REVIEW OF APPLE TREE ARCHITECTURE PARAMETERS AND THEIR POTENTIAL APPLICATIONS IN BREEDING THROUGH HIGH-THROUGHPUT PHENOTYPING

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Abstract
This review paper examines the importance of apple tree architecture parameters in breeding programmes, focussing on the roles of canopy volume, tree shape, and fruit-bearing habits in optimising orchard management and breeding efficiency. Canopy volume is a critical indicator of tree growth and productivity, often measured using advanced methods such as LiDAR and UAVs, which provide high-resolution 3D data, especially useful in dense orchards. Tree shape, including branching patterns, angles, and overall structure, plays a key role in optimizing light capture, airflow, space utilization, and tree vigour, which can be efficiently assessed through remote sensing technologies. Early selection of desirable branching traits, such as internode length and branch angle, enables optimisation of tree architecture and improved fruit production in high-density orchards. Fruit-bearing habits, including the timing and position of flowering and fruiting, significantly influence yield regularity and fruit quality and can be analysed using technologies such as photogrammetry, multispectral imaging, and RGB cameras. These tools enable automated identification of key tree characteristics, allowing for better management of tree health, pruning, and fruit-bearing zones. Despite advances in these technologies, further research is needed to better understand the relationship between tree shape, productivity, and longevity, to refine orchard management strategies and improve the efficiency of breeding programmes. This article emphasises the growing role of smart technologies in improving phenotyping and accelerating apple tree breeding processes.
Keywords: *Malus domestica*, phenotyping, tree architecture traits, smart breeding.

Introduction

Apple trees are the most widely cultivated fruit crop species in Europe. In 2017, they comprised 36.6% of the total fruit tree area in the European Union, covering 473,550 hectares (Eurostat, 2017). Similarly, apple trees are the main fruit tree species in Latvia, with an area of 3,508 hectares in 2023 (CSBRL, 2023).

The most significant challenge facing agriculture today is climate change; therefore, specific solutions for various geographic regions are required to reduce environmental impacts while improving crop yield. Breeding innovative, resilient, and robust cultivars offer the ability to reduce environmental impact while promoting sustainable agriculture (Chawade et al., 2019; Naqvi et al., 2022).

More than 100 apple tree breeding programmes are currently underway worldwide, aiming to develop promising apple cultivars (Letschka et al., 2021). For example, the University of Minnesota, one of the most prominent and extensive apple breeding institutions in the United States, currently has 20,000 to 25,000 apple seedlings in different stages of evaluation (Clark & Bedford, 2022). The Latvian apple breeding programme involves more than 5,000 apple seedlings handled and more than 40 unique characteristics phenotyped at various stages by the Institute of Horticulture (Ikase et al., 2022).

Apple breeding is time-consuming and resource-intensive, necessitating ongoing efforts to shorten the breeding cycle and reduce resource investment in trait phenotyping. The goal is to obtain faster and more accurate data to select the most promising hybrids. Consequently, there is a growing interest in the development and implementation of high-throughput field phenotyping tools to improve the efficiency of the breeding process (Chawade et al., 2019; Huang et al., 2020).

Machine learning has advanced rapidly and is now widely used in plant genotyping and phenotyping globally. High-throughput tools enable the collection of large amounts of data on plant genotypes and phenotypes, thus optimising resource investment. Machine learning encompasses a range of computer-based modelling techniques that identify data patterns and facilitate automated decision-making. These machine-learning algorithms are sufficiently robust to process even large-scale datasets (Naqvi et al., 2022). Advances in DNA sequencing have significantly enhanced genotyping efficiency; however, phenotyping has not progressed at the same pace. Automated phenotyping, in particular, has developed gradually over the past three decades, limiting breeders' ability to accurately assess the genetics of quantitative traits, such as crown architecture parameters. Most breeders still rely on traditional phenotyping methods, which involve visual evaluation of traits, often influenced by the breeder's personal experience. This process is labour-intensive, time-consuming, and requires considerable human resources to select the best hybrids from large populations. As a result, the adoption of high-throughput phenotyping techniques is urgently needed. These methods not only accelerate the breeding process, but also conserve resources, provide more objective results, and are applicable year-round, including during winter (Reynolds et al., 2020; Yang et al., 2020). This review article provides a comprehensive summary of research on the potential application of smart technologies in apple tree breeding, with a particular focus on apple tree

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APPLICATIONS IN BREEDING THROUGH HIGH-THROUGHPUT PHENOTYPING

Dāniels Udalovs,
Arta Kronberga

architecture parameters. This paper aims to review the latest research achievements on the current state of the art in the application of smart technologies to apple tree breeding, with an emphasis on the exploration of potential phenotyping parameters that are associated with apple tree architecture.

Materials and Methods
This study used a monographic approach to analyse the architectural traits of apple trees and their possible utility in breeding, with numerous phenotyping techniques used for precise identification. The analysis was based on scientific literature from a range of journals and monographs, drawing from studies conducted in the United States, China, the United Kingdom, Germany, France, the Netherlands, Japan, Australia, Canada, Italy, Spain, and other countries with advanced agricultural research programmes.

Results and Discussion
The architecture of the apple tree is the spatial configuration and structural desing of the components of the tree, including the trunk, branches, canopy, and root system. A comprehensive understanding of these architectural characteristics is necessary not only for effective tree management and yield forecasting but also for breeding programmes aimed at optimising the tree's morphological qualities and functional performance (Jiang et al., 2025). The evaluation of architectural traits of apple trees, such as trunk height, branch number, and branch length, is crucial in breeding programmes because these characteristics influence the structure, light capture, and overall biomass of the tree, which in turn affect its growth and fruit production (Béland & Baldocchi, 2021).

The branching topology of apple trees is a direct reflection of their gene expression and optimal adaptation to environmental factors. Consequently, a detailed and accurate characterisation of apple tree architecture facilitates a deeper understanding of how structural organisation governs functional performance and ecological adaptability (Lau et al., 2018).

Assessment technologies for tree parameters
Unmanned aerial vehicles (UAVs) equipped with cameras and sensors capture high-resolution images and 3D data, which provide detailed insights into tree architecture, height, canopy volume, and vigour (Wu et al., 2020). UAVs are particularly useful for collecting data on tree height, canopy volume, branching patterns, and fruit-bearing zones, thus improving the precision and efficiency of apple breeding programmes (Huang et al., 2020). While UAVs offer high spatial resolution and are capable of covering large areas quickly, they are limited by weather conditions and can be costly (Sangjan & Sankaran, 2021). Furthermore, the data processing involved can be time-consuming, which can pose a challenge in large-scale, real-time breeding applications (Wu et al., 2020).

LiDAR technology (light detection and ranging) is utilised to measure tree height, canopy structure, and volume by emitting laser pulses and analysing their return time (Sinha et al., 2022). This method is particularly advantageous in dense orchards where precise measurements are required, allowing for detailed 3D modelling of tree structures (Sinha et al., 2022). LiDAR is highly accurate and provides valuable data to assess tree height, canopy volume, and overall structure (Huang et al., 2020). However, it is often associated with high costs and requires advanced equipment and software for data processing (Madec et al., 2017).

Satellites are used to capture images that assess large-scale tree health, canopy size, and other architectural parameters in vast areas (Huang et al., 2020). Although they offer global coverage and continuous monitoring, the resolution of satellite imagery is lower compared to UAVs or LiDAR, which can make them less precise for individual tree analysis (Huang et al., 2020). Additionally, the temporal resolution can be limited, meaning that detailed real-time monitoring may not be achievable (Sangjan & Sankaran, 2021). Despite these limitations, satellite technology provides valuable insights for monitoring overall orchard growth trends and offers a broader view of potential changes in tree performance over time (Huang et al., 2020).

Multispectral and hyperspectral imaging capture data at multiple wavelengths to assess vigour, leaf area, tree canopy characteristics, and tree health (Tsoulias et al., 2023). Multispectral and hyperspectral imaging are powerful tools for detecting early signs of stress or disease and for evaluating the tree's overall vigour (Best et al., 2008). However, they tend to be expensive and require specialised equipment, and their data interpretation is often complex. Despite these challenges, these methods are invaluable in selecting traits such as optimal tree vigour and disease resistance in apple breeding programmes (Tsoulias et al., 2023).

Automated ground-based systems, such as autonomous vehicles and robotic platforms, are increasingly used to capture measurements such as tree height, trunk diameter, and leaf area index (Sangjan & Sankaran, 2021). These systems offer high-throughput phenotyping and are cost-effective, particularly when applied to large-scale orchards (Sangjan & Sankaran, 2021). Automated systems are less affected by weather conditions and can provide consistent, high-efficiency phenotyping (Best et al., 2008). However, their effectiveness can be limited by the complexity of the orchard terrain and plant arrangement, which may hinder their application in certain orchard environments. Despite these limitations, automated ground-based systems are valuable for evaluating traits such as tree vigour and structural attributes across many trees (Sangjan & Sankaran, 2021).

Assessment of key tree parameters and traits
Tree height is a significant selection criterion in apple breeding programmes, especially in field settings

Dāniels Udalovs,
Arta Kronberga

REVIEW OF APPLE TREE ARCHITECTURE PARAMETERS AND THEIR POTENTIAL
APPLICATIONS IN BREEDING THROUGH HIGH-THROUGHPUT PHENOTYPING

(Moles et al., 2009), because a plant's ecological strategy is significantly affected by its height. It has a major impact on a species' ability to compete for light resources and is closely related to factors like lifespan and time to maturity. Furthermore, plant height is related to important ecosystem functions, including carbon sequestration capacity (Moles et al., 2009).

Tree height is significantly influenced by both genetic and environmental factors, such as rootstock type, growing conditions (e.g., soil fertility, water availability, temperature), and orchard management practices (Hooijdonk et al., 2011; Xu & Ediger, 2021; Jiang et al., 2025).

The height of trees can serve as an important selection criterion in breeding programmes to evaluate overall tree health (Chang et al., 2020), tree viability (Sestras R. E. & Sestras A. F., 2023), biomass (Gennaro et al., 2020) and yield (Sarron et al., 2018). Breeding programmes for modern intensive orchards aim to develop compact apple trees that reach a height of 2.5 to 3.5 metres within 3 to 4 years (Mukhanin et al., 2006; Zemisov et al., 2021).

Tree height is traditionally measured manually using a long stick or ruler from the ground to the top, which is time-consuming and error-prone, especially when analysing numerous trees (Qiu et al., 2024; Sestras R. E. & Sestras A. F., 2023; Sangjan & Sankaran, 2021). A laser rangefinder can also estimate tree height more accurately. Usually used in forestry, it also works for apple trees. This method is faster and less difficult than using a tape measure, but it needs a clear view of the tree's apex (Larjavaara & Muller-Landau, 2013). As a result, tree height is rarely monitored directly in breeding programmes, but rather as part of overall growth vigour.

Tree height, an important trait in apple breeding, can be accurately measured using high-throughput technologies such as UAVs, satellites, and LiDAR, with methods such as LiDAR-based systems showing strong correlations to manual measurements (Madec et al., 2017; Huang et al., 2020).

Tree vigour is a genetically regulated trait influenced also by environmental conditions, rootstock, scion genotype, and orchard management practices. It refers to the ability of the tree to absorb, store and use carbohydrates for growth, leading to rapid shoot development and large canopies (Rebolledo et al., 2015). Vigour is a complex characterized by shoot elongation, leaf size, tree height, and trunk diameter, and it affects the overall growth capacity of the tree, the development of the root system, and fruit production (Hooijdonk et al., 2011; Hugalde et al., 2019). High vigour is associated with fast growth and large canopies, while lower vigour may lead to more controlled growth (Rebolledo et al., 2015).

The primary objective of modern breeding is to achieve balanced and indeterminate tree vigour, preventing excessive and uncontrolled vegetative growth (Blažek & Kelinová, 2013). According to the ECPGR (Lateur et al., 2022), it can be assessed and classified into five categories: extremely weak, weak, indeterminate, vigorous, and extremely vigorous. Vigour can be evaluated within a single year by examining the height and spread of trees older than five years, with accurate comparisons requiring the use of reference cultivars planted in the same location and grafted onto the same rootstock (Lateur et al., 2022). Tree vigour can also be assessed by measuring both height and trunk diameter, with trunk diameters recorded at 20 cm above the graft union. The trunk cross-sectional area (TCSA) is then calculated to assess the tree's growth vigour (Milošević et al., 2023). Vigour can also be classified into three categories weak, medium, and strong (Sestras R. E. & Sestras A. F., 2023). Although this method is less time-consuming and requires less effort, it is less accurate. Therefore, the use of remote sensing technologies would be a more reliable approach (Best et al., 2008). Growth vigour, a key trait in apple tree breeding, can be assessed using multispectral, hyperspectral imaging, LiDAR, and UAVs to monitor variations in tree growth, although further research is needed to optimise these technologies for large-scale breeding programmes and commercial orchards (Scalisi et al., 2021; Tsoulias et al., 2023; Jiang et al., 2025).

Canopy volume refers to the three-dimensional space occupied by the branches and leaves of an apple tree, including the entire live canopy from the base of the crown to the highest point and from the centre of the crown to the furthest tips while excluding dead branches. It is a key parameter for evaluating the growth, structure, and overall health of the tree (Usha & Singh, 2013). A larger, well-formed canopy typically reflects a healthy and vigorous tree capable of efficiently capturing energy and allocating nutrients (Wright et al., 2006).

In breeding programmes, canopy volume is an important metric used to assess tree growth and productivity, as it provides insights into how efficiently a tree captures sunlight for photosynthesis (Usha & Singh, 2013). Canopy volume can be measured manually, but accurate determination of canopy size can be challenging and labour-intensive due to complex growth patterns and irregular tree shapes. Traditionally, canopy volume is estimated by measuring a crown diameter and canopy height, assuming a simplified 3D crown shape. However, because the crown shape and branch positioning vary, calculating the precise volume can be difficult. One such method, proposed by (Wright et al., 2004), calculates the canopy volume (V) using the formula $V = (1/3) \pi r^2 h$, where h represents the canopy height and r is the average radius of the base, assuming that the surrounding trees are straight. These methods are commonly used to evaluate crown compactness and overall tree vigour in apple tree breeding (Dubrasich et al., 1997; Best et al., 2008; Zemisov et al., 2021).

The volume of the canopy can be accurately measured using LiDAR and UAV technologies to create 3D models although more research is needed to explore its impact on long-term fruit yield, quality, and tree longevity (Huang et al., 2020; Sinha et al., 2022; Paudel et al., 2023).

REVIEW OF APPLE TREE ARCHITECTURE PARAMETERS AND THEIR POTENTIAL
APPLICATIONS IN BREEDING THROUGH HIGH-THROUGHPUT PHENOTYPING

Dāniels Udalovs,
Arta Kronberga

The global shape of the tree refers to the overall form or outline of the entire tree, encompassing not only the crown but also the trunk and branches. It represents the tree's growth pattern and is influenced by factors such as genetics, pruning practices, and environmental conditions (Othman et al., 2015; Zhang et al., 2016). In addition to the overall shape of the tree, branch patterns and angles are crucial structural features that affect the canopy architecture of trees (Johansen et al., 2018). A well-structured shape influences the volume, compactness, and symmetry of the tree canopy, improving light penetration and air circulation within the canopy while reducing the risk of diseases by preventing overcrowding of the branches (Zhang et al., 2016; Lordan et al., 2018; Wang et al., 2023). The vigour of a tree's growth can also influence its shape. Trees with excessive vigour may develop irregular or overly dense shapes, which can be corrected through pruning (Sestras R. E. & Sestras A. F., 2023).

The length of the internodes and the angle of the layer relative to the shoot are heritable traits closely linked to the future canopy architecture of apple seedlings. These traits can be effectively assessed in the first year of growth in apple hybrids. An obtuse angle relative to the shoot is characteristic of weeping apple trees, while short internodes are indicative of columnar forms or compact trees. By evaluating these traits, it is possible to select up to 90% of hybrids with the desired canopy architecture from hybrid families already in the first year of seedling growth (Bendokas et al., 2012).

The trunk provides support for branch growth while transporting water and nutrients absorbed by the roots, as well as organic matter made by the leaves to ensure normal growth of fruit trees (Jurjević et al., 2020). The diameter of the trunks of individual trees is an important indicator to help describe the growth status and the development trend of apple trees (Krause et al., 2019).

In breeding programmes, tree shape is a key trait to improve orchard efficiency and maximise production. By selecting parent trees with desirable shapes, such as compact, symmetrical, or pyramidal forms, breeders can develop new cultivars that are easier to manage and harvest (Zhang et al., 2016; Lordan et al., 2018). Furthermore, selecting optimal tree shapes can reduce the need for excessive pruning, contributing to more efficient orchard management (Wang et al., 2023).

The shape of the tree is a critical consideration in the development of new apple cultivars for high-density or modern orchards, where uniformity, compactness, and productivity are essential (Lordan et al., 2018). The shape of the tree before production may differ from its form at harvest time, making it difficult to accurately assess it using traditional methods. However, this variation can be more precisely evaluated using remote sensing technologies, as individually assessing each tree in breeding programmes is often difficult and time-consuming (Sestras R. E. & Sestras A. F., 2023).

The shape of the tree can be classified into two main groups: columnar, characterised by a narrow, upright form with minimal lateral branching, and ramified, which features more extensive branching and a broader, spread-out canopy. Only varieties with a ramified tree type can be more specifically classified and described based on their shape, including upright, upright to spreading, spreading, drooping, and weeping forms (UPOV, 2023). The desired tree shape in apple breeding programmes typically emphasises compact, symmetrical forms for high-density orchards to optimise space, light capture, and fruit production, while also facilitating ease of management and harvesting (Chaploutskyi et al., 2023).

Branching patterns are typically measured early in plant development, often during the first year of hybrid apple tree growth, as these early traits are indicative of the plant's future canopy architecture. By analysing branching patterns and angles, it is possible to make early selections of desirable genotypes for further breeding or more efficient orchard management. In breeding programmes, the desired branching angles for apple trees are selected based on the form of the tree, with narrow angles (closer to vertical) favoured for columnar shapes, wide angles for weeping forms, and moderate angles (typically 45°–60°) for balanced growth and optimal fruit production (Bendokas et al., 2012).

The global shape of the tree, including parameters such as crown width, perimeter and branching patterns, can be precisely measured using UAVs with deep learning algorithms and LiDAR although further research is needed to optimise algorithms and explore the relationship between tree shape and productivity (Johansen et al., 2018; Hadas et al., 2019; Wu et al., 2020; Zhang et al., 2020).

Fruit-bearing habits refer to the pattern of flower and fruit production of the tree over time. This includes the number of flowers or fruits per tree, the distribution of spurs or branches bearing fruit, the timing of fruiting (annual or biennial), and the location of fruiting (in new or older wood). The fruit-bearing habit influences the yield and quality of the fruit and is the key factor in the orchard productivity.

In fruit trees, the relationship between vegetative growth and flowering, and fruiting processes is key to achieving regular fruit production. For apple trees, this relationship is also determined by the specific variety and how fruits are positioned on long shoots, either in lateral or terminal locations, known as the fruiting type (Lauri et al., 1997). Fruit tree cultivars are typically categorised as 'annually bearing' or 'biennially bearing' (Evans, 2017).

Flowering is mainly influenced by physiological factors, especially carbohydrates and hormones. The quality of flower buds depends on their position; terminal buds in fruiting branches are larger and of higher quality due to better nutrient supply and more developed vascular tissues. In contrast, flower buds at the ends of long vegetative growths tend to be of lower quality (Obrucheva, 2014).

Dāniels Udalovs,
Arta Kronberga

REVIEW OF APPLE TREE ARCHITECTURE PARAMETERS AND THEIR POTENTIAL
APPLICATIONS IN BREEDING THROUGH HIGH-THROUGHPUT PHENOTYPING

The primary objective of breeding programmes is to develop apple varieties that exhibit consistent and reliable bearing, ensuring fruit production every season (Laurens et al., 2000). This includes optimising fruit bearing on spurs to maximise fruit production per unit of tree size, while also focussing on cultivars with predictable and high yields, and minimising excessive vegetative growth that could negatively impact fruit production (Sedov, 2014).

Fruit-bearing habits can be evaluated in a single year, ideally on trees that have not been excessively pruned Béland be classified into five types: columnar branches produce fruit only on spurs with few branches. Type I features short, long-lived spurs with a fruit zone close to the trunk and sparse, upright branching. Type II also bears fruit on spurs, but the fruit zone moves slightly outward and the tree spreads with age due to more frequent branching. Type III branches fruit in both spurs and 1 to 3-year-old shoots, spreading outward with frequent branching. Type IV branches primarily fruit at the ends of 1-year-old shoots, with a drooping tendency and fruit mostly at the extremities (Watkins & Smith, 1982; Lateur et al., 2022).

Fruit-bearing habits can be analysed and optimised using high-throughput technologies such as UAVs equipped with multispectral sensors, RGB cameras, and LiDAR to model tree structures, assess canopy density, and identify fruiting zones, improve orchard management (Straub et al., 2022; Mao et al., 2024).

Conclusions

1. Canopy volume, tree shape, and fruit-bearing habits are key traits in apple tree breeding programmes, directly influencing productivity, fruit quality, and orchard management efficiency.

2. Early identification of heritable traits related to branching patterns and canopy structure allows for faster and more accurate selection of desirable hybrids in apple tree breeding programmes.

3. The integration of advanced technologies such as LiDAR, UAVs, and multispectral imaging significantly enhances the precision of phenotyping, improving the accuracy and efficiency of breeding programmes.

4. Automated phenotyping systems and remote sensing technologies streamline the breeding process by reducing manual labour and providing high-resolution real-time data on tree architecture.

5. While high-throughput phenotyping has advanced, challenges such as cost, data complexity, and standardisation remain. More research is needed to enhance these technologies for better breeding applications.

Acknowledgements

References

Béland, M. & Baldocchi, D. D. (2021). Vertical structure heterogeneity in broadleaf forests: Effects on light interception and canopy photosynthesis. *Agricultural and Forest Meteorology*, 307, Article 108525. https://doi.org/10.1016/J.AGRFORMET.2021.108525

Bendokas, V., Gelvonauskiene, D., Siksnianas, T., Staniene, G., Siksnianiene, J. B., Gelvonauskis, B., & Stanys, V. (2012). Morphological traits of phytomers and shoots in the first year of growth as markers for predicting apple tree canopy architecture. *Plant Breeding*, *131*(1), 180–185. https://doi.org/10.1111/J.1439-0523.2011.01902.X

Best, S., Salazar, F., Bastías, R., & Leon, L. (2008). Crop-load estimation model to optimize yield-Quality ratio in apple orchards, Malus Domestic Borkh, var. Royal Gala. *Journal of Information Technology in Agriculture*, 3, 11-18. https://www.researchgate.net/publication/289676267_Crop-load_estimation_model_to_optimize _yield-Quality_ratio_in_apple_orchards_Malus_Domestic_Borkh_var_Royal_Gala

Blažek, J. & Křelinová, J. (2013). Tree vigour and productivity within a set of progenies evaluated during an apple breeding program. *Scientific Papers of Pomology*, 23, 165–178.

Central Statistical Bureau Republic of Latvia (CSBRL). (2024, March 28). *Area of fruit trees and berry plantations, ha - Crops and Time period*. https://data.stat.gov.lv/pxweb/en/OSP_PUB/START__NOZ__LA__LAG/LAG080/

Chang, A., Yeom, J., Jung, J., & Landivar, J. (2020). Comparison of Canopy Shape and Vegetation Indices of Citrus Trees Derived from UAV Multispectral Images for Characterization of Citrus Greening Disease. *Remote Sensing 2020*, *12*(24), 4122. https://doi.org/10.3390/RS12244122

Chaploutskyi, A., Polunina, O., Kucher, I., Chetskyi, B., Borysenko, V., & Zabolotnyi, O. (2023). The growth activity and productivity of apple trees depending on the form of the crown and the time of pruning. *Journal of Horticultural Research*, *2023*(2), 55–62. https://doi.org/10.2478/johr-2023-0027

Chawade, A., van Ham, J., Blomquist, H., Bagge, O., Alexandersson, E., & Ortiz, R. (2019). High-Throughput Field-Phenotyping Tools for Plant Breeding and Precision Agriculture. *Agronomy 2019, 9*(5), 258. https://doi.org/10.3390/AGRONOMY9050258

Clark, M. & Bedford, D. (2022). *Apple breeding at the University of Minnesota*. Minnesota Hardy. https://mnhardy.umn.edu/apples

Dubrasich, M. E., Hann, D. W., & Tappeiner, J. C. (1997). Methods for evaluating crown area profiles of forest stands. *Canadian Journal of Forest Research*, *27*(3), 385–392. https://doi.org/10.1139/X96-206/ASSET/X96-206.FP.PNG_V03

REVIEW OF APPLE TREE ARCHITECTURE PARAMETERS AND THEIR POTENTIAL
APPLICATIONS IN BREEDING THROUGH HIGH-THROUGHPUT PHENOTYPING

Dāniels Udalovs,
Arta Kronberga

Eurostat. (2017). *Agricultural production - orchards.* https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Agricultural_production_-_orchards

Evans, K. M. (2017). *Achieving sustainable cultivation of apples.* London, Burleigh Dodds Science Publishing. https://doi.org/10.4324/9781351114233

Gennaro, S. F. di, Nati, C., Dainelli, R., Pastonchi, L., Berton, A., Toscano, P., & Matese, A. (2020). An Automatic UAV Based Segmentation Approach for Pruning Biomass Estimation in Irregularly Spaced Chestnut Orchards. *Forests 2020, 11*(3), 308. https://doi.org/10.3390/F11030308

Hadas, E., Jozkow, G., Walicka, A., & Borkowski, A. (2019). Apple orchard inventory with a LiDAR equipped unmanned aerial system. *International Journal of Applied Earth Observation and Geoinformation*, 82. https://doi.org/10.1016/J.JAG.2019.101911

Hooijdonk, B., Woolley, D., Warrington, I., & Tustin, S. (2011). Rootstocks Modify Scion Architecture, Endogenous Hormones, and Root Growth of Newly Grafted 'Royal Gala' Apple Trees. *Journal of the American Society for Horticultural Science*, *136*(2), 93–102. https://doi.org/10.21273/JASHS.136.2.93

Huang, Y., Ren, Z., Li, D., & Liu, X. (2020). Phenotypic techniques and applications in fruit trees: A review. In *Plant Methods, 16*(1). https://doi.org/10.1186/s13007-020-00649-7

Hugalde, I. P., Riaz, S., Agüero, C. B., Vila, H., Talquenca, S. G., & Walker, M. A. (2019). Studying Growth and Vigor as Quantitative Traits in Grapevine Populations. *Integrated View of Population Genetics*. https://doi.org/10.5772/INTECHOPEN.82537

Ikase, L., Drudze, I., & Lācis, G. (2022). Current achievements of the Latvian apple breeding programme. *Proceedings of the Latvian Academy of Sciences*, *76*(4), 424–431. https://doi.org/10.2478/prolas-2022-0066

International Union for the Protection of New Varieties of Plants (UPOV). (2023). *Guidelines for the conduct of tests for distinctness, uniformity and stability.* https://www.upov.int

Jiang, L., Li, C., & Fu, L. (2025). Apple tree architectural trait phenotyping with organ-level instance segmentation from point cloud. *Computers and Electronics in Agriculture*, 229, Article 109708. https://doi.org/10.1016/J.COMPAG.2024.109708

Johansen, K., Raharjo, T., McCabe, & M. F. (2018). Using Multi-Spectral UAV Imagery to Extract Tree Crop Structural Properties and Assess Pruning Effects. *Remote Sensing 2018*, *10*(6), Article 854. https://doi.org/10.3390/RS10060854

Jurjević, L., Liang, X., Gašparović, M., & Balenović, I. (2020). Is field-measured tree height as reliable as believed – Part II, A comparison study of tree height estimates from conventional field measurement and low-cost close-range remote sensing in a deciduous forest. *ISPRS Journal of Photogrammetry and Remote Sensing*, 169, 227–241. https://doi.org/10.1016/J.ISPRSJPRS.2020.09.014

Krause, S., Sanders, T. G. M., Mund, J. P., & Greve, K. (2019). UAV-based photogrammetric tree height measurement for intensive forest monitoring. *Remote Sensing*, *11*(7). https://doi.org/10.3390/RS11070758

Larjavaara, M. & Muller-Landau, H. C. (2013). Measuring tree height: A quantitative comparison of two common field methods in a moist tropical forest. *Methods in Ecology and Evolution*, *4*(9), 793–801. https://doi.org/10.1111/2041-210X.12071

Lateur, M., Dapena, E., Szalatnay, D., Gantar, M. E., Guyader, A., Hjalmarsson, I., & Ordidge, M. (2022). *ECPGR Characterization and Evaluation Descriptors for Apple Genetic Resources.* European Cooperative Programme for Plant Genetic Resources. https://www.ecpgr.org/resources/latest-news/news-detail/ecpgr-characterization-and-evaluation-descriptors-for-apple-genetic-resources-published

Lau, A., Bentley, L. P., Martius, C., Shenkin, A., Bartholomeus, H., Raumonen, P., & Herold, M. (2018). Quantifying branch architecture of tropical trees using terrestrial LiDAR and 3D modelling. *Trees - Structure and Function*, *32*(5), 1219–1231. https://doi.org/10.1007/S00468-018-1704-1

Laurens, F., Audergon, J.-M., Claverie, J., Duval, H., Germain, É., Kervella, J., …, & Lespinasse, J.-M. (2000). Integration of architectural types in French programmes of ligneous fruit species genetic improvement. *Fruits*, *55*(2), 141–151. https://revues.cirad.fr/index.php/fruits/article/view/35697

Lauri, P. E., Terouanne, E., & Lespinasse, J. M. (1997). Relationship between the early development of apple fruiting branches and the regularity of bearing - An approach to the strategies of various cultivars. *Journal of Horticultural Science*, *72*(4), 519–530. https://doi.org/10.1080/14620316.1997.11515539

Letschka, T., Öttl, S., & Guerra, W. (2021). Die Züchtung schorfwiderstandsfähiger Apfelsorten. [The breeding of short-resistant apple varieties]. *Obstbau Weinbau-Fachmagazin des Südtiroler Beratungsringes*, *58*(6), 5-9. https://hdl.handle.net/10863/27770

Lordan, J., Francescatto, P., Dominguez, L. I., & Robinson, T. L. (2018). Long-term effects of tree density and tree shape on apple orchard performance, a 20 year study - Part 1, agronomic analysis. *Scientia Horticulturae*, 238, 303–317. https://doi.org/10.1016/J.SCIENTA.2018.04.033

Madec, S., Baret, F., de Solan, B., Thomas, S., Dutartre, D., Jezequel, S., …, & Comar, A. (2017). High-throughput phenotyping of plant height: Comparing unmanned aerial vehicles and ground lidar estimates. *Frontiers in Plant Science*, 8, Article 304033. https://doi.org/10.3389/FPLS.2017.02002/BIBTEX

Dāniels Udalovs,
Arta Kronberga

REVIEW OF APPLE TREE ARCHITECTURE PARAMETERS AND THEIR POTENTIAL
APPLICATIONS IN BREEDING THROUGH HIGH-THROUGHPUT PHENOTYPING

Mao, W., Murengami, B., Jiang, H., Li, R., He, L., & Fu, L. (2024). UAV-Based High-Throughput Phenotyping to Segment Individual Apple Tree Row Based on Geometrical Features of Poles and Colored Point Cloud. *Journal of the ASABE*, *67*(5), 1231–1240. https://doi.org/10.13031/JA.15895

Milošević, T., Milošević, N., & Mladenović, J. (2023). Diversity of plums belonging to *P. domestica* L., *P. insititia* L. and *Prunus × rossica* Erem. Tree vigour, yielding and fruit quality attributes. *Scientia Horticulturae*, 320, Article 112220. https://doi.org/10.1016/J.SCIENTA.2023.112220

Moles, A. T., Warton, D. I., Warman, L., Swenson, N. G., Laffan, S. W., Zanne, A. E., & A., Leishman, M. R. (2009). Global patterns in plant height. *Journal of Ecology*, *97*(5), 923–932. https://doi.org/10.1111/J.1365-2745.2009.01526.X

Mukhanin, V. G., Grigoryeva, L. V., & Mukhanin, V. N. (2006). Results of research of apple production intensification in various types of plantings. *Reports of the Russian Academy of Agricultural Sciences,* 4, 27-30.

Naqvi, R. Z., Siddiqui, H. A., Mahmood, M. A., Najeebullah, S., Ehsan, A., Azhar, M., & Asif, M. (2022). Smart breeding approaches in post-genomics era for developing climate-resilient food crops. *Frontiers in Plant Science*, 13, Article 972164. https://doi.org/10.3389/FPLS.2022.972164/PDF

Obrucheva, N. V. (2014). Hormonal regulation during plant fruit development. *Ontogenez*, *45*(1), 14–27. https://doi.org/10.7868/s0475145014010066

Othman, N., Isa, M. M., Mohamed, N., & Hasan, R. (2015). Street Planting Compositions: The Public and Expert Perspectives. *Procedia - Social and Behavioral Sciences*, 170, 350–358. https://doi.org/10.1016/J.SBSPRO.2015.01.045

Paudel, A., Davidson, J. R., Grimm, C., & Karkee, M. (2023). Vision-based normalized canopy area estimation for variable nitrogen application in apple orchards. *Smart Agricultural Technology*, 5, Article 100309. https://doi.org/10.1016/J.ATECH.2023.100309

Qiu, T., Wang, T., Han, T., Kuehn, K., Cheng, L., Meng, C., & Yu, J. (2024). AppleQSM: Geometry-Based 3D Characterization of Apple Tree Architecture in Orchards. *Plant Phenomics*, 6, Article 0179. https://doi.org/10.34133/PLANTPHENOMICS.0179

Rebolledo, M. C., Dingkuhn, M., Courtois, B., Gibon, Y., Clément-Vidal, A., Cruz, D. F., & Luquet, D. (2015). Phenotypic and genetic dissection of component traits for early vigour in rice using plant growth modelling, sugar content analyses and association mapping. *Journal of Experimental Botany*, *66*(18), 5555–5566. https://doi.org/10.1093/JXB/ERV258

Reynolds, M., Chapman, S., & Crespo-Herrera, L. (2020). Breeder friendly phenotyping. *Plant Science*. 295, 1–21. https://doi.org/10.1016/j.plantsci.2019.110396

Sangjan, W. & Sankaran, S. (2021). Phenotyping architecture traits of tree species using remote sensing techniques. *Transactions of the ASABE*, *64*(5), 1611–1624. https://doi.org/10.13031/TRANS.14419

Sarron, J., Malézieux, É., Sané, C. A. B., & Faye, É. (2018). Mango Yield Mapping at the Orchard Scale Based on Tree Structure and Land Cover Assessed by UAV. *Remote Sensing, 10*(12), Article 1900. https://doi.org/10.3390/RS10121900

Scalisi, A., McClymont, L., Underwood, J., Morton, P., Scheding, S., & Goodwin, I. (2021). Reliability of a commercial platform for estimating flower cluster and fruit number, yield, tree geometry and light interception in apple trees under different rootstocks and row orientations. *Computers and Electronics in Agriculture*, 191, Article 106519. https://doi.org/10.1016/J.COMPAG.2021.106519

Sedov, E. N. (2014). Apple breeding programs and methods, their development and improvement. *Russian Journal of Genetics: Applied Research*, *4*(1), 43–51. https://doi.org/10.1134/S2079059714010092

Sestras, R. E. & Sestras, A. F. (2023). Quantitative Traits of Interest in Apple Breeding and Their Implications for Selection. *Plants*, *12*(4), 903. https://doi.org/10.3390/PLANTS12040903/S1

Sinha, R., Quirós, J. J., Sankaran, S., & Khot, L. R. (2022). High resolution aerial photogrammetry based 3D mapping of fruit crop canopies for precision inputs management. *Information Processing in Agriculture*, *9*(1), 11–23. https://doi.org/10.1016/J.INPA.2021.01.006

Straub, J., Reiser, D., Lüling, N., Stana, A., & Griepentrog, H. W. (2022). Approach for graph-based individual branch modelling of meadow orchard trees with 3D point clouds. *Precision Agriculture, 23*(6), 1967–1982. https://doi.org/10.1007/S11119-022-09964-6/FIGURES/9

Tsoulias, N., Zhao, M., Paraforos, D. S., & Argyropoulos, D. (2023). Hyper- and Multi-spectral Imaging Technologies. *Encyclopedia of Smart Agriculture Technologies*, 1–11. https://doi.org/10.1007/978-3-030-89123-7_65-1

Usha, K. & Singh, B. (2013). Potential applications of remote sensing in horticulture - A review. *Scientia Horticulturae*, 153, 71–83. https://doi.org/10.1016/J.SCIENTA.2013.01.008

Wang, H., Yuan, J., Liu, T., Chen, L., Ban, Z., Duan, L., & Li, J. (2023). Fruit canopy position and harvest period affect watercore development and quality of the 'Fuji' apple cultivar fruit. *Scientia Horticulturae*, 311, Article 111793. https://doi.org/10.1016/J.SCIENTA.2022.111793

Watkins, R. & Smith, R. A. (1982). Descriptor list for Apple (*Malus*). *International Board for Plant Genetic Resources*. https://hdl.handle.net/10568/72794

REVIEW OF APPLE TREE ARCHITECTURE PARAMETERS AND THEIR POTENTIAL
APPLICATIONS IN BREEDING THROUGH HIGH-THROUGHPUT PHENOTYPING

Dāniels Udalovs,
Arta Kronberga

Wright, A. H., Embree, C. G., Nichols, D. S., Prange, R. K., Harrison, P. A., & Delong, J. M. (2006). Fruit mass, colour and yield of 'Honeycrisp'™ apples are influenced by manually-adjusted fruit population and tree form. *Journal of Horticultural Science and Biotechnology*, *81*(3), 397–401. https://doi.org/10.1080/14620316.2006.11512079

Wright, H., Nichols, D., & Embree, C. (2004). Evaluating the accountability of trunk size and canopy volume models for determining apple tree production potential across diverse management regimes. *Acta Horticulture*, 707, 237- 243. https://doi.org/10.17660/ActaHortic.2006.707.30

Wu, J., Yang, G., Yang, H., Zhu, Y., Li, Z., Lei, L., & Zhao, C. (2020). Extracting apple tree crown information from remote imagery using deep learning. *Computers and Electronics in Agriculture*, 174, Article 105504. https://doi.org/10.1016/J.COMPAG.2020.105504

Xu, H. & Ediger, D. (2021). Rootstocks with Different Vigor Influenced Scion–Water Relations and Stress Responses in AmbrosiaTM Apple Trees (*Malus Domestica* var. Ambrosia). *Plants,* *10*(4), 614. https://doi.org/10.3390/PLANTS10040614

Yang, W., Feng, H., Zhang, X., Zhang, J., Doonan, J. H., Batchelor, W. D., & Yan, J. (2020). Crop Phenomics and High-Throughput Phenotyping: Past Decades, Current Challenges, and Future Perspectives. *Mol. Plant.*, *13*(2), 187–214. https://doi.org/10.1016/j.molp.2020.01.008

Zemisov, A. S., Youshkov, A. N., Saveleva, N. N., Grigoreva, L., Borzykh, N., Khlupova, N., & Tarova, Z. N. (2021). Growth features of apple varieties and forms with natural and compact crown types. *Conference Series: Earth and Environmental Science,* 845, Article 012014. https://doi.org/10.1088/1755-1315/845/1/012014

Zhang, C., Jiang, Y., Xu, B., Li, X., Zhu, Y., Lei, L., ..., & Yang, G. (2020). Apple Tree Branch Information Extraction from Terrestrial Laser Scanning and Backpack-LiDAR. *Remote Sensing, 12*(21), Article 3592. https://doi.org/10.3390/RS12213592

Zhang, J., Serra, S., S. Leisso, R., & Musacchi, S. (2016). Effect of light microclimate on the quality of 'd'Anjou' pears in mature open-centre tree architecture. *Biosystems Engineering*, 141, 1–11. https://doi.org/10.1016/J.BIOSYSTEMSENG.2015.11.002