of insufficient light, and fruiting sites progressively shift toward the upper and outer canopy. In 'Korla Fragrant' pear, smaller-canopy trees carried fewer fruits but showed a more uniform spatial distribution of fruit, whereas larger canopies intercepted more light and produced higher total yields but concentrated fruiting increasingly in the upper and outer canopy, thereby reducing the uniformity of fruit distribution and quality. The same study further showed that fruit distribution in smaller canopies was mainly governed by structural branch traits, whereas in larger canopies light distribution became a more important determinant.

By altering branch angle and shoot vigor, training systems also regulate the transition from vegetative to reproductive growth. More horizontally oriented branches generally have weaker apical dominance and are more favorable for the formation of medium and short fruiting shoots and flower buds, whereas overly upright branches tend to remain vigorous and may delay fruiting. In 'Korla Fragrant' pear, adjusting branch angle to 80° increased fruit set and the proportion of medium-sized fruiting spurs, while also improving individual fruit weight and the sugar-to-acid balance. This indicates that fruiting capacity is influenced not only by the overall training system but also by the spatial orientation of branches within that system (Niyaz et al., 2026). Therefore, pear training is not merely a matter of shaping tree appearance; more importantly, it regulates branch growth patterns, fruiting wood formation, and resource allocation within the tree.

Different training systems may also show clear trade-offs between yield and fruit quality. In 'Zaosu' pear, single-arm and double-arm systems improved canopy light uniformity, individual fruit quality, soluble solids content, and photosynthetic performance, with the single-arm system achieving relatively high yield per unit area under arid experimental conditions (Zhao et al., 2022; Zhao et al., 2024). In blush pear, a high-density Open Tatura trellis system increased marketable yield, but when planting density was further increased from 2 222 to 4 444 trees $ha^{-1}$, cumulative yield did not continue to increase (McClymont et al., 2021). These findings indicate that increasing planting density or canopy light interception cannot indefinitely improve production efficiency.

Cultivars also respond differently to training systems. In southern Brazil, 'Santa Maria' pear achieved higher yield and production efficiency under the Tall Spindle system, whereas 'Rocha' pear showed better vigor control under the Bi-axis system, with reduced alternate bearing and relatively little negative impact on fruit quality (Dias et al.,

2025). Therefore, from the perspective of long-term stable production, an appropriate training system should maintain sufficient canopy surface area and yield potential while also ensuring uniform internal light distribution, continuous renewal of fruiting wood, and adequate crop-load carrying capacity. Planar, trellised, spindle, and properly managed multi-axis systems all have considerable application potential, but the optimal training system should ultimately be determined according to cultivar, ecological conditions, rootstock, and planting density rather than by pursuing a single "highest-yielding" canopy structure (Yan et al., 2026).

## 4 Effects of Pruning Regulation on Pear Tree Growth and Fruiting

### 4.1 Winter pruning and renewal of fruiting wood

Winter pruning is an important component of annual pear orchard management. It regulates branch number, shoot-type composition, and tree spatial structure through heading, thinning, renewal pruning, and adjustment of fruiting branch systems, thereby helping to restore a relative balance between vegetative and reproductive growth (Jangid et al., 2023). After pear trees enter dormancy, branch distribution, diameter, and relative vigor become easier to assess, allowing pruning to be adjusted according to tree age, vigor, and the previous year's fruiting status. In young trees, winter pruning mainly serves canopy framework development and the control of competing shoots, whereas in full-bearing trees greater emphasis should be placed on fruiting wood renewal, maintenance of canopy openness, and preservation of effective fruiting space over the long term. Quantitative studies of mature pear trees have shown that dormant pruning is directed primarily at one-year-old shoots, especially vigorous upright shoots, with thinning being the dominant pruning operation. This indicates that the main purpose of winter pruning is not to uniformly head back all fruiting shoots, but rather to selectively remove vigorous new growth and adjust the composition of branch populations (Li et al., 2025).

Fruiting wood is the basic structural unit supporting sustained pear production, and its age, quantity, and growth status directly affect flower bud quality and fruiting capacity. Pear cultivars differ markedly in their patterns of fruiting wood renewal. In some cultivars, spurs are renewed mainly through bourse shoots, whereas others rely more strongly on one-year-old shoots; therefore, the choice of shoots to retain or renew during winter pruning should reflect cultivar-specific fruiting habits. In tropical pear production systems, reproductive spurs are closely associated with yield, while vegetative brindles provide important sources for future fruiting wood renewal. Accordingly, relatively moderate pruning is generally recommended to preserve productive spurs while avoiding excessive removal of shoots with renewal potential. Fruiting units that gradually weaken after several consecutive years of bearing can be rejuvenated through moderate renewal pruning, while crossing, overlapping, and unproductive branches can be removed to maintain an appropriate proportion of fruiting wood of different ages.

The effects of winter pruning are also strongly influenced by pruning severity and the initial vigor of the tree. In intensive 'Santa Maria' pear orchards, Harizia et al. (2025) reported that severe (short) winter pruning improved reproductive performance, with fruit set rates of 40.9% under severe pruning and 37.4% under conventional (long) pruning. However, this does not mean that severe pruning is universally superior to light pruning, because winter pruning generally stimulates bud break and vegetative regrowth. Excessive removal of fruiting surface may induce vigorous replacement shoots and ultimately aggravate canopy overcrowding (Ashraf and Ashraf, 2014; Goke et al., 2020). Therefore, winter pruning severity should be dynamically determined according to tree vigor, the age of fruiting wood, and potential crop load in the following season. Excessively light pruning should be avoided because it may retain too many flower buds and fruiting shoots, while excessively severe pruning should also be avoided because of the risk of vigorous regrowth. The ultimate goal is to match the amount of fruiting wood with the carrying capacity of the tree.

### 4.2 Summer pruning and regulation of flower bud formation

Summer pruning is a dynamic canopy-management practice conducted during the growing season and includes bud removal, pinching, removal of water sprouts, branch bending, shoot twisting, and branch positioning. Its primary functions differ from those of winter pruning. During summer, pear trees are undergoing rapid growth of shoots, leaves, and fruit. Timely control of competing and excessively vigorous shoots can reduce competition with developing fruit and flower buds for nutrients while improving light conditions within the canopy and around

fruiting sites (Goke et al., 2020). Modeling studies have shown that summer pruning reduces leaf area index and overall canopy size and may therefore decrease total whole-canopy light interception, but it can improve the light environment in the canopy interior and around fruiting zones (Wang et al., 2022). Thus, the value of summer pruning lies not simply in reducing leaf area, but in improving the light-use efficiency of retained leaves and fruiting sites.

Flower bud formation is closely associated with the cessation of shoot growth, carbohydrate accumulation, and hormonal status. When shoots remain excessively vigorous, a large proportion of assimilates continues to be invested in vegetative expansion, which can suppress flower bud differentiation. Appropriate branch bending and suppression of excessive shoot growth may favor flower bud differentiation, although the direction and magnitude of hormonal responses depend on cultivar and developmental stage (Banno et al., 1985). Pear vigor-control experiments have also shown that summer pruning, root pruning, trunk scoring, and paclobutrazol treatments that reduce excessive vegetative growth can improve flowering performance (Raja et al., 2018).

However, earlier or more severe summer pruning is not necessarily better. Excessive or premature removal of leaves and shoots reduces effective leaf area and assimilate supply and may stimulate secondary shoot growth, potentially compromising flower bud quality for the following year. In some pear cultivars, summer regrowth has also been associated with the loss of terminal flower buds, as reported in ‘Conference’ and ‘Doyenne du Comice’ (Ashraf and Ashraf, 2014; Goke et al., 2020). Separately, an experimental study of premature defoliation showed that leaf removal can release pear bud paradormancy and accelerate out-of-season bud development (Figure 1) (Wei et al., 2022). This defoliation experiment provides a cautionary physiological comparison but does not directly establish that standard summer pruning produces the same response. Therefore, summer pruning should follow the principle of controlling excessive vigor without weakening the tree, with timing and severity adjusted according to tree vigor, canopy density, crop load, and phenological stage.

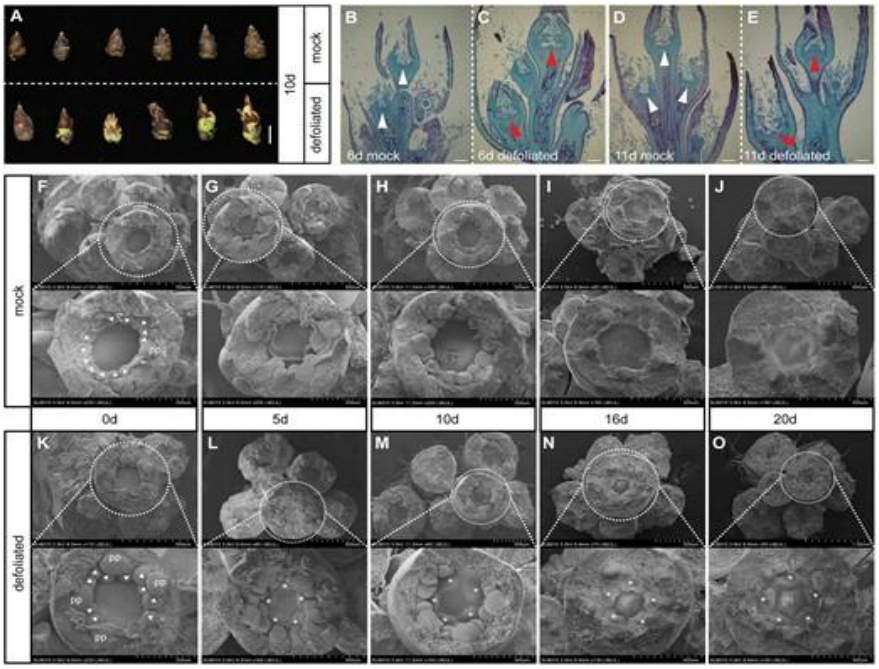



Figure 1 Defoliation accelerated flower bud development (Adopted from Wei et al., 2022)

Image caption: A, Photographs of dormant flower buds from mock control trees (top) and sprouted flower buds in different states from defoliated trees (bottom) at 10 days after defoliation in 2019. B-E, Vertical sections of flower buds collected at 6 days (B, C) and 11 days (D, E) after defoliation from mock control trees and defoliated trees in 2018. Red arrowheads indicate the pistil primordia of buds after defoliation. White arrowheads indicate the center of flower primordia without the pistil primordia of buds in the mock control group. F-O, Scanning electron micrographs of fruit spur flower buds from mock control trees (F-J) and defoliated trees (K-O) at 0, 5, 10, 16, and 20 days after defoliation in 2019. The central floral primordium is labeled with a white dashed line, with magnified images of the petal primordia, stamen primordia, and pistil primordia (bottom). Scale bars, 5 mm (A) and 200 μm (B-E). pp, petal primordium; triangles, stamen primordium; and asterisks, pistil primordium (Adopted from Wei et al., 2022)

### 4.3 Pruning intensity and tree vigor balance

Pruning intensity is a major determinant of how pear trees respond to management, and its effects are clearly nonlinear. In general, severe pruning reduces the number of shoots and buds, allowing the remaining buds to receive more water, nutrients, and assimilates, which stimulates new shoot emergence and growth. Light pruning retains more shoots and buds, thereby distributing tree resources across a greater number of growing points and reducing the vigor of individual shoots. Consequently, excessively light pruning can result in excessive branch density and crop load, whereas excessively severe pruning may induce vigorous water-sprout growth and canopy rebound. Modeling studies in pear orchards in Xinjiang showed that yield initially increased and then declined with increasing summer pruning intensity, with the highest yield occurring at approximately 20% pruning intensity under the modeled conditions (Wang et al., 2022). This indicates that moderate pruning is generally more favorable for tree balance than either extremely light or severe pruning.

Changes in pruning intensity also directly affect leaf area index, transpiration, and water consumption. Wang et al. (2022) found that increasing pruning severity progressively reduced leaf area index, transpiration, and total water use in pear trees. Under arid conditions, this response may help improve fruit water-use efficiency, but excessive pruning can substantially reduce the assimilatory canopy and thereby limit yield formation. Seasonal timing also influences pruning responses. Summer pruning generally induces less regrowth than winter pruning because pruning later in the growing season shortens the period available for vigorous replacement shoots to develop (Ashraf and Ashraf, 2014). In ‘d’Anjou’ pear, increasing summer pruning increased the proportion of large fruit, but tended to reduce total yield and average fruit dry matter content, indicating that larger fruit do not necessarily translate into higher overall production efficiency (Goke et al., 2020).

Pruning timing and pruning severity should also be coordinated. In ‘Le-Conte’ pear, summer pruning in August produced favorable overall results, while removal of approximately one-third of current-season shoot length was particularly effective in increasing the number of fruiting spurs, improving yield, and increasing fruit size (Moatamed, 2012). In excessively vigorous trees where shoot growth cannot be adequately controlled by canopy pruning alone, additional vigor-control measures such as root pruning and trunk girdling can be used to reduce shoot length, internode length, and water-sprout formation while improving fruit quality and return bloom (Sharma et al., 2026). However, these supplementary measures may also involve trade-offs. For example, root pruning alone can reduce fruit size, whereas appropriate irrigation can help mitigate this negative effect (Wang et al., 2014). Therefore, the key to stable production is not to identify a single fixed pruning percentage for all orchards, but to match pruning intensity with tree vigor, crop load, tree age, water and nutrient conditions, and cultivar characteristics.

From a practical management perspective, the ultimate goal of pruning is not simply to reduce canopy size, but to maintain appropriate shoot growth, leaf area, fruiting wood renewal rate, and flower and fruit load. Only when post-pruning tree vigor is neither excessive nor weak, the canopy retains sufficient photosynthetic area, and the amount of fruiting wood is matched to tree carrying capacity can pruning simultaneously support current-season yield, fruit quality, and flower bud formation for the following year, thereby contributing to continuous and stable production.

## 5 Effects of Crop Load Regulation on Yield and Fruit Quality

### 5.1 Flower and fruit load and nutrient allocation within the tree

Flower and fruit load reflects the number of flower buds, young fruits, and mature fruits that a pear tree supports during a given period, and changes in crop load directly affect the distribution of carbohydrates, mineral nutrients, water, and endogenous hormones among different tree organs. Developing fruits are strong sinks during the growing season. When fruit set is high, a greater proportion of photosynthates produced by leaves and nutrients absorbed by roots is allocated to developing fruits, thereby reducing the resources available for shoot growth, root development, reserve accumulation, and flower bud formation for the following year (Smith and Samach, 2013; Zhang et al., 2026). In Nashi pear, appropriate removal of excess flowers and fruits can restore the balance between fruit and shoot growth and improve the allocation of assimilates to retained fruits and vegetative organs,

thereby enhancing fruit size, appearance, and internal quality. Therefore, crop-load management is fundamentally not simply a matter of reducing fruit number, but rather of regulating the source-sink relationship within the tree.

When crop load is excessive, competition among fruits and between fruits, shoots, and roots becomes markedly stronger. As a result, each fruit receives fewer assimilates and mineral nutrients, leading to smaller fruit size, reduced quality, weaker shoot growth, and insufficient reserve accumulation. Conversely, when crop load is too low, more resources may be redirected toward vegetative growth, resulting in excessive shoot vigor, canopy overcrowding, and underutilization of production potential. Recent precision phenotyping studies in pear have likewise shown that excessive crop load reduces fruit size and quality because of intensified competition for assimilates, whereas excessively low crop load can improve individual fruit traits at the expense of total yield. Moderate crop load is therefore more favorable for balancing fruit quality and overall productivity.

Crop-load regulation is also closely related to the nutritional status of the tree. In 'Korla Fragrant' pear, increasing nitrogen input caused both sink capacity and the sink-to-source ratio to first increase and then decline, with a more balanced sink-source relationship and relatively high yield occurring at an intermediate nitrogen level (He et al., 2023). This indicates that fruit load cannot be evaluated independently of tree nutritional status. In addition, changes in crop load influence not only carbohydrate supply but also mineral nutrition and hormonal status. Research in apple also provides comparative evidence that crop load can alter sugar-hormone signaling and return bloom; however, these responses should not be treated as pear-specific experimental results (Kviklys and Samuolienė, 2020). Therefore, from the perspective of stable production, appropriate crop load should be matched to tree age, canopy size, leaf area, number of fruiting branches, and nutrient-supply capacity rather than determined using a single fixed fruit-retention standard.

### 5.2 Flower and fruit thinning for yield regulation

Flower and fruit thinning are the most direct techniques for regulating crop load in pear production. Their main function is to remove excess sinks as early as possible, reduce unnecessary resource consumption, and allow limited assimilates and mineral nutrients to be allocated more efficiently to retained fruits and vegetative growth. Flower thinning is generally conducted during or around bloom to reduce potential fruit set, whereas fruit thinning is carried out after fruit set to further adjust fruit number, position, and spacing. In Nashi pear production, crop-load management may begin as early as winter with pruning of fruiting spurs and reduction of flower bud number, followed by blossom thinning and multiple rounds of hand thinning after flowering. This indicates that the establishment of an appropriate crop load is not a single-stage operation, but a continuous process extending across the pre- and post-fruit-set periods (Bound, 2022).

The effectiveness of flower and fruit thinning is strongly influenced by timing. During the early stages of fruit development, seed development, cell division, and fruit expansion require substantial carbohydrate inputs. Therefore, reducing crop load early can limit unnecessary competition before large amounts of resources have been consumed. Early thinning can improve fruit size by reducing competition among developing fruits, but its effects on return bloom vary among cultivars and treatments. If fruit thinning is delayed too long, the carbohydrates and mineral nutrients already invested in fruits that are subsequently removed cannot be fully recovered, and the benefits for fruit size and flower bud formation in the following season are therefore reduced.

Different thinning methods have distinct advantages and limitations. Hand thinning provides high precision because fruits can be selected according to size, position, and the carrying capacity of individual fruiting branches, but it requires substantial labor. Chemical thinning can be applied over large orchard areas at relatively early developmental stages, but its effectiveness is strongly influenced by cultivar, weather, and chemical treatment conditions. Mechanical blossom thinning offers high operational efficiency and relatively low dependence on weather and is especially suitable for modern orchards with regular canopy structures and good machinery access. In 'Deveci' pear, treatment with 2% KTS reduced crop load and improved fruit quality and was considered a potential alternative to hand thinning. However, neither blossom thinning nor fruit thinning treatments significantly improved return bloom in that experiment, indicating a clear cultivar-specific response to chemical crop-load regulation (Kaçal, 2018). In central leader pear orchards, mechanical blossom thinning reduced fruit set

while increasing average fruit weight and soluble solids content of high-quality fruit without markedly reducing final yield or overall fruit quality, and it also substantially reduced labor inputs (Lei et al., 2021; Lei et al., 2023).

In addition, flower and fruit thinning should also take the spatial distribution of fruit into account. Even when total crop load per tree is not excessive, overconcentration of fruit on a small number of fruiting branches or in the outer canopy can lead to local branch overloading, uneven fruit size, and weakening of fruiting wood. Therefore, fruit retention should be spatially adjusted according to branch diameter, leaf number, fruiting wood age, canopy position, and light exposure so that crop load remains relatively balanced among different fruiting units.

### 5.3 Crop load, fruit quality, and fruiting in the following year

Flower and fruit load generally show a clear negative relationship with pear fruit size and also influence a broader range of marketable quality traits, including soluble solids, sugar content, acidity, firmness, ripening progression, and storability. Under excessive crop load, each fruit receives fewer photosynthates and mineral nutrients, which limits fruit expansion and reduces both size uniformity and internal quality. Studies on European pear have shown that higher crop load is generally associated with smaller fruit. In unthinned ‘Conference’ pear, once crop load exceeded 100 fruits per tree, average fruit weight decreased by approximately 7 g for every additional 10 fruits (Bound, 2021). High crop load may also reduce fruit firmness and sugar content, whereas moderate load reduction generally contributes to improved coloration, internal quality, and storage performance.

Crop-load management also has a marked influence on postharvest quality. In high-russet ‘Conference’ pear, lower crop loads consistently improved fruit size, firmness, acidity, mid-term storability, and commercially desirable fruit russeting, indicating that crop-load regulation is not only a yield-management practice but also an important preharvest quality-management strategy (Guerra et al., 2024). However, lower crop load is not always better. Although very low crop loads may increase individual fruit size, they can also stimulate excessive vegetative growth and reduce total yield per unit area. Therefore, production systems must balance individual fruit quality against total yield.

Return bloom and fruiting potential in the following year represent another major consideration in crop-load management. High crop load consumes large quantities of tree carbohydrates and mineral nutrients and can suppress floral initiation and subsequent flowering through strong sink effects and hormonal signaling, thereby promoting alternate bearing (Smith and Samach, 2013; Bound, 2021). The number of retained fruits and the intensity of competition for tree resources, rather than total harvested yield alone, should therefore be considered when evaluating subsequent flowering. Studies of sugar-hormone interactions in apple have also shown that high crop load can reduce return bloom by altering the balance between sugars and plant hormones (Kviklys and Samuolienė, 2020), providing a useful physiological reference for understanding alternate bearing in pear.

Therefore, crop-load management in pear should simultaneously consider three objectives: current-season yield, fruit quality, and return bloom in the following year, rather than simply maximizing the number of retained fruits in a single season. With the development of precision orchard technologies, mechanistic models, machine vision, and three-dimensional point-cloud methods are increasingly being used to estimate appropriate crop loads for individual trees. The orchard model developed by Sousa et al. (2022) can predict yield, fruit-size distribution, and resource-use performance, while Zhang et al. (2026) used three-dimensional point-cloud data to estimate leaf number and canopy structure in pear trees and adjusted crop load accordingly. This approach increased individual fruit weight, fruit size, and postharvest quality without reducing total yield. These advances suggest that future crop-load management may shift from experience-based fixed fruit-retention targets toward dynamic and precise regulation based on actual canopy carrying capacity (Figure 2).

## 6 Synergistic Effects of Tree Training, Pruning, and Crop Load Regulation

### 6.1 Matching tree structure with appropriate crop load

Stable pear production does not depend on a single training system or a fixed fruit-retention standard, but rather on the degree to which tree structure is matched with crop load. Different training systems vary in canopy volume, total branch length, fruiting area, leaf number, and light distribution, and consequently differ in their actual

carrying capacity. Training systems that increase canopy surface area and total branch volume generally provide greater potential yield, but as the canopy expands, internal light conditions and the spatial distribution of fruit may become increasingly heterogeneous, while fruiting sites tend to shift toward the outer and upper canopy. Therefore, a larger canopy does not necessarily mean that fruit retention can be increased without limit (Yan et al., 2026). In 'Korla Fragrant' pear, canopy expansion achieved primarily through branch thinning markedly increased canopy volume and economic returns, but the proportion of high-quality fruit was lower than that in more compact training systems, indicating a trade-off between increased yield potential and uniform fruit quality (Yan et al., 2025).

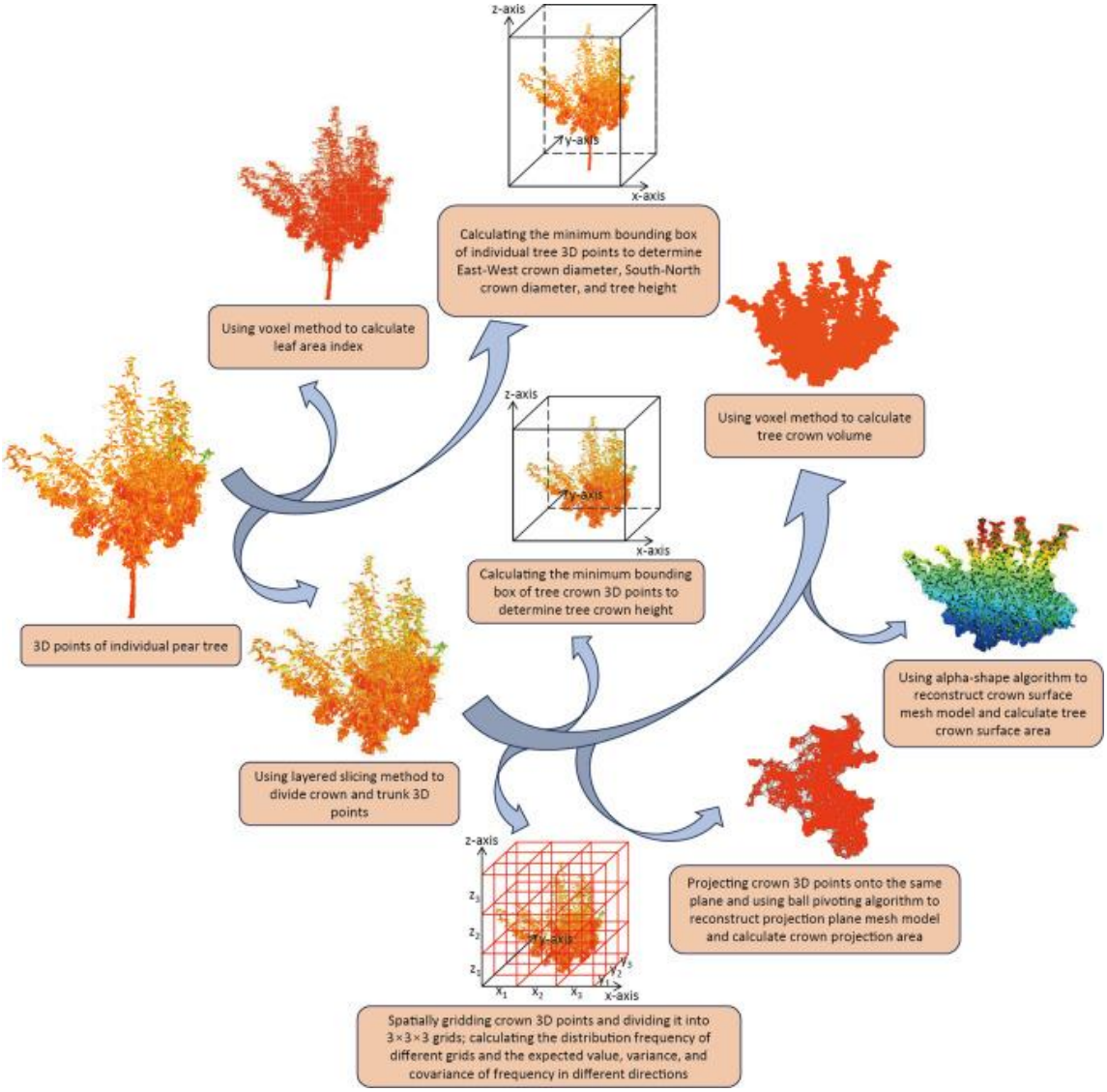



Figure 2 Workflow of pear tree 3D traits extraction (Adopted from Zhang et al., 2026)

Image caption: Tree crown point cloud, leaf area index, East-West crown diameter, South-North crown diameter, and tree height were divided or calculated from individual pear tree. Tree crown height, tree crown volume, tree crown surface area, crown projection area, point cloud distribution frequency, expected value of point cloud distribution frequency, variance of point cloud distribution frequency, and covariance of point cloud distribution frequency were calculated from tree crown 3D points data (Adopted from Zhang et al., 2026)

An important function of tree training and pruning is to establish the spatial and photosynthetic basis for an appropriate crop load by regulating tree height, canopy thickness, fruiting branch number, and branch angle. When the canopy is well ventilated and illuminated, fruiting wood is evenly distributed, and sufficient leaf area is maintained, trees can generally support a higher number of fruits. Conversely, when the canopy is not fully developed, fruiting wood is sparse, light conditions are poor, or tree vigor is weak, fruit retention should not

simply be increased even if a large number of flower buds is present. McClymont et al. (2021) showed that increasing planting density and canopy radiation interception can increase yield per unit area, but cumulative yield does not continue to increase indefinitely as density rises further, indicating that marketable yield remains constrained by tree carrying capacity and fruit size. Therefore, crop-load regulation should be based on an assessment of canopy size and structure rather than on a uniform fruit-retention standard applied across different tree ages, cultivars, and training systems.

In recent years, precision phenotyping technologies have gradually shifted "structure-crop-load matching" from experience-based judgment toward quantitative estimation. Zhang et al. (2026) used three-dimensional structural traits, including canopy leaf number and canopy volume, to estimate reasonable crop load in pear trees and adjusted fruit number accordingly, resulting in increased individual fruit weight and fruit size without reducing total yield. The value of these three-dimensional metrics is that estimates of crop load can be linked to the measured canopy of the pear tree rather than transferred from thresholds established in other fruit crops. Accordingly, young trees should prioritize canopy expansion and framework development while limiting early crop load; full-bearing trees should make full use of effective fruiting space; and weakened trees should proactively reduce crop load and strengthen fruiting wood renewal so that tree structure and reproductive demand remain synchronized over time.

### 6.2 Coordination between fruiting wood and fruit retention

Fruiting wood is the direct structural link between training and pruning and crop-load regulation. Its quantity, age, diameter, spatial position, and light exposure jointly determine where fruits can develop and how much crop load each part of the canopy can support. Pruning first determines the quantity and quality of potential fruiting sites, whereas crop-load regulation subsequently determines how many flowers and fruits are actually retained on those sites. In full-bearing pear trees, dormant pruning adjusts the branch population mainly by removing one-year-old shoots, particularly vigorous upright shoots. Crop-load management is therefore conducted within the fruiting framework established by pruning (Li et al., 2025). If fruiting branches are weak, senescent, or located in poorly illuminated interior canopy zones, their leaf supply and nutrient transport capacity are limited even when they carry many flower buds, and they should therefore not be assigned a high crop load.

Cultivars differ in the way their fruiting wood is renewed, and consequently fruiting wood management and fruit-retention strategies should not follow a completely uniform approach. Some pear cultivars renew fruiting spurs mainly through bourse shoots, whereas others depend more heavily on one-year-old shoots. If pruning disregards cultivar-specific fruiting habits, canopy simplification may inadvertently reduce future fruiting capacity. In tropical pear production systems, reproductive spurs support current-season yield, whereas vegetative brindles provide important sources for future fruiting wood renewal. Therefore, relatively light pruning and appropriate retention of renewal shoots are more favorable for maintaining continuous production. From a practical perspective, fruiting wood should be managed as a dynamic hierarchy of "old wood for renewal, moderately vigorous mature wood for fruiting, and young wood for future development," rather than allowing all fruiting units to carry the same crop load over prolonged periods.

Fruit retention should also be spatially adjusted according to the actual condition of individual fruiting branches. In 'YaLi' pear trained to a cordon system, Sharma et al. (2026) found that root pruning combined with trunk girdling suppressed excessive vegetative growth and increased fruit retention, indicating that controlling shoot vigor can redirect more resources toward retained fruits rather than excessive new shoot growth. Harizia et al. (2025) similarly observed that relatively severe winter pruning in 'Santa Maria' pear increased floral bud initiation, flower abundance, and fruit set, demonstrating that pruning can directly alter subsequent potential crop load and therefore needs to be followed by fruit thinning to regulate actual fruit retention. Yan et al. (2025, 2026) further found that canopy expansion increased flower buds and potential fruiting sites, but stronger fruit thinning was still necessary to maintain fruit quality. Thus, fruiting wood management should not stop at the question of "how many branches to retain," but should also address "how many fruits each fruiting unit should carry."

### 6.3 Balance between vegetative and reproductive growth

The ultimate goal of coordinated tree training, pruning, and crop-load management is to maintain a dynamic balance between vegetative and reproductive growth over multiple years. Pruning directly affects shoot growth by altering branch number, bud distribution, and the canopy light environment, whereas crop-load regulation changes fruit number and sink strength, thereby influencing the allocation of assimilates among branches, leaves, roots, and fruits. Numerous studies have shown that excessive tree vigor reduces light penetration into the canopy, intensifies competition between shoots and reproductive organs, and reduces return bloom and fruit quality, whereas excessive crop load suppresses structural growth, renewal of fruiting wood, and flower bud formation for the following year (Wang et al., 2014; Lordan et al., 2019). Stable production therefore does not mean minimizing vegetative growth as much as possible, but rather maintaining sufficient shoot renewal capacity while preventing excessive vigor.

This balance is inherently dynamic. As trees age and canopies expand, the branch structural traits, leaf area, and light distribution that determine yield also change; consequently, appropriate pruning intensity and crop-load level must be adjusted accordingly (Plavcová et al., 2022; Yan et al., 2025). If pruning is too severe while crop load is too low, the remaining buds receive abundant resources, often stimulating vigorous shoot growth and directing more assimilates toward canopy expansion. Conversely, if pruning is too light and crop load is too high, a large proportion of resources is redirected toward fruit, resulting in insufficient shoot growth, delayed fruiting wood renewal, and reduced reserve accumulation. A mechanistic modeling study by Bevacqua et al. (2021) showed that, in perennial fruit trees, combinations of branch pruning and fruit thinning often provide a better compromise among current-season yield, fruit size, and shoot growth in the following year than either practice alone. This indicates that long-term stable production depends on balancing multiple objectives rather than maximizing any single trait.

Integrated management measures generally provide more stable results than single interventions. Wang et al. (2014) found that root pruning suppressed vegetative growth in pear trees, but when combined with irrigation, it improved fruit yield and fruit size while maintaining the vigor-control effect, indicating that sufficient resource supply to retained fruits is still necessary after growth suppression. Lordan et al. (2019) further reported that, in vigorous pear orchards, combining root pruning with growth-regulating treatments such as paclobutrazol or prohexadione-Ca (ProCa) generally had stronger effects on shoot control, individual fruit weight, yield, and return bloom than root pruning alone. Pear orchard simulations likewise indicate that yield responses to pruning intensity can be nonlinear, reinforcing the importance of matching pruning severity to tree vigor (Wang et al., 2022). Therefore, stable pear production should adopt a dynamic management model in which pruning regulates structure, crop load regulates resource allocation, tree vigor provides feedback, and resource management compensates for changing physiological demands.

Over the long term, indicators such as shoot length, branch diameter, leaf condition, flower bud number, fruit size, and return bloom can be used to assess whether the tree remains within an appropriate balance. When shoots are excessively long and flower bud formation declines, stronger vigor control and a moderate increase in crop load may be appropriate. When shoots are too short, fruiting wood becomes weak, and flowering declines in the following season, crop load should be reduced and renewal strengthened. Only when trees maintain moderate vegetative growth, fruiting wood is continuously renewed, and crop load remains within the structural and physiological carrying capacity of the tree can current-season fruit quality and subsequent-year production potential be simultaneously maintained, thereby reducing alternate-bearing fluctuations and improving long-term production stability.

## 7 Integrated Regulation Strategies for Stable Pear Production

### 7.1 Pruning regulation according to tree age and cultivar

Pear trees differ markedly in growth objectives and fruiting characteristics across developmental stages; therefore, pruning strategies should be dynamically adjusted according to tree age. During the juvenile stage, management should focus on canopy expansion, framework development, and establishment of a well-organized branch system.

Light pruning, branch spreading, and wider branch angles are generally appropriate, with particular attention given to controlling competing and excessively vigorous shoots while retaining sufficient leaf area to promote rapid canopy establishment. As trees enter the early fruiting stage, management should gradually shift from canopy construction toward development of fruiting wood, with the aim of balancing vegetative and reproductive growth. During the full-bearing stage, greater emphasis should be placed on renewal of fruiting wood, control of canopy overcrowding, and maintenance of stable fruiting positions to prevent branch aging and outward displacement of fruiting sites. In senescent trees, renewal pruning, crop-load reduction, and development of new fruiting branches are required to restore a suitable level of vegetative growth. Quantitative analysis of mature pear trees has shown that dormant pruning is concentrated mainly on one-year-old shoots, which account for 78.62% of the number of pruned shoots and 94.90% of total pruned shoot length, with thinning being the dominant operation. This indicates that pruning in mature orchards gradually shifts from canopy shaping during the juvenile phase toward maintenance and renewal of fruiting wood (Li et al., 2025).

Pear cultivars also differ markedly in apical dominance, bud break, shoot-forming ability, spur-renewal patterns, and susceptibility to alternate bearing; therefore, identical pruning systems should not be applied universally. Some cultivars renew fruiting spurs mainly through bourse shoots, whereas others rely more strongly on one-year-old shoots, meaning that the priorities for retaining or removing young shoots should differ among cultivars. In tropical pear production systems, reproductive spurs are important structures for maintaining yield, whereas vegetative brindles contribute to subsequent fruiting wood renewal. Pruning should therefore remain relatively moderate to avoid excessive removal of renewal shoots in the pursuit of canopy simplification (Pio et al., 2018). Long-term responses to training systems and pruning methods also vary among cultivars. For example, ‘Santa Maria’ pear produced relatively high yield and production efficiency under the Tall Spindle system, whereas ‘Rocha’ pear showed better vigor control and reduced alternate bearing under the Bi-axis system. These results indicate that stable production management should emphasize integrated matching among cultivar, training system, and pruning strategy (Dias et al., 2025).

Pruning severity should also be determined in relation to tree age and vigor. Mature trees with excessive vigor and high branch density may benefit from somewhat stronger thinning and vigor control, but severe pruning should not be applied mechanically. Harizia et al. (2025) found that relatively severe winter pruning in intensive ‘Santa Maria’ pear orchards increased flower bud formation, flower abundance, and fruit set, but such responses are better regarded as targeted measures for specific vigor conditions rather than as universal recommendations for all ages and cultivars. Modeling by Wang et al. (2022) likewise showed a clear nonlinear relationship between summer pruning intensity and yield, with both practical management and higher yield concentrated around approximately 20% pruning intensity. Therefore, pear pruning should gradually shift from fixed technical prescriptions toward differentiated management based on tree age, cultivar, and vigor.

### 7.2 Dynamic adjustment of tree vigor and crop load

Tree vigor is an important basis for determining crop-load capacity and pruning intensity, while crop load in turn influences vigor; therefore, the two must be dynamically coordinated. Pear trees with moderate vigor are generally characterized by suitable shoot length, normal leaf function, well-matured branches, and relatively uniform flower bud distribution, allowing them to sustain comparatively stable fruiting levels. When vigor is excessive and crop load is low, more resources are redirected toward shoot growth, which can aggravate canopy overcrowding. Under such conditions, an appropriate crop load should be maintained within the tree’s carrying capacity and fruit-quality requirements to avoid further stimulation of vegetative growth caused by excessively low crop load. In weak trees, by contrast, fruit retention and unproductive branch biomass should be reduced to lower resource consumption and promote recovery. The key to stable production is therefore not a fixed crop load, but a relative balance among canopy size, tree vigor, and fruiting level (Bound, 2021).

Crop load should also be adjusted in stages according to flower abundance, fruit set, canopy size, and annual climatic conditions. Early fruit thinning is particularly important because crop load and fruit size are generally negatively correlated. Retaining large numbers of young fruits that will ultimately be removed later results in

unnecessary consumption of carbohydrates and mineral nutrients during early development (Bound, 2021). Pear-focused studies similarly indicate that target crop load must account for cultivar, tree size, and orchard management rather than use one universal fruit-retention threshold. At the same time, excessive crop load can suppress return bloom through effects on carbon metabolism and hormonal signaling, thereby increasing the risk of alternate bearing (Kviklys and Samuolienė, 2020). Therefore, fruit retention should be adjusted repeatedly according to flowering and fruit set rather than determined once for the entire season.

In excessively vigorous pear orchards, vegetative growth can be further controlled through root pruning, trunk girdling, or growth-regulating treatments, but fruit resource supply must be considered simultaneously after vigor suppression. Lordan et al. (2019) showed that root pruning, paclobutrazol, prohexadione-Ca (ProCa), and combinations of these treatments can improve vigor control in pear trees, although treatment intensity should vary according to the vigor level of the orchard. Wang et al. (2014) further found that root pruning reduced total shoot length by 72% and shoot number by 43%, whereas supplemental irrigation subsequently improved yield and fruit size. This demonstrates that vigor control cannot be separated from the resource requirements of retained fruit. Sharma et al. (2026) similarly reported that root pruning and trunk girdling in 'YaLi' pear reduced vegetative growth, improved the canopy light environment, and increased yield and fruit quality under high-density conditions. Accordingly, regulation of tree vigor and crop load should follow a dynamic cycle of "assessment-adjustment-feedback-readjustment."

### 7.3 Coordination of pruning, crop load, irrigation, and fertilization

Pruning and crop-load regulation determine tree structure and resource demand, whereas irrigation and fertilization directly determine resource supply. These four components therefore interact strongly. After pruning, branch and leaf number and canopy area decline, resulting in changes in transpiration and nutrient demand; as crop load increases, fruit demand for water and mineral nutrients rises substantially. Water and fertilizer management should therefore not be implemented independently of canopy structure and actual crop load, but should be adjusted according to tree vigor, fruit number, and phenological stage. Orchard modeling by Sousa et al. (2022) demonstrated close relationships among crop load, fruit size, yield, and water use, providing a practical basis for incorporating crop-load information into irrigation and fertilization decisions.

The interaction between water management, pruning, and crop load is particularly evident. In a Mediterranean semi-arid pear orchard, an integrated irrigation strategy reduced water use by 15.8% and increased yield per tree, but also reduced vegetative growth, produced smaller fruit, and lowered the soluble solids-to-acidity ratio. The authors therefore concluded that water-saving irrigation should not be implemented independently of fruit thinning and crop-load management (Maletsika et al., 2026). By contrast, in root-pruned pear trees, both full irrigation and deficit irrigation stabilized return bloom and improved fruit yield and fruit size without re-stimulating excessive vegetative growth (Wang et al., 2014). These findings indicate that the effects of either "water control" or "vigor control" vary depending on pruning method and crop-load status. Seasonal pruning should likewise be coordinated with expected water and carbon status. For example, although summer pruning in 'd'Anjou' pear can reduce competition between shoots and fruit and increase the proportion of large fruit, it may also decrease total yield and fruit dry matter content. Thus, summer pruning should not be applied routinely without considering orchard resource status (Goke et al., 2020).

Fertilization management should likewise be matched to crop load and tree vigor. In high-crop-load years, particular attention should be given to ensuring adequate supplies of nitrogen, phosphorus, potassium, and other mineral nutrients required for fruit expansion, flower bud differentiation, and postharvest reserve accumulation. However, excessive nitrogen application may stimulate vigorous shoot growth and aggravate canopy overcrowding. Li et al. (2024) found that appropriate coupling of irrigation and fertilization in arid-region pear orchards promoted root growth, maintained a relatively high leaf area index, increased soluble solids and sugar contents, and reduced titratable acidity and stone cell content. The authors reported that moderate irrigation and fertilization improved the balance of vegetative growth and fruit quality, while response-surface optimization gave estimated input levels of approximately 6 510 $m^3 \cdot ha^{-1}$ irrigation water, 337.5 kg $N \cdot ha^{-1}$ nitrogen, and 262.5 kg

P·ha$^{-1}$ phosphorus. These findings indicate that stable production requires appropriate rather than maximal resource inputs.

Therefore, stable pear production should be based on an integrated system of "structural regulation-crop-load management-water and nutrient supply-production feedback." Pruning determines canopy structure and the number of effective fruiting branches, flower and fruit thinning regulate actual crop load, and irrigation and fertilization provide resources matched to tree vigor, crop load, and developmental stage. Trees carrying high crop loads require sufficient water and nutrient support, but excessive stimulation of vegetative growth should be avoided. In low-crop-load vigorous trees, nitrogen and water inputs should be moderately restricted to prevent further enhancement of vegetative growth. In organic or low-input orchards where chemical thinning options are limited, appropriate crop load can still be maintained through hand thinning, mechanical blossom thinning, and tree-specific management based on yield efficiency (Guerra et al., 2024). Only by integrating these components into an annual management system can current-season yield and fruit quality be balanced with flower bud formation for the following year, thereby supporting long-term stable pear production.

## 8 Summary and Prospects

Tree training, pruning, and crop-load regulation are closely interrelated core practices for achieving stable pear production. Tree training establishes a well-ventilated and well-illuminated canopy with appropriate fruiting positions by regulating tree height, canopy thickness, and branch distribution. Pruning subsequently adjusts branch number, shoot-type composition, and the age structure of fruiting wood to maintain appropriate vigor and effective fruiting space, while crop-load regulation controls flower and fruit number to balance fruit development, shoot growth, flower bud formation, and reserve accumulation. A larger canopy does not necessarily result in higher effective yield, excessively severe pruning may stimulate vigorous regrowth, and excessive crop load can reduce fruit size and quality while suppressing flower bud formation for the following year. Therefore, stable production depends on integrating tree training, pruning, and crop-load regulation into a unified system in which tree architecture defines the available space, pruning regulates fruiting wood, and crop-load management controls source-sink balance, thereby maintaining a relative equilibrium among current-season yield, fruit quality, fruiting wood renewal, and subsequent-year production.

At present, pruning and crop-load management in pear orchards still rely heavily on grower experience, while substantial differences among cultivars, rootstocks, tree ages, planting densities, and ecological conditions make universally applicable pruning and fruit-retention standards difficult to establish. Management decisions are often based mainly on branch number, flower bud abundance, or fruit number per tree, with insufficient consideration of effective leaf area, canopy volume, fruiting branch carrying capacity, tree nutritional status, and annual climatic variation. This can result in local overloading or mismatches between tree vigor and crop load. Alternate bearing remains an important constraint on stable pear production and is associated with source-sink competition, carbohydrate storage, hormonal regulation, rootstock effects, and environmental stress. In addition, hand pruning and fruit thinning are labor-intensive, mechanized operations are constrained by tree architecture, and pruning, crop-load management, irrigation, and fertilization are still insufficiently coordinated in some orchards. These limitations continue to restrict the standardization and large-scale application of stable-production technologies.

Future pear production should move from experience-based management toward quantitative, dynamic, and precision regulation. Three-dimensional phenotyping, machine vision, sensor monitoring, and intelligent algorithms can be used to characterize canopy structure, branch composition, flower and fruit number, and tree vigor, and can further support the estimation of appropriate crop load and pruning targets. Mechanistic models and decision-support systems can integrate crop load, water and nutrient supply, tree vigor, and environmental conditions to enable a dynamic "monitoring-prediction-regulation-feedback" management framework. At the same time, orchard architecture should increasingly shift toward planar, narrow-canopy, and mechanization-friendly systems, combined with mechanical blossom thinning, precision irrigation and fertilization, and non-chemical crop-load regulation to improve management efficiency. On this basis, longer-term research may also place appropriate emphasis on the intrinsic capacity of plant materials to support stable

production. Breeding-related approaches, including high-throughput phenotyping, molecular markers, genome-wide association studies, and rootstock breeding, may help identify germplasm and rootstocks with moderate vigor, improved crop-load adaptability, and greater buffering capacity against environmental variation, thereby providing a more stable biological basis for precision orchard management. Ultimately, an integrated production system coordinating suitable plant material, optimized canopy architecture, and precision orchard management may contribute to more stable pear production.

## Conflict of Interest Disclosure

The author affirms that this research was conducted without any commercial or financial relationships that could be construed as a potential conflict of interest.

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