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Primary Assessment of Grapevine Cultivars' Bud Fertility with Diverse Ancestry Following Spring Frost Under Central Poland Environmental Conditions

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Abstract: Vine damage caused by spring frosts remains one of the main factors threatening grapevine yields in Central European countries, such as Poland. April frosts that followed a very early and warm spring in 2024 caused massive damage to young shoots and primary buds after budburst. This study was conducted on vines of fifty cultivars belonging to *Vitis vinifera*, interspecific hybrids, and inter-intra- or intra-interspecific hybrids (classified by some sources as *V. vinifera*), which were obtained via field collection. The aim of this study was to obtain primary results regarding the fertility of secondary, basal, and latent buds. The presence of inflorescences in these buds determines the ability to compensate for yield, i.e., produce a crop after damage to the primary buds. The tested cultivars, which were within the three groups mentioned above, differed significantly in their ability to compensate for yield. The majority of the analyzed *V. vinifera* cultivars were characterized by lower fertility in their secondary, basal, and latent buds and a reduced ability to compensate for yield after post-budburst freeze damage compared to interspecific hybrids and inter-intra- or intra-interspecific hybrids. Future research, with more comprehensive data collected over a longer period, will provide stronger suggestions for suitable cultivars in regions at risk of spring frost damage.

Keywords: *Vitis* spp.; collection; secondary buds; basal buds; latent buds; compensatory yielding; Poland

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1. Introduction

As a result of climate change, viticulture has become possible and is increasingly practiced in regions previously considered too cold for the crop, including in Poland, a Central European country [1,2]. Vine damage caused by spring frost remains one of the main factors threatening yields and affecting the distribution of grapevines in various locations in Europe [3,4], North America [5], and New Zealand [6]. Frost damage negatively impacts the health and productivity of grapevines in the present and in subsequent years [7]. The main crop of the grapevine forms on young shoots arising from dormant buds on one-year-old shoots. A dormant bud is a compound bud consisting of the best-developed and most fertile primary buds, along with secondary and tertiary buds, which mainly develop after the primary bud is damaged [7,8]. The differences between secondary and tertiary buds may be difficult to distinguish [8,9], and both types are sometimes referred to as replacement buds [10]. After damage to the primary shoots, basal (base) buds, which are located at the base of one-year-old shoots below clearly defined nodes, and latent (quiescent) buds, which are located on the perennial parts of the vine (the trunk and arms), develop in larger numbers than usual [7,8]. Basal and latent buds are referred to as non-count buds during pruning [7,11]. The shoots arising from latent buds are called watersprouts or suckers [7,8].

Bud fruitfulness depends on the cultivar; the type of bud; and its position along the annual shoot; environmental factors such as temperature, light, water availability, and nutrient availability; and endogenous factors such as carbohydrate reserves and hormonal balance. Cultivation practices can further modify bud fruitfulness [9,12–15]. The potential fertility of buds during the dormant period can be determined by dissecting the bud and conducting a histological analysis [9,12–15]. Observed, actual, or practical fertility can be assessed after bud development by counting the inflorescences on the shoot (also in field conditions) [9,13]. The fertility of secondary, basal, and latent buds varies greatly depending on the genotype [10,16]. The ability of *Vitis vinifera* (VIN) cultivars to compensate for yield losses after post-budburst frosts by producing yields on shoots arising from secondary and non-count buds is most often described as low [17,18]. Nevertheless, significant differences can be observed within this group, depending on the cultivar and growing conditions [5,9,18–21].

Some interspecific hybrids (IHs) from the subgroup known as French–American hybrids, such as 'Marechal Foch', 'Chancellor', 'Seyval Blanc', and 'Vidal Blanc', form numerous inflorescences on shoots arising from secondary and basal buds [22,23]. The response of newer IHs, such as 'Marquette', 'Noiret', and 'Traminette', to spring frosts was evaluated under local conditions in Michigan and Pennsylvania (USA) and was found to be cultivar-dependent [24,25]. The yield of 'Concord' (an IH with a predominance of *V. labrusca* genes and features) was reduced by 22% after an early frost and by 52% after a late frost [26]. The yield was produced on shoots from primary buds that had not started growing during the frost and from secondary, basal, and latent buds [26].

Due to climate change, viticulture is being practiced in new locations. New cultivars are also being introduced. The main knowledge gaps include the lack of results of methodological studies on the consequences of spring frosts for grapevine cultivation in Poland, specifically concerning the cultivar response to frost, the ability to compensate for yield, and the differences between VINs and IHs. The second equally important gap is the lack of information on the yield of secondary, basal, and latent buds in inter-intraspecific (*Vitis* interspecific hybrid × *V. vinifera*) or intra-interspecific (*V. vinifera* × *Vitis* interspecific crossing) hybrids (IIHs). Genotypes from this category were isolated into a separate group [27] or classified as *Vitis vinifera* cultivars [28]. Due to their relatively good resistance to fungal diseases and the high quality of wine that is produced, IIHs are considered promising for viticulture in Central Europe [29].

The objectives of this primary study were as follows: (i) to examine the effects of spring frosts that occurred in central Poland in 2024 on fifty selected grapevine cultivars, (ii) to assess potential differences in the fruitfulness of secondary and non-count buds, and (iii) to identify which cultivars can restore yield from shoots other than the damaged primary ones, highlighting those that are most promising for further research in locations exposed to spring frost.

2. Materials and Methods

2.1. Study Site and Grapevine and Cultivar Characteristics

The performance of grapevines damaged by spring frosts was assessed in 2024, using the grapevine field collection samples of the National Institute of Horticultural Research in Skierniewice, Poland (latitude 51.9627° N, longitude 20.1666° E). This study was conducted on samples grown in luvisol soil, which was slightly acidic (pH 6.3 in 1 m KCl). The soil contained 2.2% organic matter. These soil parameters are monitored and corrected annually. In the studied year, they did not differ significantly from previous years. The temperate climate of Central Poland, which is in between maritime and continental, is characterized by cold winters and hot summers and relatively low and variable precipitation. In 2014–2023, the average air temperature was −0.2 °C in January, 19.4 °C in July, and 14.2 °C during the grapevine growing season (1.04–31.10). The average frost-free period lasted 164 days, and the growing degree days (GDD) value amounted to 1133 °C. The GDD is given in the following equation:

$$\mathrm{GDD} = \sum_{1.04}^{31.10} (T_d - 10), \text{ for } T_d - 10^{\circ} > 0;$$

where T_d is the daily mean air temperature.

The average annual precipitation in the last decade was 542 mm. The year 2024 was extremely warm and dry in Central Poland. The GDD reached a record value of 1357 °C. The average air temperature during the grapevine vegetation period was 15.8 °C. The total precipitation between 1 April and 31 October was 218 mm, while the long-term average is 370 mm. The frost-free period was relatively short and amounted to 156 days.

Each genotype under investigation was represented by three vines that were at least 6 years old; these vines were planted with a spacing of 2.5 × 1 m and maintained in a low head formation, featuring a trunk 0.2 m high, with short arms and 4–5 spurs pruned into 2–3 buds (ultimately resulting in 8–10 young shoots per vine). Due to the potentially frosty winter, the vines were covered for the season (December) with cereal straw (in 0.4 m mounds). Fertilization and plant protection were carried out according to current recommendations for commercial vineyards. Mineral fertilization was carried out using 'Azofoska', a multi-component fertilizer containing the macronutrients N, P, K, and Mg and the micronutrients Cu, Zn, Mn, B, Mo, along with triple superphosphate (P) and potassium sulfate (K). This was applied in spring, at the beginning of April. Half of the necessary nitrogen dose was applied as calcium nitrate in the first half of June. The annual doses of macronutrients were as follows: N: 40 kg ha^{-1}; P: 30 kg ha^{-1}; and K: 100 kg ha^{-1}. Fungicides containing copper (1 treatment per season), sulfur, and pyraclostrobin + boscalid (2 treatments per season) were used to provide chemical protection against fungal diseases. In July, young shoots were pruned above the 10th–12th leaf past the last cluster of grapes. Lateral shoots were removed or shortened regularly.

Fifty valuable grapevine cultivars with diverse geographic and genetic origins were selected from the 360 genotypes represented in the collection to present the study results. Among the chosen cultivars, sixteen were VINs, eleven were IHs, and twenty-three were IIHs. Information on the cultivars, such as their origin group (species), country of origin, and berry skin color, and the study results are provided in Table 1.

2.2. Spring Frost Damage

Grapevine growth stages were identified using the Biologische Bundesanstalt, Bundessortenamt und CHemische Industrie (BBCH) system [30]. In 2024, in Skierniewice, as a result of a warm spring, the "wool stage" of the buds (BBCH 05) occurred in most interspecific hybrids on March 24–26, in inter-intraspecific hybrids on March 27–30, and in *V. vinifera* cultivars between April 1 and 5. Bud development occurred 3 weeks earlier than usual. Waves of frost were recorded in Skierniewice on the following days of April: 17 (−2.1 °C), 18 (−3.6 °C), 19 (−2.1 °C), 22 (−2.1 °C), and 26 (−0.8 °C). The frosts damaged all primary buds in the budburst phase: green shoot tips were visible (BBCH 07–09), and young shoots unfolded with 1–5 leaves (BBCH 11–15). The last spring frost was recorded on May 12 (−0.9 °C). Consecutive frosts resulted in exceptional damage to the shoots after budburst compared to other years.

2.3. Assessment of Inflorescence Occurrence as a Fertility Parameter

After spring frost damage to the shoots growing from primary buds, the shoots developed from secondary, basal, and latent buds. Between May 13 and 17, on each vine and for each of the three types of buds mentioned, all shoots that developed, including fertile shoots (those with at least one inflorescence), and the total number of inflorescences were counted separately. Two indices were used to express the actual fertility of the three types of buds: the percentage of fertile buds (PF) and the fruitfulness index (FI), which shows the mean number of inflorescences (clusters) per bud.

$$\text{PF} = \frac{\text{number of fertile shoots arised from buds of a given type}}{\text{number of all shoots arised from buds of a given type}} \times 100\%$$

$$\text{FI} = \frac{\text{number of inflorescences per vine on shoots arised from buds of a given type}}{\text{number of all shoots arised from buds of a given type}}$$

The value of both indices for each of the fifty cultivars, calculated separately for shoots arising from the three types of buds (secondary, basal, and latent), was calculated as the mean of three vines. Each vine was considered a replication. Based on data regarding individual cultivars, the mean values of the PF and FI indices were calculated in three groups of cultivars: VINs, IHs, and IIHs. When analyzing data on groups of cultivars, three replications consisting of vines were maintained.

2.4. Yield Assessment

In the second half of May, after collecting data on fertility, excess shoots were removed from the vines. Approximately 8–10 evenly spaced shoots with inflorescences were left on each vine. In cultivars with low fertility, some of the young shoots left were infertile. Unnecessary shoots were removed again in June. As in previous years, yield data were assessed, including the harvest date, the weight of fruits collected from the vine, the mean weight of clusters and berries, and the concentration of soluble solids and titratable acid, which was determined using a Brix-acidity meter PAL-BXIACID F5 (Atago, Tokyo, Japan). The cultivar's ability to compensate for yield after damage to the young primary buds in 2024 was recorded as a percentage of the standard yield (SY). The mean yield from the three previous seasons was used as the standard. The ability to produce compensatory yield was expressed on a five-point scale: very high (VH) > 81% of SY, high (H)—61–80% of SY, medium (M)—41–60% of SY, low—21–40% of SY, and very low (VL) < 20% of SY.

2.5. Statistical Analysis

The results concerning bud fertility were statistically analyzed using analysis of variance. The significance of the means was evaluated using Duncan's test at $p = 0.05$. Data were expressed as percentages and transformed according to the Bliss function. Statistical analyses were performed using the STATISTICA 10.0 package (StatSoft Inc., Tulsa, OK, USA).

3. Results

3.1. Actual Fertility Parameters

3.1.1. Actual Fertility Parameters in Cultivars

Secondary and non-count budburst began 10–14 days after the first frost. During the fertility assessment, there were, on average, 30–35 young shoots on each vine, with at least 10 from each of the three types of buds analyzed. In *V. vinifera* cultivars characterized by a later or extended bud-break date, such as 'Riesling', 'Rubinet', 'Zweigeltrebe', and 'Turan', there were 3 to 4 shoots arising from the primary buds, with the 'Riesling' cultivar having the most shoots. In the remaining cultivars, there were few primary shoots (1–2), or they were absent. Depending on the vine and cultivar, from 10 to 30% of blind nodes were observed on the vines. The occurrence of double shoots was also noticed.

The values of fertility parameters in the analyzed cultivars varied significantly.

1. The Percentage of Fertile Buds (PF)

Among the fifty cultivars, the highest percentage of fertile secondary buds was found in the IIHs 'Regent (82.1%), 'Villaris' (81.1%), and 'Accent' (79.9%), and for IHs, 'St. Pepin' (73.7%) and 'Bianca' (70.8%) (Table 1). In two cultivars, 'Nektar' (VIN) and 'Muscaris' (IIH), all secondary buds were infertile. A high percentage of fertile basal buds (at least 80%) was recorded in 'Rubinet' (VIN), five IHs ('Bianca', 'Frontenac', 'Seyval Blanc', 'St. Pepin', and 'Vidal Blanc') and eight IIHs ('Accent', 'Cabernet Cantor', 'Calandro', 'Helios', 'Hibernal', 'Monarch', 'Regent', and 'Villaris'). A high percentage of fertile latent buds was found in the IIHs 'Villaris' (90.2%), 'Accent' (82.7%), 'Regent' (78.4%), and 'Helios' and 'Hibernal' (both 75.7%) and the IHs 'Seyval' (80.4%) and 'St. Pepin' (78.0%). Latent buds in seven VINs ('Chardonnay', 'Dornfelder', 'Merlot', 'Pinot Gris', 'Rubinet', 'Siegerrebe', and 'Traminer Rot') and three IIHs ('Cabernet Cortis', 'Muscaris', and 'Prior') were infertile.

Table 1. Percentage of fertile buds in fifty grapevine cultivars.

Cultivar and Color of Berry Skin *	Country of Origin of the Cultivar	The Percentage of Fertile Buds (PF) (%)		
		Secondary	Basal	Latent
		Vitis vinifera		
Chardonnay (B)	France	7.3 ± 0.58 b	12.2 ± 3.51 b	0.0 ± 0 a
Chasselas Dore (B)	France	12.4 ± 4.16 c	18.0 ± 2.64 bcd	8.0 ± 1.00 bc
Dornfelder (N)	Germany	7.6 ± 1.15 b	14.6 ± 2.52 bc	0.0 ± 0 a
Merlot (N)	France	21.9 ± 3.00 def	20.3 ± 2.08 cde	0.0 ± 0 a
Muscat Ottonel (B)	France	17.3 ± 2.31 cd	23.0 ± 2.00 d–g	8.6 ± 2.08 bcd
Nektar (B)	Hungary	0.0 ± 0 a	12.9 ± 3.00 b	11.9 ± 2.65 cde
Pinot Blanc (B)	France	38.3 ± 3.51 ij	40.0 ± 2.00 j	8.6 ± 2.08 bcd
Pinot Gris (R)	France	21.9 ± 4.00 def	17.3 ± 3.10 bcd	0.0 ± 0 a
Pinot Noir (N)	France	16.6 ± 2.52 cd	26.6 ± 4.16 e–h	7.3 ± 0.58 b
Riesling (B)	Germany	22.3 ± 4.00 def	40.0 ± 2.00 j	8.6 ± 2.08 bcd
Rubinet (N)	Czechia	25.6 ± 4.73 efg	88.9 ± 4.12 v–y	0.0 ± 0 a
Sauvignon Blanc (B)	France	17.9 ± 4.00 cd	21.9 ± 4.00 def	7.3 ± 0.58 b
Siegerrebe (R)	Germany	32.6 ± 3.52 ghi	41.3 ± 3.21 j	0.0 ± 0 a
Traminer Rot (R)	Germany	7.6 ± 0.56 b	28.0 ± 3.00 fgh	0.0 ± 0 a
Turan (N)	Hungary	26.9 ± 5.57 efg	53.7 ± 4.93 k	12.9 ± 3.46 def
Zweigeltrebe (N)	Austria	21.0 ± 2.00 de	27.6 ± 3.51 fgh	9.3 ± 1.15 bcd
		Interspecific hybrids		
Aurore (B)	France	62.0 ± 4.00 lmn	74.7 ± 3.10 o–r	31.0 ± 3.61 kl
Bianca (B)	Hungary	70.8 ± 5.13 op	85.3 ± 5.57 t–w	62.7 ± 3.06 q
Concord (N)	USA	29.2 ± 6.86 fgh	28.6 ± 3.05 fgh	8.6 ± 2.08 bcd
Frontenac (N)	USA	41.3 ± 3.06 j	80.4 ± 4.04 r–u	12.3 ± 2.08 def
Leon Millot (N)	France	52.3 ± 3.79 k	68.0 ± 3.00 mno	52.0 ± 4.00 no
Marechal Foch (N)	France	31.6 ± 3.51 ghi	71.0 ± 3.61 m–p	34.6 ± 4.16 kl
Marquette (N)	USA	37.0 ± 4.58 hij	73.0 ± 2.65 n–q	28.6 ± 3.05 jk
Seyval Blanc (B)	France	66.1 ± 5.00 m–p	82.7 ± 3.05 stu	80.4 ± 3.51 st
St. Pepin (B)	USA	73.7 ± 4.51 pq	84.0 ± 2.00 tuv	78.0 ± 3.00 st
Swenson Red (R)	USA	67.0 ± 3.61 nop	63.4 ± 3.51 lm	19.2 ± 4.04 ghi
Vidal Blanc (B)	France	66.1 ± 4.58 m–p	82.1 ± 4.00 stu	62.0 ± 4.00 q

Table 1. *Cont.*

Cultivar and Color of Berry Skin *	Country of Origin of the Cultivar	The Percentage of Fertile Buds (PF) (%)		
		Secondary	Basal	Latent
Inter-intraspecific or intra-interspecific hybrids				
Accent (N)	Germany	79.9 ± 5.69 qr	80.0 ± 6.11 wxy	82.7 ± 3.05 t
Allegro (N)	Germany	65.8 ± 6.81 m–p	76.7 ± 4.16 p–s	36.0 ± 4.00 l
Baron (N)	Germany	67.4 ± 5.03 nop	72.1 ± 4.00 n–q	60.7 ± 4.04 pq
Bolero (N)	Germany	52.3 ± 5.13 k	66.0 ± 4.00 lmn	37.0 ± 3.65 l
Cabernet Cantor (N)	Germany	51.3 ± 3.51 k	86.2 ± 4.00 u–x	47.3 ± 4.16 mn
Cabernet Cortis (N)	Germany	27.2 ± 4.73 efg	43.7 ± 3.79 j	0.0 ± 0 a
Calandro (N)	Germany	55.7 ± 1.53 kl	86.3 ± 5.00 u–x	55.0 ± 6.24 op
Felicia (B)	Germany	58.0 ± 5.57 klm	67.4 ± 4.16 mno	55.3 ± 3.06 op
Helios (B)	Germany	63.0 ± 5.00 l–o	82.4 ± 3.21 stu	75.7 ± 3.51 s
Hibernal (B)	Germany	52.0 ± 6.56 k	84.4 ± 2.08 tuv	75.7 ± 4.04 s
Johanniter (B)	Germany	22.9 ± 4.58 def	42.0 ± 3.00 j	14.6 ± 3.21 efg
Monarch (N)	Germany	38.3 ± 6.03 ij	91.1 ± 2.65 xy	35.6 ± 5.51 l
Muscaris (B)	Germany	0.0 ± 0 a	7.3 ± 0.58 a	0.0 ± 0 a
Orion (B)	Germany	69.1 ± 5.57 nop	64.1 ± 6.00 lm	21.2 ± 5.03 hi
Prior (N)	Germany	14.0 ± 2.00 c	32.0 ± 2.00 hi	0.0 ± 0 a
Reberger (N)	Germany	35.6 ± 6.03 hij	38.0 ± 4.00 ij	16.9 ± 3.61 fgh
Regent (N)	Germany	82.1 ± 4.00 r	82.7 ± 3.10 stu	78.4 ± 3.51 st
Roesler (N)	Austria	36.9 ± 5.57 hij	52.7 ± 3.05 k	11.7 ± 1.15 cde
Rondo (N)	Germany	26.9 ± 4.36 efg	25.9 ± 4.00 e–h	23.3 ± 2.31 ij
Saphira (B)	Germany	55.3 ± 4.16 kl	59.4 ± 5.03 kl	44.6 ± 5.51 m
Solaris (B)	Germany	69.4 ± 3.06 nop	78.8 ± 4.51 q–t	70.2 ± 7.81 r
Souvignier Gris (R)	Germany	7.3 ± 0.58 b	30.3 ± 2.08 gh	7.3 ± 0.58 b
Villaris (B)	Germany	81.1 ± 3.00 r	91.6 ± 4.04 y	90.2 ± 3.46 u

Means followed by the same letter do not differ significantly at $p = 0.05$. Values with the prefix ± represent standard deviation. * Color of berry skin: B (blanc)—green-yellow, R—rose, N (noir)—blue-black.

2. Fruitfulness Index (FI)

The highest fruitfulness index values for secondary buds were recorded in the IHs 'Bianca' (1.31) and 'Vidal Blanc' (1.26), as well as in the IIHs 'Regent' (1.31), 'Baron' (1.28), and 'Villaris' (1.22) (Table 2). The cultivars 'Villaris', 'Monarch', and 'Accent' were characterized by the highest fruitfulness index value for basal buds (1.70–1.74) among IIHs. In 'Rubinet' (VIN), a high fruitfulness index value for basal buds (1.60) was found, which did not differ significantly from the value of this index in 'Bianca', 'Seyval Blanc', and 'Vidal Blanc' (IH). The highest latent bud fruitfulness index value (1.71) was found in 'Villaris'.

Table 2. Actual fruitfulness of buds and the ability for compensatory yielding in fifty grapevine cultivars.

Cultivar	Fruitfulness Index (FI—Mean Number of Inflorescences per Bud)			Ability for Compensatory Yielding *
	Secondary	Basal	Latent	
Vitis vinifera				
Chardonnay (B)	0.07 ± 0.01 ab	0.16 ± 0.05 ab	0.0 ± 0 a	VL
Chasselas Dore (B)	0.24 ± 0.08 cde	0.34 ± 0.05 cd	0.16 ± 0.01 bcd	L
Dornfelder (N)	0.08 ± 0.01 ab	0.16 ± 0.03 ab	0.0 ± 0 a	L
Merlot (N)	0.35 ± 0.05 e–i	0.39 ± 0.04 c–f	0.0 ± 0 a	L
Muscat Ottonel (B)	0.23 ± 0.03 cd	0.30 ± 0.03 c	0.10 ± 0.02 bc	L
Nektar (B)	0.0 ± 0 a	0.13 ± 0.03 ab	0.12 ± 0.03 bcd	L
Pinot Blanc (B)	0.46 ± 0.04 ijk	0.48 ± 0.02 fgh	0.09 ± 0.02 bc	M

Table 2. *Cont.*

Cultivar	Fruitfulness Index (FI—Mean Number of Inflorescences per Bud)			Ability for Compensatory Yielding *
	Secondary	Basal	Latent	
Pinot Gris (R)	0.22 ± 0.04 cd	0.19 ± 0.04 b	0.0 ± 0 a	L
Pinot Noir (N)	0.20 ± 0.03 c	0.35 ± 0.05 cd	0.08 ± 0.01 abc	L
Riesling (B)	0.22 ± 0.04 cd	0.44 ± 0.02 d–g	0.10 ± 0.02 bc	H
Rubinet (N)	0.33 ± 0.06 d–h	1.60 ± 0.08 st	0.0 ± 0 a	VH
Sauvignon Blanc (B)	0.22 ± 0.05 cd	0.29 ± 0.05 c	0.09 ± 0.01 bc	L
Siegerrebe (R)	0.39 ± 0.04 g–j	0.54 ± 0.04 gh	0.0 ± 0 a	M
Traminer Rot (R)	0.08 ± 0.01 ab	0.36 ± 0.03 cde	0.0 ± 0 a	L
Turan (N)	0.32 ± 0.07 d–g	0.64 ± 0.06 i	0.17 ± 0.02 cde	M
Zweigeltrebe (N)	0.27 ± 0.03 c–f	0.39 ± 0.04 c–f	0.12 ± 0.01 bcd	M
Interspecific hybrids				
Aurore (B)	1.05 ± 0.07 q	1.42 ± 0.06 pqr	0.47 ± 0.07 g	VH
Bianca (B)	1.31 ± 0.10 u	1.62 ± 0.11 st	1.19 ± 0.06 mn	VH
Concord (N)	0.41 ± 0.08 g–j	0.29 ± 0.03 c	0.09 ± 0.01 bc	M
Frontenac (N)	0.54 ± 0.04 k	1.21 ± 0.06 n	0.13 ± 0.04 bcd	VH
Leon Millot (N)	0.94 ± 0.07 op	1.29 ± 0.06 no	0.94 ± 0.08 l	VH
Marechal Foch (N)	0.41 ± 0.05 g–j	0.92 ± 0.05 jk	0.52 ± 0.06 gh	H
Marquette (N)	0.44 ± 0.05 h–k	0.88 ± 0.03 jk	0.34 ± 0.04 f	H
Seyval Blanc (B)	0.92 ± 0.07 no	1.57 ± 0.06 s	1.21 ± 0.05 mno	VH
St. Pepin (B)	1.18 ± 0.08 rst	1.34 ± 0.04 opq	1.17 ± 0.05 mn	VH
Swenson Red (R)	0.87 ± 0.05 no	0.82 ± 0.05 j	0.19 ± 0.04 de	H
Vidal Blanc (B)	1.26 ± 0.09 tu	1.56 ± 0.08 s	1.18 ± 0.08 mn	VH
Inter-intraspecific or intra-interspecific hybrids				
Accent (N)	1.04 ± 0.07 pq	1.70 ± 0.11 tuv	1.40 ± 0.05 q	VH
Allegro (N)	1.05 ± 0.11 q	1.46 ± 0.08 r	0.68 ± 0.07 jk	VH
Baron (N)	1.28 ± 0.10 tu	1.37 ± 0.08 o–r	1.15 ± 0.08 m	VH
Bolero (N)	0.68 ± 0.07 l	0.86 ± 0.05 jk	0.48 ± 0.07 g	H
Cabernet Cantor (N)	0.82 ± 0.06 mn	1.38 ± 0.07 o–r	0.76 ± 0.07 k	VH
Cabernet Cortis (N)	0.36 ± 0.06 f–i	0.70 ± 0.06 i	0.0 ± 0 a	M
Calandro (N)	1.06 ± 0.03 q	1.63 ± 0.10 stu	0.88 ± 0.09 l	VH
Felicia (B)	0.75 ± 0.07 lm	0.88 ± 0.06 jk	0.61 ± 0.04 ij	H
Helios (B)	1.13 ± 0.09 qrs	1.56 ± 0.06 s	1.36 ± 0.06 pq	VH
Hibernal (B)	0.88 ± 0.11 no	1.43 ± 0.04 qr	1.29 ± 0.07 op	VH
Johanniter (B)	0.25 ± 0.05 c–f	0.46 ± 0.04 e–h	0.17 ± 0.02 cde	M
Monarch (N)	0.65 ± 0.11 l	1.73 ± 0.05 uv	0.60 ± 0.09 hij	VH
Muscaris (B)	0.0 ± 0 a	0.07 ± 0.01 a	0.0 ± 0 a	VL
Orion (B)	1.10 ± 0.09 qr	1.02 ± 0.10 lm	0.25 ± 0.06 e	VH
Prior (N)	0.16 ± 0.03 bc	0.38 ± 0.03 c–f	0.0 ± 0 a	L
Reberger (N)	0.43 ± 0.07 g–k	0.46 ± 0.05 e–h	0.17 ± 0.04 cde	M
Regent (N)	1.31 ± 0.07 u	1.32 ± 0.05 op	1.25 ± 0.06 no	VH
Roesler (N)	0.48 ± 0.07 jk	0.84 ± 0.05 j	0.15 ± 0.04 bcd	H
Rondo (N)	0.32 ± 0.05 d–g	0.29 ± 0.04 c	0.26 ± 0.03 e	L
Saphira (B)	0.72 ± 0.05 lm	0.95 ± 0.08 kl	0.54 ± 0.08 ghi	H
Solaris (B)	1.04 ± 0.05 pq	1.11 ± 0.07 m	0.91 ± 0.09 l	VH
Souvignier Gris (R)	0.07 ± 0.01 ab	0.55 ± 0.04 h	0.07 ± 0.01 ab	L
Villaris (B)	1.22 ± 0.05 stu	1.74 ± 0.08 v	1.71 ± 0.07 r	VH

Means followed by the same letter do not differ significantly at $p = 0.05$. Values with the prefix ± represent standard deviation. * The ability for compensatory yielding: VH (very high) > 81% of SY (standard yield), H (high)—61–80% of SY, M (medium)—41–60% of SY, L (low)—21–40% of SY, and VL (very low) < 20% of SY.

3.1.2. Actual Fertility Parameters in Groups of Cultivars (PF and FI)

The mean PF value of secondary and basal buds and the FI of secondary, basal, and latent buds differed significantly in the three analyzed groups of cultivars (Tables 3 and 4).

The highest values of these indices were found in IHs, and the lowest values were found in VIN cultivars. The difference in the PF of latent buds between the IH and IIH cultivars was statistically insignificant.

Table 3. Percentage of fertile buds (PF) in grapevine cultivar groups with different ancestries.

Group of Cultivars	The Percentage of Fertile Buds (PF) (%)		
	Secondary	Basal	Latent
Vitis vinifera	18.6 ± 1.10 a	30.4 ± 0.46 a	5.2 ± 0.60 a
Interspecific hybrids	54.3 ± 1.00 c	72.1 ± 0.93 c	42.7 ± 0.78 b
Inter-intra or intra-interspecific hybrids	48.3 ± 1.40 b	63.0 ± 1.04 b	40.9 ± 1.01 b

Means followed by the same letter do not differ significantly at p = 0.05. Values with the prefix ± represent standard deviation.

Table 4. Actual bud fruitfulness (FI) in grapevine cultivar groups with different ancestries.

Group of Cultivars	Fruitfulness Index (FI-Mean Number of Inflorescences per Bud)		
	Secondary	Basal	Latent
Vitis vinifera	0.23 ± 0.02 a	0.42 ± 0.01 a	0.07 ± 0.01 a
Interspecific hybrids	0.85 ± 0.02 c	1.18 ± 0.02 c	0.68 ± 0.02 c
Inter-intra or intra-interspecific hybrids	0.73 ± 0.02 b	1.04 ± 0.02 b	0.64 ± 0.02 b

Means followed by the same letter do not differ significantly at p = 0.05. Values with the prefix ± represent standard deviation.

3.2. Yield

Among the sixteen *V. vinifera* cultivars, only two showed a very high ('Rubinet') or high ('Riesling') ability to compensate for yield after post-budburst frost damage (Table 2). In 2024, these two cultivars produced over 61% of the standard yield. Four cultivars, 'Pinot Blanc', 'Siegerrebe', 'Turan', and 'Zweigeltrebe', showed a medium ability to yield after spring frost. Nine VIN cultivars ('Chasselas Dore', 'Dornfelder', 'Merlot', 'Muscat Ottonel', 'Nektar', 'Pinot Gris', 'Pinot Noir', 'Sauvignon Blanc', and 'Traminer Rot') showed a low ability to yield, and 'Chardonnay' showed a very low ability to yield after spring frost damage. Of the eleven IHs analyzed, seven ('Aurore', 'Bianca', 'Frontenac', 'Leon Millot', 'Seyval Blanc', 'St. Pepin', and 'Vidal Blanc') showed a very high ability to yield, and three ('Marechal Foch', 'Marquette', and 'Swenson Red') showed a high ability to yield from secondary or non-count buds. Only one IH, 'Concord', was characterized by medium yield compensation. Among the twenty-three IIHs, twelve, including 'Regent', 'Solaris', and 'Hibernal'—the most frequently planted cultivars in Poland—and 'Accent', 'Allego', 'Baron', 'Cabernet Cantor', 'Calandro', 'Helios', 'Monarch', 'Orion', and 'Villaris' showed very high ability. Four ('Bolero', 'Felicia', 'Roesler', and 'Saphira') showed a high ability, three ('Cabernet Cortis', 'Johanniter', and 'Reberger') showed a medium ability, three ('Prior', 'Rondo', and 'Souvignier Gris') showed a low ability, and one ('Muscaris') showed a very low ability to compensate for yield after spring frost.

The yield parameters of the analyzed cultivars, such as harvest date, berry and cluster weight, soluble solids, and titratable acid concentration, were comparable to the mean for the last three years.

4. Discussion

The results of this study fully confirm the hypothesis of the difference in secondary, basal, and latent bud fruitfulness among grape cultivars, in accordance with previous reports [10,16,23]. A very low or low ability to compensate for yield after the freezing of primary shoots resulted from the low fruitfulness of secondary and non-count buds, and in this study, it was noted in ten out of sixteen analyzed *V. vinifera* cultivars. This is consistent with the finding that the secondary buds of most *V. vinifera* cultivars produce approximately

30% of the yield that would be obtained from primary buds [17,18]. However, the available data indicate significant differences in the fertility of secondary, basal, and latent buds, as well as in VIN cultivars. 'Chardonnay' and 'Cabernet Sauvignon' (VIN) were characterized by a higher potential secondary bud yield than 'Thompson Seedless' and 'Flame Seedless', and the observed fruitfulness was reduced under local conditions in California in relation to this potential [9]. After the artificial removal of primary shoots from 'Cabernet Sauvignon' and 'Grenache' (VINs) vines, the yield obtained from the developing secondary shoots was half that of the primary shoots under Texas conditions [5]. In 'Barbera' (VIN), under local conditions in Italy, the fruitfulness index for shoots from the secondary buds and suckers was much lower (0.4 and 0.84) compared to shoots produced from primary buds (1.44) [18]. 'Carignane' and 'Tokay' (VINs) were able to restore yield from basal and dormant buds after spring frost under Californian conditions [21].

In this study, the 'Chardonnay' and 'Pinot Noir' cultivars showed lower bud fruitfulness than when grown in New Zealand and Tasmania [19,20]. The yield from the secondary shoots of 'Chardonnay' was 32% of that from the primary shoots [19]. In our study, it was lower than 20%. The differences between this study and previous studies in 'Pinot Noir' may be due to environmental conditions, the earlier phenological phase, and cane pruning under Tasmanian conditions. A high degree of yield compensation from secondary buds was achieved in 'Pinot Noir' when most of the frozen primary buds were in the wooly bud stage [20]. 'Pinot Noir' is a cultivar in which cane pruning is recommended and may improve bud fruitfulness compared to spur pruning [31]. Regardless of the general rules regarding secondary and non-count bud fruitfulness, it should be noted that among the VINs analyzed in this study, there were cultivars with a very high ('Rubinet') and high ('Riesling') ability to compensate for yield after frost.

The present results are consistent with data showing the high fruitfulness of secondary buds and the ability to compensate for yield in IHs such as 'Marechal Foch', 'Seyval Blanc', 'Vidal Blanc' [22,23], and 'Marquette' in conditions in Michigan [24]. 'Concord' (IH) was characterized by a moderate ability to compensate for yield, similar to conditions in Washington State (USA) [26]. The yield of secondary and non-count buds in IIHs varied significantly.

The fruitfulness of secondary and non-count buds, as well as the ability to compensate for yield after frosts, was a cultivar-dependent feature. Cultivars within the group differed in their fertility indices and the ability to compensate for yield, although the PF and FI mean values in the present study were significantly higher in IHs and IIHs than in VINs. 'Rubinet' (VIN) had a very high ability to compensate for yield, while 'Concord' (IH) had a medium ability and 'Muscaris' (IIH) had a very low ability to compensate for yield. The FI of basal buds in 'Muscaris (0.07) in this study was notably lower than in the parental forms 'Solaris' (1.11) and 'Muscat Ottonel' (0.30). In previous studies, 'Muscat Ottonel' basal buds grown under Moldavian conditions were described as fairly fruitful [32].

Frost damage to primary buds and shoots and delayed grape development and maturity on secondary buds affect fruit quality to varying degrees [18,24,26]. In this study, due to the warm spring and summer in 2024, the harvest date, soluble solids, and titratable acid concentration for the analyzed cultivars did not differ significantly from the mean of the previous three years. This finding confirms the role of climate variations in shaping the quality of grapes, inducing the so-called "vintage effect" [33].

These results regarding the fertility of secondary and non-count buds confirm that the use of genetic diversity within *Vitis* spp. may be one of the solutions enabling the adaptation of vineyards to the changing climate and limiting losses caused by spring frost [34,35].

The ecology and biology of grapevine species and cultivars, including response to spring frost, are related to their origin. The genetic differentiation of *V. vinifera* occurred in the Mediterranean, Caspian, and Black Sea regions [36], which are relatively warm regions. The genotypes from this area were not exposed to frequent frost damage. Therefore, they did not create resistance mechanisms. The possibility of producing fruit with seeds after damage to primary buds should also be considered a mechanism. Seed propagation is a means of survival and expansion in the environment. 'Riesling' and 'Rubinet' (VINs) are cultivars originating from northern locations (Germany and the Czech Republic, respectively) with relatively frequent winter and spring frosts. 'Riesling' is an old variety, likely from a random seedling [29]. 'Rubinet' was created as part of a precisely planned breeding program and was carefully assessed before commercial use [29]. In Germany, 'Rubinet' is considered resistant to winter frosts and sensitive to late frosts due to early budburst [29]. However, there is no information in the literature about this cultivar's ability to compensate for yield. Despite the limited development of primary buds after frost occurrences, the good ability to compensate for the yield in 'Rubinet' in this study was determined by the yield from the basal buds.

American species, such as *V. riparia*, *V. rupestris*, *V. lincecumii*, *V. labrusca*, and the Asian *V. amurensis*, were exposed to frost damage in their natural environment. They are often used as donors of frost resistance in hybrids with *V. vinifera* [36]. On the other hand, north-distributed genotypes (*V. riparia*, *V. labrusca*, and *V. amurensis*) were all classified as low-chill, fast-bursting species [35]. Hybrids with a large proportion of *V. riparia*, *V. rupestris*, or *V. lincecumii* are characterized by the ability to compensate for yield after frost [22–24]. Cultivar breeding, especially through hybridization, has a certain element of randomness [27,36,37]. Nowadays, this process is increasingly better controlled by molecular markers and in the context of spring phenology [35].

Productivity is one of the important features characterizing a cultivar. The data collected in previous years indicated that spur-pruned 'Muscaris' yielded less than 'Rubinet', even from primary buds. Differences in fertility have a genetic basis but may be accentuated by the cultivar's pruning preferences [31]. These results confirm the hypothesis and previous reports that losses caused by spring frost may be limited in some cultivars due to yield compensation. The choice of cultivars in areas exposed to spring frost may be considered not only in the context of bud phenology [6,35] but also in the ability to compensate for yield after damage to primary shoots.

Spring frosts not only reduce yield but also disturb the balance of the vine. In this study, after frosts, numerous shoots developed on low-head, spur-pruned vines, the number of which was, on average, three times greater than the target number of shoots usually kept on the vine and needed for standard yielding. This confirms reports that an exceptional event, such as damage to vines or severe pruning, stimulates renewed development and shoot growth [7,16]. After assessing the actual fruitfulness of buds, those fertile shoots that were properly positioned to maintain a low head in the current and subsequent seasons were left on the vines, and their excess was removed. Most of the shoots left on the vines came from basal and secondary buds. The importance of basal buds for the balance of the vine seems to be particularly important after spur pruning. With a similar number of buds on a vine, spurs are more numerous than canes, which means they provide a greater number of points from which shoots develop. Primary shoots that developed after spring frost were few and occurred mainly in 'Riesling', 'Rubinet', 'Turan', and 'Zweigeltrebe'. The relatively late timing ('Riesling') or extension of the budburst phase ('Rubinet') turned out to be a helpful feature in reducing the negative consequences of spring frost. The role of watersprouts (suckers) that arise from latent buds was limited in compensatory yielding. They were most often located too low and inside the canopy, which caused the bunches to be poorly lightened and exposed to rotting. Very few suckers were left for old arm renovation the following year. The percentage of blind nodes on spurs in this study was slightly higher than on table cultivars of cane-pruned vines in Italy [13] and much higher than on 'Sauvignon Blanc' spur and cane-pruned vines in New Zealand [11]. The usual cause of blind nodes is apical dominance and correlative inhibition [11] or low carbohydrate levels [13]. Blind nodes are reported mainly in the proximal or middle part of the canes [11]. In our study, shoots that arose from the basal buds developed and grew faster than secondary shoots likely due to the closer location of the basal buds to the vascular bundles.

The approach to reducing the damage caused by spring frosts is comprehensive and includes aspects such as location, cultivar, close mowing of inter-row herbage, high training of vines, double pruning, delaying bud-break via chemical means, heating, wind machines and helicopters, sprinklers, and artificial fogs [6]. Practical, economic, and ecological aspects limit some of these methods.

The increase in the frequency of frost occurring during the vine growing season [3] and serious frost damage to grapevines recorded in Poland in 2024 indicate that further long-term research on the response of grapevine cultivars to spring frosts is highly recommended. More comprehensive data over a longer period are necessary to suggest cultivars suitable for areas exposed to spring frost. It is advisable to combine research on cultivars and vineyard management. This applies, among others, to bud fruitfulness assessments in high-trunk and cane-pruned vines. The location of the buds along the cane changes their fruitfulness, which is usually higher in the middle and distal parts of the cane than in the proximal part [9,13].

5. Conclusions

Frost damage to primary buds on low-head, spur-pruned vines stimulated renewed development, leading to the growth of shoots from secondary and non-count (basal and latent) buds. The ability to compensate for yield after frost was a cultivar-dependent feature, but most of the analyzed VINs were characterized by lower fertility in their secondary, basal, and latent buds and a reduced capacity to compensate for yield after post-budburst frost damage compared to the IHs and IIHs. A very high or high yield compensation ability was identified in two of the sixteen analyzed VINs ('Rubinet' and 'Riesling'); in ten out of eleven IHs (including 'Bianca', 'Frontenac', and 'Seyval Blanc'); and in sixteen out of twenty-three IIHs (including 'Cabernet Cantor', 'Monarch', 'Hibernal', 'Solaris', and 'Regent'). Future multi-year studies should complement the preliminary findings, providing more comprehensive results.

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