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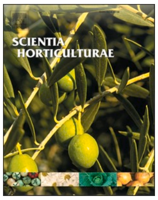

Research Paper

Corymb hierarchy modulates physiological fruit drop and chemical thinning response in apple (*Malus domestica* L. Borkh)

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ABSTRACT

Chemical thinning of apple is often highly variable because of complex interactions among fruit load, tree physiology, climate and thinning intensity. Corymb hierarchy is a key physiological driver of selective abscission, but it has never been quantified and incorporated into predictive models. In this study, we propose a hierarchy index (*Ih*) derived from the size distribution of fruitlets within the corymb and evaluate its ability to explain and predict partial fruit drop across cultivars, geographical areas and thinning strategies.

Using a large, multi-site dataset, linear and logistic models were developed by integrating *Ih* with thinning dosage, cultivar, geographical area and fruit number per corymb. The hierarchy index consistently emerged as a strong predictor of fruit drop, exceeding the effect of thinning dosage alone and remaining robust across genetic and environmental contexts. A significant interaction between *Ih* and dosage indicated that hierarchy-driven differences are most relevant at low to moderate thinning intensities and progressively diminish as thinning strength increases.

Cultivar and geographical area significantly modulated baseline fruit drop levels, while the effect of *Ih* was stable across these factors. Analyses focused on Brevis applications showed that climatic predisposition affected the probability of extreme thinning responses, emphasizing the importance of dosage context and dataset composition.

Overall, the *Ih*-based framework provides a physiologically grounded, parsimonious and transferable approach for predicting apple fruit drop. Its limited data requirements and additive structure make it particularly suitable for integration into decision support systems aimed at improving thinning reliability and reducing the risk of under- or overthinning.

1. Introduction

Crop load regulation through fruit thinning is a central component of apple orchard management, as it directly influences yield, fruit size, quality, and return bloom (Dennis, 2000; Wünsche and Ferguson, 2005; Costa et al., 2018). Excessive fruit set leads to strong competition for assimilates, reduces fruit quality, and increases biennial bearing, and non-optimal thinning may result in yield losses and inefficient orchard performance (Greene and Costa, 2013). For these reasons, chemical thinning remains a widely adopted practice in commercial apple production, particularly during the early stages of fruitlet development, when its efficacy is optimal (Greene, 2002).

Despite decades of research, thinning responses remain highly variable and difficult to predict (Greene, 2002; Lakso et al., 2006; Robinson and Lakso, 2011; Greene et al., 2013). Identical thinning strategies may result in under-thinning, optimal thinning, or over-thinning depending on cultivar, environmental conditions, and tree physiological status (Lordan et al., 2018; Robinson et al., 2024). This uncertainty

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complicates thinning decisions and increases economic risk (Lordan et al., 2019), especially under increasingly variable climatic conditions (Yoder et al., 2009). Improving the predictability of thinning outcomes therefore remains a major challenge for both researchers and practitioners (Greene et al., 2013). Traditionally, thinning efficacy has been described primarily in terms of dose–response relationships, where increasing thinning agent concentration is expected to produce progressively higher fruit drop (Wertheim, 2000; Byers et al., 2003). While dosage is undoubtedly a key driver, numerous studies have shown that dose alone is insufficient to explain observed variability in thinning responses (Robinson and Lakso, 2004; Lakso et al., 2006). Climatic conditions around the time of thinning application, including temperature, radiation, and carbohydrate balance, strongly influence fruitlet abscission (Lakso et al., 2006; Greene, 2010; Gonzalez Nieto et al., 2023). As a result, several decision-support tools integrating climatic variables have been developed to guide thinning strategies and reduce uncertainty (Robinson et al., 2024). However, even when climatic conditions and thinning dosage are carefully considered, substantial unexplained variability in fruit drop often persists (Lakso and Robinson, 2015). This suggests that additional factors intrinsic to the tree may play an important role in modulating thinning responses (Byers, 2003; Greene, 2010). Among these factors, the internal structure of the inflorescence and the relative competitive status of individual fruitlets have received comparatively limited quantitative attention (Bangerth, 2000; Jakopic et al., 2015).

Apple inflorescences (corymbs) typically consist of a central ("king") flower surrounded by several lateral flowers that bloom sequentially and differ in developmental timing (Pratt, 1988; Ferree and Warrington, 2003). These differences translate into variability in fruitlet growth rates and size early after bloom, resulting in size hierarchies within the corymb (Bangerth, 2000). Larger fruitlets generally exhibit greater sink strength and higher survival probability, while smaller fruitlets are more prone to abscission (Bangerth, 1989; Dal Cin et al., 2009; Botton et al., 2011). This phenomenon is widely recognised by growers and frequently invoked to explain selective fruit drop, yet it is not quantified or explicitly integrated into thinning models. Fruitlet size differences are closely linked to competition for carbohydrates and hormonal signals regulating abscission zone activation (Bangerth, 2000; Botton et al., 2011). Fruitlets that establish earlier or grow more rapidly may exert dominance over neighbouring fruitlets, reducing their access to assimilates and increasing their likelihood of abscission (Bangerth, 1989). While this competitive framework is well supported conceptually, its interaction with chemical thinning intensity has not been systematically explored at the corymb level (Greene, 2010).

Chemical thinning agents act by disrupting physiological processes involved in fruitlet retention, including carbohydrate balance, photosynthesis, and hormonal regulation (Untiedt and Blanke, 2001; Byers, 2003; Dorigoni and Lezzer, 2007). As thinning intensity increases, the abscission response may become less selective, affecting fruitlets regardless of their initial competitive status (Greene et al., 2013). This raises a key question: to what extent does chemical thinning override the intrinsic competitive hierarchy among fruitlets, and under which conditions does hierarchy remain an important determinant of fruit drop? (Lakso and Robinson, 2015). Addressing this question requires a quantitative description of fruitlet hierarchy that is robust, comparable across corymbs with different fruitlet numbers, and independent of absolute fruit size. Previous studies have often relied on categorical descriptions (e.g. king vs lateral fruitlets; Botton et al., 2011) or relative size rankings without formalising hierarchy into a continuous metric. As a result, hierarchy is not currently incorporated into any predictive model of fruit drop. In addition, climatic conditions influence both carbohydrate availability and thinning agent efficacy, while cultivar and geographical location introduce further sources of variability (Lakso et al., 2006; Robinson et al., 2024). Without explicitly accounting for these factors, the role of fruitlet hierarchy may be obscured or confounded.

Recent advances in data availability and statistical modelling provide new opportunities to integrate structural, chemical, spectral, and climatic drivers of fruit drop within a unified framework (Robinson et al., 2024; Biegert et al., 2025). Linear modelling approaches applied to large, heterogeneous datasets allow the quantification of interacting effects while controlling for genetic and environmental variability and support the derivation of compact operational indices for decision-making, such as the BreviSmart® prediction tool for the metamitron-based Brevis® thinner (Schmidt, 2025).

In this context, the objectives of the present study were to (i) quantify fruitlet size hierarchy within apple corymbs using a continuous hierarchy index based on physiological evidence, (ii) assess the role of hierarchy as a determinant of fruit drop, (iii) evaluate how hierarchy interacts with thinning intensity under different climatic conditions, and (iv) explore the potential of a hierarchy-based operational index to improve the prediction of thinning response across cultivars, environments, and management scenarios.

2. Materials and methods

2.1. Measurements and dataset structure

The study was conducted using a multi-year (2015–2025), multi-location dataset including a total of 14,130 apple (*Malus domestica* L. Borkh) corymbs measured and monitored across different cultivars (ten), locations (ten, grouped into 7 different geographical areas), climatic conditions (5, available only for Brevis® treatment), and thinning treatments (untreated control – UTC, plus three different chemical thinners: 6-benzyladenine, BA; metamitron, Brevis®; 1-aminocyclopropane carboxylic acid, ACC) (Table 1). The thinners used in this study differ in their physiological mode of action, including cytokinin-mediated effects (BA; Botton et al., 2011), photosynthesis inhibition (Brevis®; McArtney and Obermiller, 2012) and ethylene precursor

Table 1

Composition of the modelling dataset by cultivar, geographical area, thinning treatment, and climatic conditions. Overview of the dataset used for model development, including the number of analysed corymbs for each cultivar, geographical area (number of locations and corymbs), thinning treatment and dosage, and climatic conditions as defined by the BreviSmart class. Asterisk indicates the reference level for each factor. More details can be found in **Supplementary Table 1**.

Cultivars	Geographical areas	Thinning treatment	Climatic conditions[a]
Golden Delicious* (5578) Gala (2690) Braeburn (2560) Joya (1100) Fuji (597) Elstar (518) Pink Lady (427) Envy (300) RedPop (200) Red Delicious (160)	Italy-mountains* (2; 8565) Italy-plain (2; 3054) Germany (1; 1285) France (2; 496) Switzerland (1; 374) Spain (1; 200) Belgium (1; 156)	UTC*, untreated control (3061) 1.1, 1.65, 2.2 Kg/ha (6831) ACC@0.5, 0.88, 1, 1.5, 2 Kg/ha (2984) BA[b] (1254)	0*, high probability of overthinning (624) 1, favourable conditions with very high thinning efficacy (1583) 2, favourable conditions with high thinning efficacy (2235) 3, favourable conditions with good thinning efficacy (1754) 4, unfavaourable conditions with low thinning efficacy (635) BreviSmart prediction not available[a] (7299)

[a] The BreviSmart output was available as an optimized prediction only for Brevis thinner.

[b] Since different commercial formulations were used at different rates, the dosage was omitted from the model.

activity (ACC; Cline and Bakker, 2026). Each observation corresponded to a single corymb, which was labelled and its fruitlets cross diameters measured before the thinning treatment with a Bluetooth® S_Cal EVO Smart digital caliper (Sylvac, Switzerland). Measurements were carried out when central fruitlet diameters ranged approximately between 7 and 25 mm depending on cultivar, optimal time of application of the thinner and meteorological conditions. The number of fruitlets per corymb (*n*) was defined as the number of fruitlets with a measurable diameter greater than zero, as deducted from the number of measurements. To ensure consistency across corymbs with variable fruitlet number, a maximum of six fruitlets per corymb was considered in hierarchy calculations. When more than six fruitlets were present, only the six largest fruitlets were retained. This approach ensured comparability across corymbs while retaining biologically relevant competitive structure. Measurements were carried out mostly on corymbs with a number of fruitlets which was representative of the cultivar and the average situation the orchard.

For each corymb, fruitlets were ranked by size from the largest to the smallest, regardless their position. Fruit drop was assessed at the end of the completion of physiological fruitlet drop (approximately at the end of June) on the labelled corymbs and expressed as the proportion of fruitlets abscised relative to the initial number of fruitlets per corymb as measured before. Corymbs showing 0% (1063) or 100% (4019) fruit drop were excluded from the modelling dataset, as these extreme outcomes represent boundary conditions that do not provide relevant information on the selective abscission processes addressed in this study. These extreme responses are often associated with boundary physiological or experimental conditions that may override the selective abscission processes herein investigated. Examples include corymbs located in poorly illuminated inner canopy positions, which are frequently associated with complete fruit abscission (Buban and Faust, 1982), as well as experimental applications involving unusually high thinning dosages. The analysis therefore focused on partial abscission responses, which better reflect the interaction between fruitlet hierarchy, thinning intensity, and environmental conditions.

2.2. Cultivars and experimental locations

Ten commercial cultivars were used in this study, including not only globally widespread genotypes, but also newly released club varieties (Table 1).

Trials were carried out at eleven European locations, grouped into seven geographical areas based upon both the main pedological characteristics and the agronomical management of the reference territory, as follows: 1, Cesena (Italy-plain); 2, Massa Fiscaglia (Italy-plain); 3, Legnaro (Italy-plain); 4, Borgo Valsugana (Italy-mountains); 5, Laimburg (Italy-mountains); 6, Wädenswil (Switzerland); 7, Sint-Truiden (Belgium); 8, Jork (Germany); 9, La Moriniere (France); 10, Balandran (France); 11, Mollerussa (Spain). Locations are shown in Fig. 1.

Unequal sample sizes among cultivars and regions reflect commercial orchard availability and were accounted for by including cultivar and geographical area as fixed effects in the model. More details on the dataset can be found in **Supplementary Table 1**.

2.3. Thinning treatments

Chemical thinning treatments included different active ingredients and application dosages, expressed as normalised dosage values (kg ha^{-1}), except for 6-benyladenine (BA). For this thinning agent the dosage was omitted from the model due to the known effects caused by the different commercial formulations (Table 1). Treatment type was included as a categorical variable. Untreated controls (UTC) were retained when present, to allow the model to predict fruit drop also under natural conditions, with no chemical thinning.

2.4. Climatic conditions

Climatic conditions around the thinning period were summarised

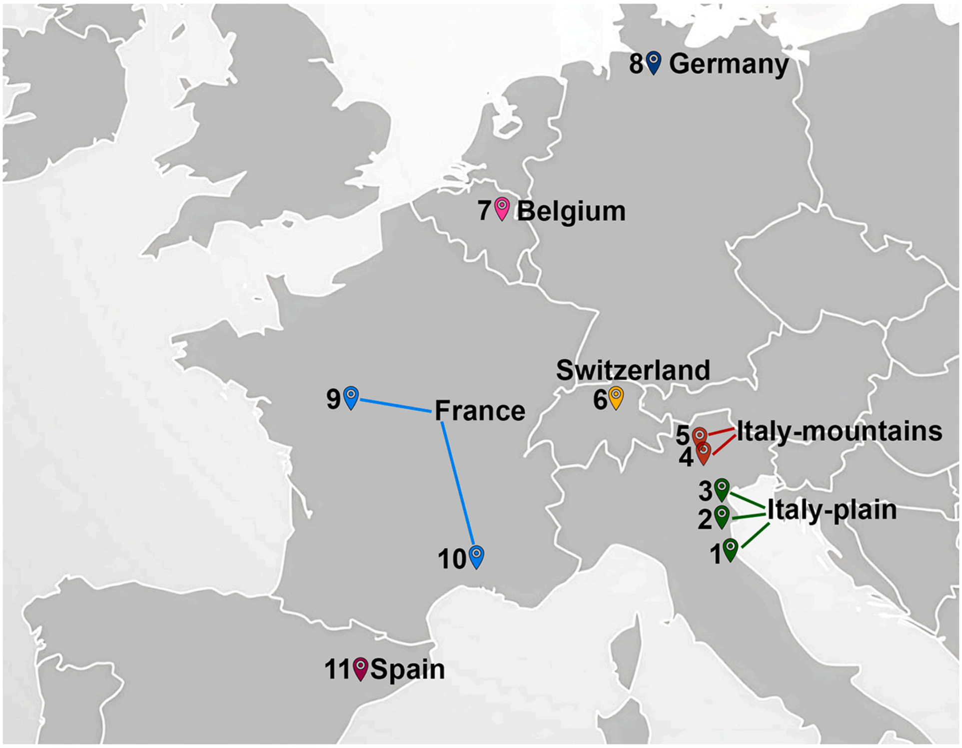

Fig. 1. The eleven locations where data were collected, grouped into the seven geographical areas (GeoArea) used in the model. The locations were: 1, Cesena (Italy-plain); 2, Massa Fiscaglia (Italy-plain); 3, Legnaro (Italy-plain); 4, Borgo Valsugana (Italy-mountains); 5, Laimburg (Italy-mountains); 6, Wädenswil (Switzerland); 7, Sint-Truiden (Belgium); 8, Jork (Germany); 9, La Moriniere (France); 10, Balandran (France); 11, Mollerussa (Spain).

using the BreviSmart® prediction tool by Adama Agan Ltd (Israel; https://shorturl.at/zH4vM), which integrates multiple weather-related variables relevant to thinning response only for the Brevis treatment, taking into account also the mean diameter of central fruitlets and the type of cultivar (i.e. easy-to-thin, medium difficult-to-thin or difficult-to-thin). The index was treated as a categorical factor representing increasing classes of thinning favourability, from 0 to 5, ranging from high probability of overthinning to low thinning efficacy, respectively (Table 1).

2.5. *Calculation of the corymb hierarchy index (Ih)*

Fruitlet hierarchy within each corymb was quantified using a physiology-informed index (*Ih*) designed to capture both (i) dominance between the two largest fruitlets and (ii) size gradients among lateral fruitlets (Botton et al., 2011). Let $F1, \ldots, F7$ be the measured fruitlet diameters for a corymb. Fruitlets with diameter equal to zero were treated as absent and excluded. The remaining diameters were sorted in decreasing order and truncated to the six largest fruitlets, yielding a vector $x = (x_1, \ldots, x_n)$ with $2 \leq n \leq 6$. Diameters were then normalised to the largest fruitlet:

$$d_1 = x_i/x_1 \ (i = 1, \ldots n) \tag{1}$$

so that $d_1 = 1$. Pairwise differences were defined as:

$$D_{i-j} = d_i - d_j \tag{2}$$

Dominance of the largest fruitlet over the second largest was captured by D_{1-2}, with the following stabilisation rules applied to avoid degenerate values:

$$D_{1-2} = \begin{cases} 0.0005 & \text{if } d_1 - d_2 = 0 \\ 0.5000 & \text{if } d_1 - d_2 = 1 \\ d_1 - d_2 & \text{otherwise} \end{cases} \tag{3}$$

A lateral hierarchy component was computed as a weighted sum of successive differences among lateral fruitlets:

$$D_L = 5D_{2-3} + 4D_{3-4} + 3D_{4-5} + 2D_{5-6} \tag{4}$$

where terms involving missing fruitlets (i.e., when $n < 6$) were set to zero. When $D_L = 0$, it was set to 1 to prevent null values. The raw hierarchy index was then defined as:

$$Ih_{raw} = n \cdot (6D_{1-2}) \cdot D_L \cdot \frac{1}{D_{F1,abs}} \tag{5}$$

where $D_{F1,abs} = 1$ is the absolute value of $F1$ diameter, which was used to preserve size (and thus time) dependence in the hierarchy index. When $Ih_{raw} = 0$, a small constant (0.00064) was assigned based upon previous simulations.

The operational hierarchy index used in modelling (Ih_{0-1}) was obtained by min–max scaling across the modelling dataset:

$$Ih_{0-1} = \frac{Ih_{raw} - min(Ih_{raw})}{\max(Ih_{raw}) - \min\,(Ih_{raw})} \tag{6}$$

yielding values in the 0–1 range.

For external application, observations exceeding the original training range may generate extrapolated Ih_{0-1} values. Therefore, the scaling constants $\min(Ih_{raw})$ and $\max(Ih_{raw})$ computed on the modelling dataset should be retained to ensure consistent normalization of new observations.

2.6. *Statistical modelling and other statistics*

Fruit drop was modelled using linear regression. Linear models were fitted using ordinary least squares (OLS) estimation implemented through the lm() framework in R. Alternative approaches for bounded proportion data, including beta regression and generalized linear models, were considered. Although fruit drop is bounded between 0 and 1, ordinary least squares regression was retained because of its interpretability, operational simplicity and satisfactory residual behaviour within the observed response range. The main model included the fruitlet hierarchy index (*Ih*), the number of fruitlets per corymb (*n*), cultivar, geographical area, treatment type, thinning dosage, and their interaction. Fruit drop was treated as a continuous response variable. The interaction between *Ih* and thinning dosage was included a priori to test whether the influence of fruitlet hierarchy varied with thinning intensity. Cultivar and geographical area were included as fixed effects to account for genetic and environmental variability not explicitly captured by other covariates.

Since BreviSmart classes were available only for the Brevis treatment, climatic effects were analysed in a dedicated subset model restricted to Brevis treatment observations. The main model fitted to the full dataset therefore excluded BreviSmart to avoid structural confounding between treatment identity and climatic class. Model assumptions were assessed through inspection of residual distributions and fitted versus observed values. Statistical significance was evaluated at $\alpha = 0.05$.

For categorical predictors, reference levels were defined a priori to represent standard or baseline conditions (‘Golden Delicious’ as reference cultivar, ‘Italy-mountains’ as a reference geographical area, ‘UTC’ for the treatment, class ‘0’ for BreviSmart; see Table 1). Corresponding coefficients therefore represent deviations from these baseline conditions.

Differences in the hierarchy index (*Ih*) among cultivars were evaluated using linear models with cultivar as fixed factor. To account for potential confounding effects, geographical area, thinning treatment, and the number of fruitlets per corymb were included as covariates. Estimated marginal means of *Ih* were computed for each cultivar, and pairwise comparisons among cultivar means were performed using a Sidak-adjusted multiple comparison procedure. Results were summarized using a compact letter display, in which different lowercase letters indicate statistically significant differences among cultivar means ($p < 0.05$). To evaluate the robustness of the modelling framework, a sensitivity analysis including corymbs with 0% and 100% fruit drop was additionally performed and is reported in the Supplementary Materials.

2.7. *‘Brevis-only’ modelling approach*

In addition to the main modelling framework applied to the full dataset, a specific analysis was conducted on the subset of corymbs treated with Brevis®, for which the BreviSmart climatic index was available. BreviSmart is a decision-support indicator integrating multiple climatic variables to classify environmental conditions according to their suitability for chemical thinning with the commercial formulation Brevis®. Since BreviSmart is currently implemented only for Brevis® applications, it was not included in the main model but analysed separately.

Two complementary modelling approaches were adopted to disentangle the effects of climatic conditions on thinning response. First, an ordinary least squares (OLS) regression model was fitted to analyse partial fruit abscission responses, using fruit drop expressed as a continuous proportion. Corymbs showing 0% or 100% fruit drop were excluded from this analysis in order to focus on selective abscission processes and avoid the influence of extreme, potentially stochastic outcomes. The model included the hierarchy index (*Ih*), thinning dosage, their interaction, cultivar, geographic area and the number of fruitlets per corymb (*n*) as fixed effects, with BreviSmart included as a categorical predictor.

Second, to specifically address the occurrence of extreme thinning events that may be specifically associated with Brevis treatments and explicitly capture non-linear drivers of extreme outcomes, a logistic regression model (glm, binomial family) was applied to the unfiltered Brevis dataset, including all levels of fruit drop. Overthinning was defined as fruit drop equal to or greater than 95% and modelled as a binary response variable. The same set of explanatory variables was used, allowing direct comparison between the drivers of partial abscission and those associated with extreme thinning responses.

This dual modelling strategy allowed a separation of the physiological mechanisms governing selective fruitlet abscission from those leading to excessive fruit loss and enabled a more robust interpretation of the role of climatic conditions, thinning dosage and fruitlet hierarchy in shaping thinning outcomes.

2.8. *Cross-validation and model performance assessment*

Robustness and predictive performance of both the main model and the 'Brevis-only' model were evaluated using 10-fold cross-validation. The dataset was randomly partitioned into ten subsets of approximately equal size. In each iteration, the model was fitted on nine subsets and evaluated on the remaining subset.

Predictive performance was quantified using the coefficient of determination (R^2), root mean square error (RMSE), and mean absolute error (MAE), calculated on held-out data. Performance metrics were averaged across folds, and their standard deviations were used as indicators of model stability and sensitivity to data partitioning.

2.9. *Software*

All statistical analyses and graphical outputs were generated using R software v4.5.1 within RStudio version 2026.01.0 + 392 with specific packages for statistics (R Core Team, 2025).

3. Results

3.1. *The index of hierarchy*

The fruitlet hierarchy index (*Ih*) captured a wide range of dominance structures across the analysed corymbs, as illustrated by both its frequency distribution and by schematic representations of typical corymb configurations (Fig. 2**A-B**). The distribution of *Ih* values across the full dataset showed a marked concentration at low-to-intermediate hierarchy levels, with progressively fewer corymbs exhibiting strongly hierarchical structures. Corymbs associated with extreme abscission responses (0% or 100% fruit drop) were distributed across the *Ih* range but tended to cluster toward the lower and upper portions of the hierarchy spectrum, respectively, supporting the interpretation of *Ih* as an integrative descriptor of within-corymb dominance relationships. However, as pointed out above, since these extreme behaviours represent boundary conditions that do not provide useful information for developing a prediction model, the corresponding measurements were discarded from the input dataset. Indeed, the filtered model was retained because it more specifically captures selective abscission processes, while the sensitivity analysis confirmed that the main physiological relationships remained stable when extreme responses were included (**Supplementary Table S2**).

The schematic corymb representations along with some representative real images of apple corymbs (cv Golden Delicious) provide a conceptual framework for interpreting *Ih* values in physiological terms. Low hierarchy corymbs are characterised by relatively uniform fruitlet sizes, indicating weak dominance relationships and a limited capacity for selective abscission. Intermediate hierarchy corymbs display a moderate size gradient, reflecting partial dominance of the largest fruitlet and a competitive balance that favours selective thinning responses. In contrast, highly hierarchical corymbs are dominated by a single large fruitlet, accompanied by sharply reduced sizes of subordinate fruitlets, a configuration typically associated with strong sink competition and enhanced susceptibility of smaller fruitlets to abscission. This interpretation is consistent with the original physiological concept of fruitlet hierarchy proposed by Botton et al. (2011), who first demonstrated that size-based dominance relationships within apple corymbs reflect underlying differences in carbon allocation, hormonal signalling, sink strength, and, consequently, the final destiny of the fruitlets. The present results extend that conceptual framework by quantifying hierarchy through a continuous index and by demonstrating its prevalence and variability across a large, multi-environment dataset. Together, the frequency distribution of *Ih* values and the representative corymb configurations support the use of *Ih* as a biologically meaningful descriptor of within-corymb competitive structure, providing a mechanistic bridge between fruitlet growth patterns and thinning outcomes.

3.2. *Main model performance and overall explanatory power*

Fruit drop showed substantial variability across corymbs, cultivars, treatments, climatic conditions, and geographical areas. The final linear model including the fruitlet hierarchy index (i.e. Ih_{0-1}, herein indicated as *Ih*), the number of fruitlets per corymb (*n*), cultivar, treatment type, thinning dosage, geographical area, and their interaction was highly significant (F-test, $p < 0.001$). The model explained approximately 24% of the observed variability in fruit drop (adjusted $R^2 = 0.240$), with a residual standard error of 0.172 (Table 2).

Model diagnostics indicated no major deviations from linear model assumptions. Residuals were symmetrically distributed and showed no systematic patterns with fitted values. Model performance was consistent across cultivars and environments, supporting the suitability of a unified modelling framework.

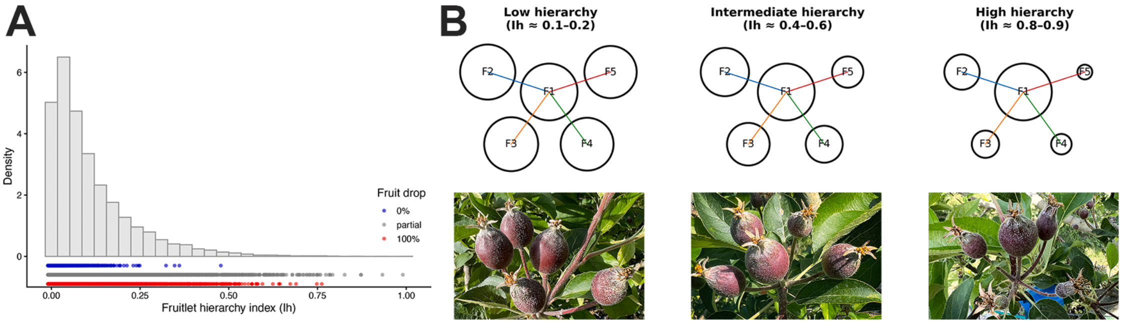

Fig. 2. . A. Distribution of the fruitlet hierarchy index (*Ih*) across the full dataset. The histogram represents the density distribution of Ih values. Individual corymbs are displayed as jittered points below the density distribution and grouped by fruit drop class: 0% (blue), partial (grey), and 100% (red). B. Schematic representation and real pictures (cv Golden Delicious) of "typical corymbs" with three levels of fruitlet hierarchy. Circles represent five fruitlets ranked by size (F1–F5; F1 the largest), and circle diameter is proportional to the normalized fruitlet diameter within each corymb. The three panels illustrate low, intermediate, and high hierarchy configurations, corresponding to increasing dominance of the largest fruitlet and steeper size gradients among the remaining fruitlets.

Table 2

Overall goodness-of-fit statistics of the final linear regression model explaining apple fruit drop using the fruitlet hierarchy index (*Ih*), thinning dosage, their interaction, and contextual covariates.

Metric	Value
Residual standard error	0.1719
Degrees of freedom (residual)	9025
Multiple R^2	0.2421
Adjusted R^2	0.2402
F-statistic (df)	131 (22, 9025)
Model *p*-value	< 0.001

Table 3

Estimated coefficients of continuous predictors included in the final linear model explaining fruit drop. *Ih* represents the min–max scaled fruitlet hierarchy index (0–1). Statistical significance is reported as: $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***). The dot (.) indicates marginal significance ($0.05 \leq p < 0.10$).

Predictor	Symbol	Estimate	*p*-value	Significance
Intercept	β_0	0.315882	< 0.001	***
Fruitlet hierarchy index (*Ih*)	β_1	0.454773	< 0.001	***
Thinning dosage	β_2	0.018664	0.037	*
Ih × Dosage	β_3	−0.035198	0.051	.
Number of fruitlets per corymb (*n*)	β_4	0.037321	< 0.001	***

Table 4

Estimated effects of thinning treatments on fruit drop relative to the untreated control (UTC). Coefficients represent additive deviations after accounting for fruitlet hierarchy (*Ih*), thinning dosage, cultivar, geographical area, and number of fruitlets per corymb. Statistical significance is indicated as $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (**); n.s. indicates non-significant effects.

Treatment	Coefficient	*p*-value	Significance
UTC (reference)	0	–	–
ACC	−0.003072	0.753	n.s.
BA	0.059143	< 0.001	***
Brevis	0.055250	0.00234	**

3.3. Effect of corymb hierarchy and structure on fruit drop

The fruitlet hierarchy index *Ih* had a strong positive effect on fruit drop (estimate = 0.455, $p < 0.001$). Corymbs characterised by high *Ih* values, indicating pronounced dominance of the largest fruitlet and steep size gradients among lateral fruitlets, exhibited substantially higher abscission levels compared with more uniform corymbs (Fig. 3).

The effect of *Ih* remained highly significant after accounting for thinning dosage, climatic conditions, cultivar, geographical area, and fruitlet number per corymb. Among continuous predictors, *Ih* showed the largest effect sizes in the model, highlighting the importance of within-corymb structural competition as a determinant of fruitlet fate (Table 3).

The number of fruitlets per corymb (*n*) had a strong positive effect on fruit drop (estimate = 0.037, $p < 0.001$), consistent with increased competitive pressure and the discrete nature of proportional abscission.

3.4. Treatment effects on fruit drop

In addition to structural and environmental predictors, thinning treatment type exerted a significant influence on fruit drop after accounting for fruitlet hierarchy, thinning dosage, climatic conditions, cultivar, geographical area, and fruitlet number. Among the treatments considered, 6-benzyladenine (BA) showed the strongest positive deviation relative to the untreated control (UTC), indicating that BA applications were associated with increased fruit drop under comparable hierarchical and environmental contexts (Table 4). Brevis also showed a positive effect on fruit drop, though with slightly lower significance ($p \approx 0.0023$), suggesting a tendency toward higher abscission compared to UTC that may depend on interaction with climatic or dosage factors. The lower statistical significance for Brevis may be also because it is a new-generation thinner and the dataset may be partially biased by some ‘unsuccessful’ trials, with application of Brevis either under non-optimal conditions and/or at ineffective dosages.

By contrast, the overall thinning response associated with ACC was not significantly different from the UTC when evaluated against the pooled control conditions of the entire dataset (Table 4). However, this result should be interpreted considering the structure of the dataset and the developmental status of ACC-based thinning strategies. A comparison between ACC treatments and their experiment-specific controls consistently showed positive thinning responses, although the magnitude of the effect varied substantially among trials (data not shown). ACC is still under development as a chemical thinning agent, and the dataset includes experimental applications spanning a wide range of dosages, including a significant proportion of trials carried out at rates that were subsequently identified as suboptimal or ineffective. The inclusion of these non-effective treatments likely contributed to increased variability in thinning responses and to the reduced statistical significance of the overall ACC effect in the aggregated model.

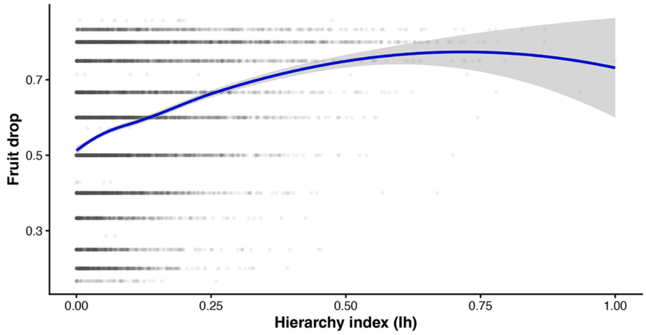

Fig. 3. Relationship between the fruitlet hierarchy index (*Ih*) and fruit drop. Scatterplot showing observed fruit drop as a function of *Ih*, with a locally weighted regression (LOESS) curve and 95% confidence band. Higher *Ih* values, indicating stronger dominance of the largest fruitlet and steeper size gradients among lateral fruitlets, are associated with increased fruit drop.

These results indicate that the apparent weak ACC response observed at the dataset level does not necessarily reflect limited intrinsic thinning potential but rather highlights the strong context dependence of ACC efficacy and the importance of dosage optimisation. Consequently, ACC responses should be interpreted with caution when analysed across heterogeneous experimental conditions, and future datasets incorporating optimised application strategies are expected to better resolve its thinning performance.

3.5. Interaction between corymb hierarchy and dosage

Thinning dosage had a significant positive effect on fruit drop (estimate = 0.019, $p = 0.037$), confirming the expected increase in abscission with increasing thinning intensity. However, the relationship between dosage and fruit drop depended on fruitlet hierarchy (Table 3).

A negative interaction between *Ih* and thinning dosage, although with marginal statistical significance (estimate = −0.035, $p = 0.051$), indicated that the influence of structural dominance decreased as thinning intensity increased. At low thinning dosages, fruit drop was modulated by *Ih*, with highly hierarchical corymbs showing markedly higher abscission than weakly hierarchical ones. At higher thinning dosages, differences among corymbs with contrasting hierarchy levels were reduced, resulting in a more uniform abscission response (Fig. 4). Predicted values slightly exceeding the biological response range

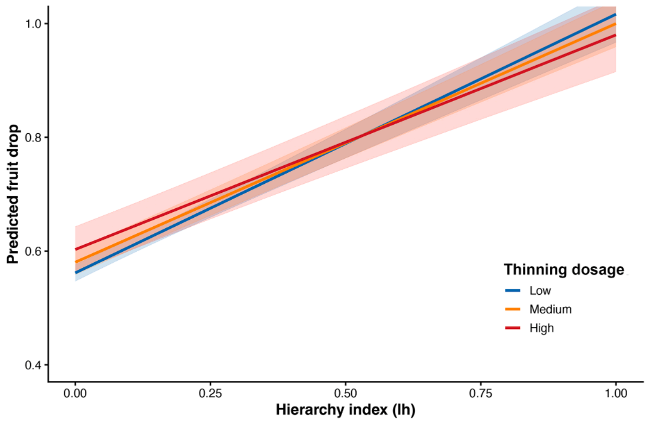

Fig. 4. Interaction between fruitlet hierarchy (*Ih*) and thinning dosage on predicted fruit drop. Model-predicted fruit drop as a function of *Ih* at three representative dosages (low, medium, high). Shaded areas indicate 95% confidence intervals. The negative interaction indicates that the influence of hierarchy decreases as thinning intensity increases.

occurred only under extreme combinations of hierarchy and dosage and were not considered operationally relevant.

3.6. *Effect of cultivar on fruit drop*

The cultivar had a significant effect on fruit drop after accounting for fruitlet hierarchy, thinning dosage, climatic conditions, geographical area, treatment, and fruitlet number per corymb. Several cultivars differed significantly from the reference cultivar, indicating marked genetic variability in baseline abscission propensity.

Estimated cultivar effects ranged from strong negative to positive deviations (Table 5). Cultivars such as ‘Fuji’ and ‘Joya’ showed significantly lower fruit drop relative to the reference, whereas cultivars including ‘Envy’ and ‘Pink Lady’ exhibited higher abscission levels. Other cultivars showed intermediate or non-significant responses.

Importantly, the inclusion of cultivar effects did not alter the magnitude or direction of the main effects of fruitlet hierarchy, thinning dosage, or their interaction. This indicates that the relationship between within-corymb dominance and thinning response was consistent across genetic backgrounds, while cultivar primarily influenced baseline fruit drop levels.

3.7. *Cultivar differences in fruitlet hierarchy*

The hierarchy index (*Ih*) differed significantly among cultivars (adjusted ANOVA, $p < 0.001$), revealing marked cultivar-specific patterns in fruitlet size organization within the corymb (Table 6).

Table 5
Cultivar-specific effects on fruit drop relative to cv Golden Delicious, estimated by the main model after accounting for hierarchy (*Ih*), thinning dosage, treatment, geographical area, fruitlet number per corymb, and the $Ih \times$ dosage interaction. Statistical significance is indicated as $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***). The dot (.) indicates marginal significance ($0.05 \leq p < 0.10$).

Cultivar	Coefficient	*p*-value	Significance
Golden Delicious (reference)	0	–	–
Braeburn	0.059861	< 0.001	***
Elstar	0.024820	0.082	.
Envy	0.122207	< 0.001	***
Fuji	−0.079581	< 0.001	***
Gala	0.065344	< 0.001	***
Joya	−0.090593	< 0.001	***
Pink Lady	0.095236	< 0.001	***
Red Delicious	0.058242	0.00193	**
RedPop	0.091357	< 0.001	***

Table 6
Ranking of apple cultivars according to the mean hierarchy index (*Ih*). Values represent estimated marginal means (± SE) derived from a linear model including cultivar as fixed factor and adjusted for geographical area, thinning treatment, and fruitlet number per corymb. Different lowercase letters indicate statistically significant differences among cultivar means according to a Sidak-adjusted multiple comparison procedure ($p < 0.05$).

Rank	Cultivar	Mean Ih	SE	Group
1	Braeburn	0.1720	0.0046	e
2	RedPop	0.1512	0.0094	de
3	Pink Lady	0.1439	0.0067	d
4	Red Delicious	0.1244	0.0107	cd
5	Gala	0.0968	0.0039	c
6	Envy	0.0764	0.0069	b
7	Golden Delicious	0.0724	0.0038	b
8	Fuji	0.0671	0.0061	b
9	Elstar	0.0653	0.0075	b
10	Joya	0.0338	0.0053	a

Braeburn exhibited the highest mean *Ih* value, indicating a strong hierarchical differentiation among fruitlets, followed by RedPop and Pink Lady. Intermediate hierarchy levels were observed in Red Delicious and Gala, whereas Envy, Golden Delicious, Fuji and Elstar showed relatively low and statistically similar *Ih* values. Joya consistently displayed the lowest hierarchy index, significantly differing from all other cultivars. These results indicate that cultivar identity strongly influences the degree of hierarchical dominance among fruitlets, independently of geographical area, thinning treatment and fruitlet number per corymb.

The cultivar ranking based on *Ih* showed a moderate to strong correlation with cultivar effects estimated in the fruit drop model (Pearson’s $r = 0.64$), indicating that cultivars characterized by a stronger fruitlet hierarchical organization also tended to exhibit a higher intrinsic propensity to fruit abscission.

3.8. *Effect of geographical area on fruit drop*

Geographical area significantly influenced fruit drop, indicating the presence of region-specific baseline differences in thinning response (Table 7). Relative to the reference area (i.e. ‘Italy-mountains’), important negative deviations were observed in ‘Belgium’ and in the ‘Italy-plain' area, both of which were associated with lower fruit drop with very high statistical significance. In contrast, and ‘Switzerland’ area exhibited significantly higher fruit drop compared with the reference, along with ‘France’, the latter showing a marginal significance. ‘Germany’ and ‘Spain’ did not differ significantly from ‘Italy-mountains’.

The magnitude of geographical effects was generally smaller than that of fruitlet hierarchy and fruit number, but remained statistically significant for three regions, highlighting the contribution of location-specific factors to thinning outcomes. These differences persisted after controlling for treatment identity and thinning intensity, suggesting that

Table 7
Estimated effects of geographical area on fruit drop relative to the Italy-mountains reference area, derived from the main linear model. Coefficients represent baseline deviations after accounting for fruitlet hierarchy (*Ih*), thinning dosage, treatment, the $Ih \times$ dosage interaction, cultivar, and number of fruitlets per corymb. Statistical significance is indicated as $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***). The dot (.) indicates marginal significance ($0.05 \leq p < 0.10$), while ‘n.s.’ indicates non-significant effects.

Geographical area	Coefficient	*p*-value	Significance
Italy-mountains (reference)	0	–	–
Belgium	−0.215843	< 0.001	***
France	0.020738	0.0618	.
Germany	0.003452	0.716	n.s.
Italy-plain	−0.044894	< 0.001	***
Spain	−0.010565	0.725	n.s.
Switzerland	0.027141	0.0278	*

geographical area captures integrated effects of long-term climatic conditions, orchard management practices and cultivar–environment interactions rather than short-term weather variability.

3.9. The ‘Brevis-only’ model: effects of hierarchy, dosage and climatic conditions

To further investigate the role of climatic conditions on thinning response, a dedicated analysis was performed on the subset of corymbs treated with Brevis, for which the BreviSmart climatic index was available. The Brevis-only model included the hierarchy index (*Ih*), thinning dosage, their interaction, cultivar, geographic area and the number of fruitlets per corymb (*n*).

In the Brevis-only linear model, *Ih* exerted a significant positive effect on partial fruit drop (Table 8), confirming that increasing hierarchical differentiation among fruitlets was associated with higher abscission levels. The number of fruitlets per corymb also had a strong positive effect ($p < 0.001$), while thinning dosage showed only a marginal influence. The interaction between *Ih* and dosage was not significant, indicating that hierarchy-driven responses were largely independent of thinning intensity within the explored dosage range.

BreviSmart classes were weakly associated with partial fruit drop. Compared with the reference class, only class 1 showed a significant positive effect, whereas higher classes (2–4) did not differ significantly (Table 8). Cultivar and geographic area effects were highly significant, highlighting strong genotype- and environment-dependent variability in thinning response within the Brevis subset.

Extreme abscission responses were analysed using a logistic regression applied to the unfiltered Brevis dataset (Table 9). In this model, thinning dosage emerged as the dominant driver of overthinning probability ($p < 0.001$), while the hierarchy index (*Ih*) did not significantly affect the occurrence of extreme fruit drop.

BreviSmart classes were not monotonically related to overthinning risk. Relative to class 0, only BreviSmart class 1 was associated with a significantly higher probability of overthinning, whereas no significant differences were detected for classes 2 and 3, and only a weak trend was observed for class 4 (Table 9, Table 10). Cultivar, geographic area and fruit number per corymb all significantly influenced overthinning probability, confirming the multifactorial nature of extreme thinning responses.

3.10. The predictive model

The final predictive model is expressed as a linear function of the fruitlet hierarchy index (*Ih*), thinning dosage, their interaction, and the number of fruitlets per corymb, with additional additive corrections accounting for treatment, cultivar, and geographical area. This is the general predictive model, built without the BreviSmart climatic information and without the data related to corymbs with 0% and 100% of fruit drop. The formulas of the ‘Brevis-only” model are reported in detail in the Supplementary material.

Table 8
Brevis-only linear model for partial fruit drop. Effects of hierarchy index (*Ih*), thinning dosage, climatic conditions (BreviSmart), cultivar, geographic area and fruit number per corymb (*n*) on partial fruit drop in the Brevis-treated subset.

Effect	Estimate	Std. Error	*t* value	*p*-value	Significance
Intercept	0.252	0.038	6.62	<0.001	***
Ih	0.604	0.209	2.89	0.0039	**
Dosage	0.031	0.016	1.94	0.053	.
BreviSmart 1	0.058	0.010	5.64	<0.001	***
BreviSmart 2	0.014	0.012	1.16	0.248	ns
BreviSmart 3	0.013	0.012	1.08	0.280	ns
BreviSmart 4	−0.029	0.017	−1.69	0.092	.
n (fruit number)	0.046	0.003	14.98	<0.001	***
Cultivar (overall)	—	—	—	<0.001	***
GeoArea (overall)	—	—	—	<0.001	***
Ih × Dosage	−0.109	0.101	−1.09	0.278	ns

Table 9
Logistic regression for overthinning events in the Brevis-only dataset. Effects of climatic conditions (BreviSmart), hierarchy index (Ih), thinning dosage, cultivar, geographic area and fruit number per corymb (N) on the probability of extreme fruit drop (≥95%) in the unfiltered Brevis dataset.

Effect	Estimate (log-odds)	Std. Error	*z* value	*p*-value	Significance
Intercept	−3.913	0.513	−7.63	<0.001	***
BreviSmart 1	0.358	0.108	3.32	<0.001	***
BreviSmart 2	0.094	0.128	0.73	0.463	ns
BreviSmart 3	−0.004	0.127	−0.03	0.973	ns
BreviSmart 4	0.326	0.177	1.84	0.066	.
Ih	−0.366	0.283	−1.30	0.195	ns
Dosage	0.541	0.151	3.59	<0.001	***
n (fruit number)	0.142	0.028	5.15	<0.001	***
Cultivar (overall)	—	—	—	<0.001	***
GeoArea (overall)	—	—	—	<0.001	***

Table 10
Frequency of overthinning events by BreviSmart class (Brevis-only, unfiltered dataset).

BreviSmart class	n	Overthinning rate
0	624	0.300
1	1583	0.446
2	2235	0.397
3	1754	0.319
4	635	0.328

The model calculates $\widehat{Fruitdrop}_i$ as a proportion – from 0 to 1 - of fruit drop of the corymb *i*-th:

$$\widehat{Fruitdrop}_i = \beta_0 + \beta_1 Ih_i + \beta_2 Dosage_i + \beta_3 (Ih_i \times Dsosage_i) + \beta_4 n_i + \sum_{t \in \mathscr{T}} \gamma_t \mathbb{I}(Treatment_i = t) + \sum_{c \in \mathscr{C}} \alpha_c \mathbb{I}(Cultivar_i = c) + \sum_{g \in \mathscr{G}} \theta_g \mathbb{I}(GeoArea_i = g) + \varepsilon_i \quad (7)$$

The intercept β_0 represents the expected fruit drop under the reference conditions (reference cultivar, reference geographical area and untreated control, UTC) when continuous predictors are set to zero. β_1 quantifies the marginal effect of the hierarchy index (Ih_i, scaled 0–1) on fruit drop, i.e. the expected change in $\widehat{Fruitdrop}_i$ for a one-unit increase in Ih_i when all other predictors are held constant. β_2 is the marginal effect of thinning dosage ($Dosage_i$ in kg/ha). β_3 is the interaction coefficient for ($Ih_i \times Dosage_i$) and describes how the effect of hierarchy on fruit drop changes with dosage (and equivalently how the dosage effect changes with hierarchy). β_4 is the marginal effect of corymb fruit number (n_i), representing the expected change in fruit drop per additional fruitlet, conditional on the other predictors.

Categorical predictors (Treatment, Cultivar and GeoArea) are introduced using dummy variables. The indicator functions $\mathbb{I}(Treatment_i = t)$, $\mathbb{I}(Cultivar_i = c)$ and $\mathbb{I}(GeoArea_i = g)$ take value 1 when the *i*-th observation belongs to level *t*, *c* or *g*, respectively, and 0 otherwise. The corresponding coefficients γ_t, α_c and θ_g represent deviations from the reference levels for treatment, cultivar and geographical area. The residual term ε_i accounts for unexplained variation and is assumed to have mean zero and constant variance. Although some predictor combinations associated with β_0 (e.g., *Dosage* or $n = 0$) are outside the observed biological range, the intercept is required to anchor the linear predictor; inference focuses on marginal effects and contrasts among factor levels.

3.11. *Cross-validation of the **Ih**-based model*

Ten-fold cross-validation confirmed the robustness and generalisability of the Ih-based model. Cross-validated performance metrics showed an R^2 of 0.239, RMSE of 0.172, and MAE of 0.143. The low standard deviations of these metrics across folds (RMSE SD = 0.0022; R^2 SD = 0.028) indicated stable performance and limited sensitivity to data partitioning.

Observed and cross-validated predicted fruit drop values showed good agreement across the full response range (Fig. 5), supporting the predictive reliability of the model under heterogeneous conditions.

3.12. *Operational relevance of the hierarchy–dosage framework for decision support systems*

The final predictive model provides a quantitative framework that is directly transferable to decision support systems (DSS) for chemical thinning management. By explicitly integrating corymb hierarchical structure and thinning dosage, the model translates measurable orchard-level variables into expected partial fruit drop responses. The hierarchy index (*Ih*) represents an intrinsic, physiologically meaningful descriptor of fruitlet competition, while dosage captures the externally imposed thinning intensity. Their negative interaction indicates that the predictive value of fruitlet hierarchy decreases as thinning intensity increases, delineating a transition from hierarchy-driven selective abscission to dosage-dominated thinning responses.

From a DSS perspective, this formulation allows thinning recommendations to be modulated according to the initial hierarchical status of the corymb. Under low to moderate thinning intensities, small variations in *Ih* lead to substantial differences in predicted fruit drop, highlighting conditions in which conservative or finely tuned dosing strategies are required. Conversely, when higher thinning intensities are applied, predicted responses become less sensitive to hierarchical differences, indicating operational contexts in which dosage adjustments may have diminishing returns.

Importantly, the additive structure of the model and the explicit representation of the *Ih* –dosage interaction enable robust prediction across cultivars, geographical areas and thinning agents without reliance on treatment-specific climatic indices. This facilitates implementation within DSS architectures, where input variables must be available across diverse production systems. By embedding a physiologically grounded hierarchy descriptor within a predictive framework, the model supports hierarchy-informed thinning decisions aimed at improving consistency, reducing the risk of under- or overthinning, and enhancing the reliability of chemical thinning recommendations under variable orchard conditions.

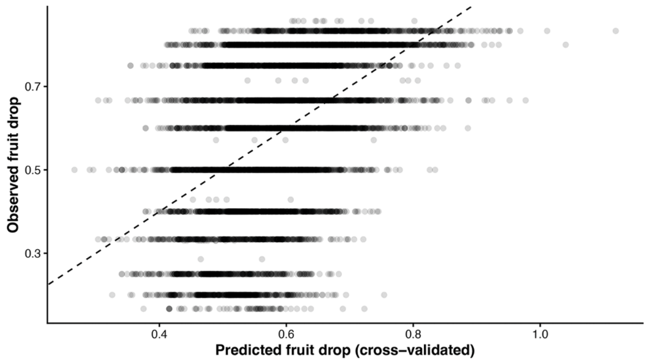

Fig. 5. Cross-validation of the *Ih* -based model. Observed versus cross-validated predicted fruit drop obtained from 10-fold cross-validation. The dashed line represents the 1:1 relationship, indicating good agreement between observed and predicted values.

4. Discussion

4.1. *Corymb hierarchy as a physiological driver of abscission*

The present study demonstrates that within-corymb fruitlet hierarchy, quantified through the *Ih* index, is a major determinant of partial fruit drop in apple. Across a large, multi-environment dataset, *Ih* consistently exerted one of the strongest effects in the predictive model, exceeding the contribution of thinning dosage alone and remaining highly significant after accounting for cultivar, geographical area, treatment type and fruit number per corymb. A sensitivity analysis performed on the full dataset, including corymbs with 0% and 100% fruit drop, confirmed the overall stability of the modelling framework. The main predictors retained the same direction and relative importance observed in the filtered model, with *Ih* remaining one of the strongest determinants of fruit drop and the negative *Ih* × dosage interaction becoming even more pronounced (**Supplementary Table S2**). These results indicate that excluding extreme responses primarily affects the response range and variance structure of the dataset without altering the main physiological relationships captured by the model.

These results are fully consistent with the physiological concept of fruitlet hierarchy originally proposed by Botton et al. (2011), who showed that size-based dominance within apple corymbs reflects underlying differences in sink strength, carbon allocation and hormonal balance, ultimately determining fruitlet fate. The present work extends this concept by translating hierarchy into a continuous, operational index and by demonstrating its explanatory power at a continental scale. The positive relationship between *Ih* and fruit drop supports the interpretation that stronger dominance of the largest fruitlet enhances competitive exclusion of subordinate fruitlets, increasing their susceptibility to abscission, in agreement with previous studies linking fruitlet growth rate, carbohydrate availability and abscission risk (Lakso et al., 2006; Greene et al., 2013).

Importantly, *Ih* captured structural information that is not fully represented by fruit number alone. While the number of fruitlets per corymb also had a strong positive effect on fruit drop, the two variables were complementary rather than redundant, indicating that hierarchy integrates qualitative physiological aspects of competition beyond simple fruit load effects.

Despite the strong and consistent effect of *Ih*, a substantial fraction of fruit drop variability remained unexplained by the model (Table 2). This result is not unexpected given the inherently complex and partially stochastic nature of fruit abscission processes, which are influenced by numerous physiological and environmental factors that were not explicitly quantified in the present study. These may include local carbohydrate availability, spur leaf area, seed viability, branch position within the canopy, tree vigour, microclimatic heterogeneity and orchard-specific management practices. In this context, the explanatory power of the model should not be interpreted as a limitation of the hierarchy framework itself, but rather as a reflection of the multifactorial nature of fruit drop regulation under field conditions. Importantly, the hierarchy index consistently emerged as a strong and stable predictor across all modelling approaches, supporting its physiological relevance despite the residual variability inherent to orchard systems.

4.2. *Interaction between hierarchy and dosage*

The negative interaction between *Ih* and thinning dosage suggested by the main model indicates that hierarchy-driven differences in abscission are progressively dampened as thinning intensity increases (Table 3 and Fig. 4). Under low to moderate thinning intensities, corymbs with contrasting hierarchical structures showed markedly different fruit drop responses, whereas at higher dosages abscission tended to converge across hierarchy levels.

This pattern aligns with classical thinning theory, according to which selective abscission driven by endogenous competition dominates under mild stress, while stronger chemical perturbations override intrinsic competitive gradients (Greene and Autio, 1994; Wertheim, 2000; Robinson and Lakso, 2011). From a physiological standpoint, high thinning dosages likely impose a supra-threshold stress on carbohydrate balance and hormonal signalling, reducing the relative importance of pre-existing dominance relationships. The observed interaction thus suggests a mechanistic explanation for the often-reported variability of thinning outcomes under low-dose strategies and the overthinning episodes occurring at high dosages, thus supporting hierarchy-informed dosage modulation.

4.3. *Treatment-specific responses*

Among thinning agents (Table 4), BA showed the most consistent positive effect on fruit drop, in agreement with its well-documented role in disrupting apical dominance, cytokinin balance and sink competition (Greene et al., 1990, 1992; Greene, 2002). Brevis also exhibited a significant positive effect, albeit of smaller magnitude, reflecting its more recent introduction and narrower operational window (Dorigoni and Lezzer, 2007).

By contrast, ACC did not differ significantly from the pooled untreated control. This result should not be interpreted as evidence of low intrinsic thinning potential, but rather as a consequence of dataset structure. ACC efficacy is typically evaluated relative to experiment-specific controls, whereas in the present analysis it was contrasted against a global UTC pooling heterogeneous trials, cultivars and environments. Moreover, the dataset includes early experimental applications with non-optimized dosages, likely diluting the overall signal. Similar context-dependent responses to ACC have been reported in recent studies emphasizing the importance of dosage calibration and phenological timing (McArtney et al., 2022; Petri et al., 2023).

4.4. *Cultivar effects*

The cultivar significantly affected both fruit drop and mean *Ih* values, revealing a strong genetic component in corymb structural organization (Tables 5 and 6). The ranking of cultivars by mean *Ih* showed a moderate-to-strong correlation with cultivar effects on fruit drop, suggesting that cultivars with inherently stronger hierarchical differentiation tend to exhibit higher baseline abscission propensity.

This relationship supports the hypothesis that cultivar-specific growth patterns, spur architecture and early fruitlet growth dynamics influence thinning sensitivity (Wünsche and Lakso, 2000; Costa et al., 2010). However, the persistence of the *Ih* effect across cultivars indicates that hierarchy acts as a general physiological driver, while cultivar primarily modulates baseline levels rather than altering the hierarchy–abscission relationship itself.

4.5. *Geographical area as an integrative environmental factor*

Geographical area emerged as a significant predictor of fruit drop (Table 7) even after accounting for hierarchy, treatment and dosage. The observed differences likely reflect integrated effects of long-term climatic regimes, orchard management practices and habits, and cultivar–environment interactions rather than short-term climatic conditions alone. Similar region-dependent thinning responses have been reported in multi-site trials and are often attributed to differences in radiation, temperature patterns and tree vigour (Robinson and Lakso, 2011).

The relatively smaller magnitude of GeoArea effects compared with *Ih* underscores the robustness of hierarchy as an internal driver, while highlighting the necessity of including geographical corrections for accurate large-scale predictions.

4.6. *Insights from the ‘Brevis-only’ models and climatic indices*

The ‘Brevis-only’ analysis clarified the role of climatic conditions as captured by the BreviSmart index. Within the partial fruit drop dataset, BreviSmart classes showed weak and non-monotonic effects (Table 8), with only class 1 differing significantly from the reference. This apparent inconsistency with the expected overthinning risk of class 0 can be explained by two factors. First, class 0 contained fewer observations (thinning treatments are not usually performed when the risk of overthinning is high), reducing statistical power. Second, the exclusion of 100% fruit drop corymbs removed the very outcomes that BreviSmart is designed to predict.

This interpretation is supported by the logistic regression on the unfiltered dataset (Table 9), where thinning dosage emerged as the dominant driver of overthinning probability, while BreviSmart class 1 - but not class 0 - showed increased risk (Table 10). These results suggest that BreviSmart captures climatic predisposition, but its predictive power is strongly modulated by dosage and by the inclusion of extreme responses. Similar limitations of climatic indices, when analysed outside their intended operational context, have been reported for other thinning decision tools, such as the BreviSmart itself (Schmidt, 2025).

4.7. *Implications for decision support systems*

The *Ih*-based framework offers clear advantages for integration into decision support systems. The present framework should therefore be viewed as complementary to existing thinning prediction approaches, rather than as a replacement for current climatic or carbohydrate-balance models.

By combining a physiologically grounded descriptor of corymb structure with thinning dosage and simple categorical corrections, the model (Eq. (7)) provides robust predictions that can be integrated with treatment-specific climatic indices. While alternative bounded-response modelling approaches may further improve prediction under extreme conditions, the OLS framework adopted here provides a transparent and operationally interpretable structure suitable for decision support applications. Overall, the generality of this approach enhances portability across cultivars, regions and thinning agents.

The present implementation of the operational hierarchy index relies on min–max scaling derived from the modelling dataset. While this approach facilitates interpretability and direct integration into predictive models, future applications involving cultivars, orchard systems or environmental conditions outside the current training range may generate observations exceeding the original scaling boundaries. In such cases, the retained training scaling constants would still allow projection of new observations, although extrapolated values may partially reduce comparability and operational interpretability. Future developments may therefore explore more dataset-independent normalization strategies or adaptive scaling procedures capable of accommodating progressively expanding datasets within DSS environments.

The negative *Ih*–dosage interaction further suggests adaptive recommendations, identifying conditions under which fine-tuned dosing is critical versus situations where higher dosages reduce sensitivity to initial structural variability. Together, these features support the development of hierarchy-informed thinning strategies aimed at improving consistency and reducing the risk of under- or overthinning. To further validate the hierarchy × dosage interaction identified in the present study, additional datasets specifically designed to characterize dosage-dependent thinning responses across contrasting corymb structures would be valuable.

5. Conclusion

This study demonstrates that within-corymb fruitlet hierarchy, quantified through the *Ih* index, is a key physiological determinant of apple fruit drop and a robust predictor of thinning response across cultivars, geographical areas and thinning agents. By formalizing the long-standing concept of fruitlet dominance into a continuous, operational index, the proposed framework bridges fundamental physiology and applied orchard management.

The strong and consistent effect of *Ih* highlights the central role of internal competitive structure in regulating selective abscission, independently of fruit load and external thinning intensity. The interaction between hierarchy and dosage further clarifies why thinning responses are highly variable under low to moderate dosages and progressively converge as thinning intensity increases. These findings provide a mechanistic explanation for inconsistencies often reported in chemical thinning outcomes and emphasize the need for hierarchy-aware dosage calibration.

Cultivar-specific differences in both hierarchy and abscission propensity indicate a genetic control over corymb structural organization, while geographical area effects reveal the contribution of long-term environmental and agronomical context. Importantly, the *Ih* effect remained stable across these sources of variability, underscoring its general applicability.

The ‘Brevis-only’ analyses showed that climatic indices such as BreviSmart provide useful but context-dependent information, particularly for extreme responses. Their predictive value is strongly influenced by dataset composition and dosage distribution, reinforcing the importance of integrating climatic tools with intrinsic tree-level descriptors.

Overall, the *Ih*-based model offers a physiologically meaningful, parsimonious and transferable approach for predicting fruit drop. Its additive structure and limited data requirements make it particularly suitable for implementation in decision support systems, where it can support hierarchy-informed thinning strategies aimed at improving reliability, reducing risk and enhancing the sustainability of chemical thinning practices. Future implementations of this model with AI-based field imaging systems able to identify the single corymbs and measure their fruitlets would allow to perform a real-time hierarchy assessment to finely tune the thinning treatments to optimize their efficacy.

CRediT authorship contribution statement

Giorgia Bettio: Data curation, Investigation, Resources, Validation, Visualization. **Francesco Girardi:** Data curation, Investigation, Resources, Validation, Visualization. **Christian Andergassen:** Data curation, Investigation, Resources. **Magdalena Peterlin:** Data curation, Investigation, Resources. **Daniel Pichler:** Data curation, Investigation, Resources. **Franco Micheli:** Data curation, Investigation, Resources. **Andrea Waldner:** Data curation, Investigation, Resources. **Guglielmo Costa:** Conceptualization, Data curation, Investigation, Resources. **Alessandro Botton:** Conceptualization, Data curation, Formal analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.scienta.2026.114955.

Data availability

Data will be made available on request.

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