

Potential of Faba Bean (*Vicia faba* L.) for Dual-purpose Vegetable Production and Cover Cropping

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Abstract. Cover cropping has been strongly promoted, but few growers have realized the benefits of this practice due to challenges linked to economic returns and whole-system management. In the western United States, winter legumes including faba bean have the potential to add economic value while offering soil health benefits compared with fallow fields. This experiment assessed the potential of five vegetable faba bean varieties for fresh pod yield, fresh pod quality, and biomass N return under a single and multiple pod harvest scheme. Vegetable faba bean varieties were further compared with two popular cover crop faba bean varieties, ‘Bell bean’ and ‘Sweet Lorane’ for cover crop and biomass N return benefits. The experiment revealed significant ($P \leq 0.05$) genotypic variation for vegetable fresh pod yield, dry biomass, fresh pod quality, pod N removal, biomass N return, and C:N in three testing environments under the single and multiple harvest schemes. Finally, the vegetable variety ‘Vroma’ produced high average fresh pod yield under the single ($16,178 \text{ kg}\cdot\text{ha}^{-1}$) and multiple ($38,928 \text{ kg}\cdot\text{ha}^{-1}$) harvest schemes while maintaining high biomass N return under the single ($119 \text{ kg}\cdot\text{ha}^{-1} \text{ N}$) and multiple harvests ($97 \text{ kg}\cdot\text{ha}^{-1} \text{ N}$) compared with the cover crop varieties ($128 \text{ kg}\cdot\text{ha}^{-1} \text{ N}$). This experiment demonstrated that a single fresh pod harvest on an early and high yielding faba bean variety can generate economic returns while also providing cover crop benefits that are comparable to termination of a faba bean cover crop on the same date.

Since its domestication in the Levant more than 10,000 years ago, faba bean (*Vicia faba*) has been an important grain and vegetable crop for global cuisines and cultures (Caracuta et al. 2015; Flint-Hamilton 1999). Faba bean is popular in countries including Egypt and India and has gained substantial popularity in North America in recent years as consumers’ interests shift to plant-based foods (Liu et al. 2022), protein alternatives

(Arbach et al. 2021), emerging niche markets (Black et al. 2019), and locally sourced and sustainably produced foods (Cholez et al. 2020). In addition, the diversity of dishes and products from faba bean (e.g., roasted, cooked, fried, and canned), its nutrient profile and composition, and its health benefits have attracted many food scientists who are investigating the possible incorporation of faba bean into healthy diets (Dhull et al. 2021). In

keeping with these efforts, plant breeders have invested in the removal of antinutritional factors that can induce hemolytic anemia upon digestion of the bean for those with a genetic condition called favism (Khazaei et al. 2019) while improving more routine agronomic traits (Rubiales and Khazaei 2022). Faba bean is typically harvested when seeds are fully mature, yet the consumption of vegetable faba (i.e., fresh pods and immature seeds) remains popular in many parts of the world (Etemadi et al. 2018a). California’s cultural diversity has created a unique situation where locally grown and specialty crops such as vegetable faba bean have strong consumer demands, especially within Middle Eastern, Asian, and Hispanic communities. In addition, California’s Mediterranean climate is exceptionally suited for a fall planting of faba bean to take advantage of winter rainfall (Brasier et al. 2021).

In California, faba bean is popular as cover crop due to its high biological nitrogen fixation (BNF) potential, strong tap root, and upright growth habit (Smither-Kopperl 2019). As a member of the legume family, faba bean provides benefits in rotational cropping systems as a cash or cover crop (Luce et al. 2016) by adding N to the plant–soil system through the BNF. Faba bean’s BNF benefits are particularly notable due to the crop’s high BNF compared with other legumes (Hossain et al. 2017). This point is clearly observed at a global scale where faba bean makes up roughly 4% of the land area dedicated to pulse crops yet accounts for about 10% of cultivated legume BNF (Herridge et al. 2008). When grown as a cover crop, faba bean is typically ended at the flowering stage and worked into the soil to reduce the risk of reseeding and to enable rapid decomposition (Brennan et al. 2013). Although this approach provides good risk mitigation for farmers, termination at the flowering stage typically reduces the potential economic (i.e., food production) and N benefits compared with continuing crop growth and management for vegetable pod production. In a study of faba bean BNF and accumulation, Silsbury (1990) reported that BNF begins roughly 10 d before flowering and can continue fixing N at a near constant rate through the late reproductive stages. When the crop was taken to full maturity, Silsbury (1990) found that nearly 80% of the faba bean N was fixed during the pod fill stage. The authors further noted that dry faba bean grain contained roughly three-quarters of the plant N—accounting for significant N removal from the plant–soil system. This study demonstrated the potential for leveraging faba bean’s indeterminate growth habit past the flowering stage to produce seed while also continuing to fix N that can be harvested as fresh pods or returned to the soil system. However, limited work has been done to assess N pod removal and N return through unharvested biomass for vegetable faba bean production.

The concept of using faba bean for cover cropping and food is not novel. This dual-purpose approach is routinely practiced by highly innovative community gardeners who

want to build soil N in their garden without sacrificing vegetable production. Further, the exploration of crop production techniques for multiple uses has become a popular area of study in forage systems due farmer needs for greater flexibility and economic returns (Janhi et al. 2019; Sadeghpour et al. 2022; Simon et al. 2021). An important example of modern dual-purpose cropping can be seen on a farmer's field in the southern Great Plains where winter wheat (*Triticum aestivum*) is commonly grown for both cattle grazing and grain harvest (Carver et al. 2001). Another example of this dynamic cropping strategy can be seen in crops such as cowpea (*Vigna unguiculata*) by subsistence farmers where the leaves are harvested as a vegetable before grain harvest (Dube and Fanadzo 2013). Finally, there is evidence for faba bean's dual-purpose use as a vegetable and cover crop where a recent experiment reported a range of 1600 to 16,200 kg-ha⁻¹ fresh faba bean pod across several faba bean varieties before the crop was ended to build soil N (Etemadi et al. 2018b). The common element across these examples is a management decision made at key developmental stages to optimize plant growth or the accumulation and translocation of nutrients to maximize yield or economic value. Dual-purpose production schemes can provide growers with greater management flexibility and can result in net benefits to the soil profile and cash flow of the grower.

The objective of this experiment was to evaluate five vegetable faba bean varieties and two cover crop varieties four dual-purpose cultivation by quantifying 1) vegetable pod production and pod quality from a single harvest at the early pod development stage compared with multiple harvests throughout pod development and 2) N removed in pods and N returned to the soil as biomass after harvesting vegetable pods compared with whole-plant termination as a cover crop.

Materials and Methods

Testing environments and experimental design. The faba bean plots were fall planted at a rate of six seeds/m in tilled soils at the Chico State University Farm in Chico, CA (39°41' N, 121°49' W) during the 2019–20 and 2020–21 growing seasons and at the

Cal Poly Pomona Horsehill Microfarm in Pomona, CA (34°01' N, 117°82' W) during the 2020–21 growing season. Testing environments are hereafter referred to as Chico 2020, Chico 2021, and Pomona 2021 to indicate the combination of testing location and growing season. In Chico 2020 and Pomona 2021, faba bean plots were planted as a single row plot and measured 0.8 m wide and 2.5 m long, whereas the Chico 2021 environment was established as two-row plots that measured 1.5 m wide and 2.5 m long. Soils at the Chico testing location were Chico loam while soils at the Pomona location were Zaca-Apollo clay loam. Cumulative precipitation ranged from 108 mm at Pomona 2021 to 598 mm at Chico 2020 and the Chico environments generally experienced colder minimum and maximum temperatures than the Pomona environment (Table 1).

Faba bean seeds were inoculated with N-DURE Premium Inoculant (Verdesian Life Sciences, Cary, NC) using a slurry method before planting and were sown as a randomized complete block design with three replications per testing environment. The study combined five vegetable faba bean varieties with two harvest schemes for a total 10 experimental units. Each replication also contained two faba bean cover crop varieties (two plots) that were not treated as experimental units but instead served as checks. Vegetable faba bean plots were then subjected to a single early harvest (single harvest) or three harvests over a period of 22 to 26 d depending on the testing environment (multiple harvests; Table 2). The first harvest date was selected to coincide with the first pod stage of the cover crop faba bean varieties. Cover crop varieties were not harvested for vegetable pods and were ended at the same date as the first harvest in each testing environment.

Winter wheat (*Triticum aestivum*) reference strips were sown around the perimeter of the trial at the same time as faba bean planting to estimate the percent of N derived from the atmosphere (%Nd_{fa}) using the natural abundance method (Unkovich 2013) with one reference wheat sample per replication (Cox et al. 2022) according to the following equation:

$$Nd_{fa} = 100 \times \frac{(\delta^{15}N_{wheat} - \delta^{15}N_{faba\ bean})}{(\delta^{15}N_{wheat} - \beta_{faba\ bean})},$$

where $\delta^{15}N_{wheat}$ is the relative abundance of stable isotopic N (¹⁵N/¹⁴N ratio) of sample compared with atmospheric ratio) in the reference plant, $\delta^{15}N_{faba\ bean}$ is the relative abundance of stable isotopic N in the faba bean plant, and $\beta_{faba\ bean}$ is the relative abundance of stable isotopic N of faba bean grown in a N free medium. The $\beta_{faba\ bean}$ bean value of -1.89 was used for all faba bean lines in this experiment following literature-derived value of faba bean at the full pod stage (Nebiyu et al. 2014).

Plant materials. The experiment used five large-seeded vegetable faba bean varieties ('Aguadulce', 'Grano Violetto', 'Masterpiece',

'Vroma', and 'Windsor') that are commonly grown for fresh pod throughout the United States and are popular options for fall planting in California's Mediterranean climate. Additionally, two commonly grown small-seeded cover crop faba bean varieties ('Bell Bean' and 'Sweet Lorane') were also sown (one plot of each variety per replication per environment) to make N benefit comparisons with the five vegetable faba bean varieties (Table 3). The cover crop varieties were not treated as experimental units and therefore excluded from the statistical analysis.

Crop measurements. Plant height and flowering date were collected in the Chico 2021 environment. Plant height was measured at the first harvest (16 Apr 2021) from three random points per plot and flowering date was recorded as the day when flowers were observed on 50% of the plants per plot. At each harvest date, all fully developed fresh pods (between 80% and 90% moisture) were harvested and weighed to calculate the fresh pod yield. Fully grown and marketable pods were harvested as described in Table 2. In Chico 2020, harvested pods were counted, and 10 representative pods from each plot per harvest were measured to determine pod length and weighed to determine the average pod weight. The 10 pods were then separated into bean and shell components to estimate the ratio of bean to whole pod at each harvest date.

Aboveground biomass samples were taken from vegetable faba bean plots by cutting the plants from soil surface following fresh pod harvest (Table 2). Cover crop faba bean plots were not subjected to pod harvests and they were sampled for aboveground biomass by cutting the plant at ground level at the first harvest date, only. Aboveground biomass samples were also taken on a nearby 0.2-m² section of the wheat reference strip per replication on the final date of each harvest scheme (Table 2). Aboveground biomass samples were dried at until they reached a constant weight to calculate biomass yield following the procedure outlined by Cox et al. (2022). The faba bean and reference wheat samples were ground to pass a 2-mm sieve in a Wiley Mill then further ground using a bead beater to produce a fine and well homogenized powder. Ground samples were encapsulated for C and N isotope analysis using an Elementar vario MICRO cube elemental analyzer interfaced on an Elementar VisION isotope ratio mass spectrometer (Elementar Analysensysteme GmbH, Langensfeld, Germany). Aboveground N yield was calculated as the product of N concentration and aboveground biomass yield following vegetable pod harvest. For N analysis, pods and shells were dried, weighed, ground, and finally combusted using a Leco CNS 2000 (LECO Corp., St. Joseph, MO). Pod N removal was calculated as the product of pod dry weight and pod N concentration. Finally, C:N ratio was calculated using results from the elemental analysis and %Nd_{fa} was estimated from the ¹⁵N values of the reference wheat (one sample per replication) and faba

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Table 1. Summary of testing environments with average monthly minimum (Tmin) and maximum (Tmax) temperatures and precipitation (Precip).

Month	Chico 2020			Chico 2021			Pomona 2021		
	Tmin °C	Tmax °C	Precip mm	Tmin °C	Tmax °C	Precip mm	Tmin °C	Tmax °C	Precip mm
Nov	5.1	22.1	42.9	4.3	18.7	30.5	9.9	23.9	8.6
Dec	5.3	12.7	201.2	2.2	15.6	59.7	7.4	20.8	8.6
Jan	4.5	13.2	71.9	4.1	13.6	124.5	7.5	20.0	57.4
Feb	4.9	19.7	0.0	4.9	15.0	31.0	8.3	20.4	2.3
Mar	6.2	17.5	139.7	5.6	17.9	65.8	8.0	20.1	30.5
Apr	9.9	23.8	33.5	8.4	25.5	11.2	11.9	25.1	0.5
May	13.1	27.2	109.2	15.1	30.6	2.3	14.0	26.3	0.0

Table 2. Harvest schemes with corresponding harvest dates in each testing environment.

Environment	Single harvest	Multiple harvests		
	Harvest	First harvest	Second harvest	Third harvest
Chico 2020	20 Apr	20 Apr	29 Apr	12 May
Chico 2021	16 Apr	16 Apr	30 Apr	11 May
Pomona 2021	20 Apr	20 Apr	2 May	16 May

Table 3. End use, plant height at the time of first pod harvest, and flowering date of faba bean varieties in Chico 2021.

End use	Variety	Ht (cm)	Flowering date (Julian)
Vegetable	Aguadulce	116	48
	Grano Violetto	82	37
	Masterpiece	127	43
	Vroma	104	43
	Windsor	110	46
Cover crop	Bell bean	103	54
	Sweet Lorane	98	60

bean samples using the natural abundance method (Unkovich 2013).

Data analysis. Analysis of variance was performed using the GLIMMIX procedure in SAS 9.4 (SAS Institute Inc, 2013) where replication was treated as a random effect to determine the effects ($P \leq 0.05$) of the vegetable faba bean variety within harvest scheme and testing environment. Vegetable faba bean

variety means were compared using least significant differences test at the 95% confidence interval ($P \leq 0.05$).

Results

Fresh pod yield and %Ndfa. Faba bean fresh pod yield varied amongst environment, harvesting scheme, and variety (Table 4).

Averaged over the three environments and five varieties, 10,898 kg·ha⁻¹ of fresh pod was harvested under the single harvest scheme and 24,370 kg·ha⁻¹ of fresh pod was harvested under the multiple harvest scheme. The highest average yield was observed in Chico 2020 under the multiple harvest scheme (Table 1). The average pod yield of single harvest scheme was similar across all environments (ranging from 9900 to 12,470 kg·ha⁻¹). Two additional harvests in the multiple harvests scheme resulted in an addition of 21,704 kg·ha⁻¹ pods in Chico 2020 (+68%), 9999 kg·ha⁻¹ pods in Chico 2021 (+45%), and 8711 kg·ha⁻¹ pods in Pomona 2021 (+47%).

The pod yield of five faba bean vegetable varieties was dependent on the experimental conditions (Table 4). Averaged over three environments and two harvesting schemes, 'Vroma' was the highest yielding variety (27,553 kg·ha⁻¹ of fresh pod) and 'Masterpiece' was the lowest yielding variety (produced 8535 kg·ha⁻¹ of fresh pod). Under the multiple harvest scheme, 'Vroma' produced the highest yield across testing environments (38,928 kg·ha⁻¹), whereas 'Grano Violetto' produced the highest pod yield in single harvest scheme (18,372 kg·ha⁻¹). In comparison, 'Masterpiece' had the lowest average pod yield across environments under the multiple (12,350 kg·ha⁻¹) and the single (4,721 kg·ha⁻¹) harvest scheme. Although a greater average fresh pod yield was achieved with multiple harvests than with a single harvest for all varieties, the advantage of multiple harvests differed by variety. The largest yield increase resulting from harvest scheme was observed for 'Vroma', which produced 94% more yield across testing environments under the multiple harvest scheme than the single harvest scheme.

Total dry mass production of the cover crop varieties ('Bell Bean' and 'Sweet Lorane') and the dry biomass following pod

Table 4. Least square means for vegetable faba bean yield and agronomic traits within environment (Chico 2020, Chico 2021, and Pomona 2021) and harvest scheme (multiple and single). Unharvested (None) cover crop varieties are shown for comparison.

Pod harvest	Variety	Fresh pod yield			Dry biomass			%Ndfa		
		Chico 2020	Chico 2021	Pomona 2021	Chico 2020	Chico 2021	Pomona 2021	Chico 2020	Chico 2021	Pomona 2021
		kg·ha ⁻¹			kg·ha ⁻¹			%		
Multiple	Aguadulce	31,334 bc	21,567 b	14,917 b	5,664 b	2,400 a	1,948	74.1	54.8 ab	57.9 b
	Grano Violetto	21,950 c	20,144 bc	20,086 ab	1,902 c	1,243 b	1,135	73.7	58.8 ab	48.6 c
	Masterpiece	18,800 c	8,917 c	9,333 b	2,267 c	2,615 a	3,317	71.6	57.4 ab	68.7 a
	Vroma	44,700 a	38,434 a	33,650 a	5,175 b	2,188 a	2,727	73.1	47.3 b	57.1 b
	Windsor	43,367 ab	23,284 b	15,067 b	7,679 a	2,013 ab	3,069	70.7	63.4 a	54.2 bc
Single	Average	32,030	22,469	18,611	4,537	2,092	2,439	72.7	56.3	57.3
	Aguadulce	5,450 b	10,117 c	6,800 b	6,714 a	3,240 a	5,689 ab	69.8	39.2 b	61.2
	Grano Violetto	15,867 a	22,667 a	16,584 a	2,583 b	1,410 b	3,096 b	69.2	66.0 a	66.5
	Masterpiece	7,144 b	3,284 d	3,734 b	3,040 b	3,119 a	4,169 ab	66.2	44.6 b	66.7
	Vroma	17,367 a	14,017 b	17,150 a	4,942 ab	2,082 ab	3,744 ab	67.5	60.0 ab	64.8
None	Windsor	5,800 b	12,267 bc	5,234 b	5,016 ab	2,864 a	6,576 a	65.0	55.7 ab	63.4
	Average	10,326	12,470	9,900	4,459	2,543	4,655	67.5	53.1	64.5
	Bell Bean	—	—	—	8,213	2,471	2,873	68.3	54.4	59.6
	Sweet Lorane	—	—	—	9,483	1,830	3,913	62.6	45.5	59.3
	Average	—	—	—	8,848	2,151	3,393	65.5	50.0	59.5

Least significant difference at $P \leq 0.05$ is used to compare trait means for varieties within harvest scheme and environment; means followed by the same letter are not significantly different.

%Ndfa = nitrogen derived from the atmosphere.

harvests of the food varieties is presented in Table 4. Across environments, the two unharvested cover crop varieties produced 4797 kg·ha⁻¹ dry mass by the standard termination time (first harvest, which coincided with the first vegetable pod harvest). In comparison, the average unharvested biomass of the five food varieties over testing environments was 3023 kg·ha⁻¹ under the multiple harvest scheme and 3886 kg·ha⁻¹ under the single harvest scheme. Testing environment had significant impacts on dry biomass of both cover crop and food varieties. By termination time, the two unharvested cover crop varieties produced an average of 8848, 2151, and 3393 kg·ha⁻¹ of dry mas in Chico 2020, Chico 2021, and Pomona 2021, respectively. In the same environments, average biomass of five food varieties over the harvesting schemes was 4498, 2318, and 3547 kg·ha⁻¹, respectively. Two additional pod harvests in the multiple harvests scheme did not affect the average biomass of food varieties in Chico (both 2020 and 2021), although dry biomass did decline under the multiple pod harvest scheme by 2216 kg·ha⁻¹ in Pomona 2021.

The proportion of faba bean N derived from atmospheric fixation (%Ndfa) of cover crop and food varieties in single harvest was measured at the time of harvest and for food varieties in multiple harvest at the third harvest following the completion of the final pod harvest in the multiple harvest scheme (Table 2). Average %Ndfa of the five food varieties were 70% in Chico 2020, 55% in Chico 2021, and 60% in Pomona 2021. Similarly, average %Ndfa of the two unharvested cover crop varieties ('Bell Bean' and 'Sweet Lorane') were 65% in Chico 2020, 50% in Chico 2021, and 59% in Pomona 2021 (Table 4). The pod harvesting schemes (multiple vs. single) did not affect the average %Ndfa of food varieties. However, the multiple harvest scheme resulted in a %Ndfa reduction by 16% for 'Aguadulce' and 13% for 'Windsor' while increasing by 13% for

'Vroma' compared with the single harvest treatment in Chico 2021.

Keeping with the trend of flowering date (Table 3), the five food varieties reached maximum pod production at different times (Fig. 1). Under the multiple harvest scheme, 'Vroma' produced the highest fresh pod yield (38,928 kg·ha⁻¹) across testing environments. The bulk of 'Vroma's' fresh pods were harvested at the first harvest date (mid-April; 20,632 kg·ha⁻¹; 53%) while decreasing at the second harvest date (late-April; 9732 kg·ha⁻¹; 25%) and decreasing again at the third harvest (mid-May; 8564 kg·ha⁻¹; 22%). Keeping with the early harvest trend, 'Grano Violetto' had average fresh pod yields of 14,301 kg·ha⁻¹ at the first harvest (mid-April; 69%), 4353 kg·ha⁻¹ at the second harvest (late-April; 21%), and 2073 kg·ha⁻¹ at the third harvest (mid-May; 10%). These two varieties ('Vroma' and 'Grano Violetto') may be good candidates for single harvest and early termination. In comparison, pod production of the other three food varieties was more evenly distributed across the three harvests dates.

Fresh pod quality. Fresh pod quality traits were assessed in the Chico 2020 environment which included number of pods per square meter, pod weight, pod length, and the ratio of bean to pod (Fig. 2). The trial produced an average of 72 pods per m² at the first harvest, 69 pods per m² at the second harvest, and 89 pods per m² at the third harvest. Much of the variation across harvest dates was variety dependent. For instance, the number of pods per square meter for early-flowering varieties such as 'Grano Violetto' decreased at later harvests whereas the opposite trend was observed for later flowering varieties including 'Aguadulce'. The average pod weight stayed constant over the course of the trial starting at 27 g per pod at the first harvest and increased to 28 g per pod at the second harvest before decreasing to 26 g per pod at the third harvest. Similar to the case of pods per square meter, early-flowering varieties decreased in pod weight at later harvest dates, whereas

later flowering varieties increased in pod weight at later harvest dates. This link between flowering date and pod quality was also reflected in the bean to pod ratio. Here, the average bean to pod ratio was 0.31 at the first harvest, 0.35 at the second harvest, and 0.38 at the third harvest. Faba bean pod length tended to decrease at later harvest dates for all varieties. The average pod length was 18 cm at the first and second harvest dates and 14 cm at the third harvest.

Nitrogen removal and return. Pod N removal, biomass N return, and biomass C:N are shown in Table 5. Across testing environments, pod N removal was 65 kg·ha⁻¹ N under the multiple harvest scheme and 36 kg·ha⁻¹ N under the single harvest scheme. The single harvest scheme resulted in a removal of similar amounts of pod N from the three environments (34–37 kg·ha⁻¹ N), whereas the multiple harvest scheme resulted in pod N removal ranging from 49 kg·ha⁻¹ N in Chico 2021 to 93 kg·ha⁻¹ N in Chico 2020. Averaged across environments, 'Vroma' had the highest pod N removal (100 kg·ha⁻¹ N) and 'Masterpiece' had the lowest pod N removal (31 kg·ha⁻¹ N). Within the single harvest scheme, 'Grano Violetto' had the highest pod N removal (65 kg·ha⁻¹ N) and 'Masterpiece' had the lowest pod N removal (16 kg·ha⁻¹ N) over testing environments.

The unharvested cover crop varieties ('Bell Bean' and 'Sweet Lorane') accumulated an average biomass N return of 218 kg·ha⁻¹ N in Chico 2020, 68 kg·ha⁻¹ N in Chico 2021, and 100 kg·ha⁻¹ N in Pomona 2021 (Table 5). In the same set of environments, average biomass N return of food varieties was 184 kg·ha⁻¹ N in Chico 2020, 54 kg·ha⁻¹ N in Chico 2021, and 36 kg·ha⁻¹ N under the multiple harvest scheme and 209 kg·ha⁻¹ N in Chico 2020, 67 kg·ha⁻¹ N in Chico 2020, and 116 kg·ha⁻¹ N in the single harvest scheme. Within each environment, the multiple pod harvest scheme reduced the biomass N return by 25 (14%), 13 (24%), and 87 (341%) kg·ha⁻¹ N compared with the single harvest scheme in Chico

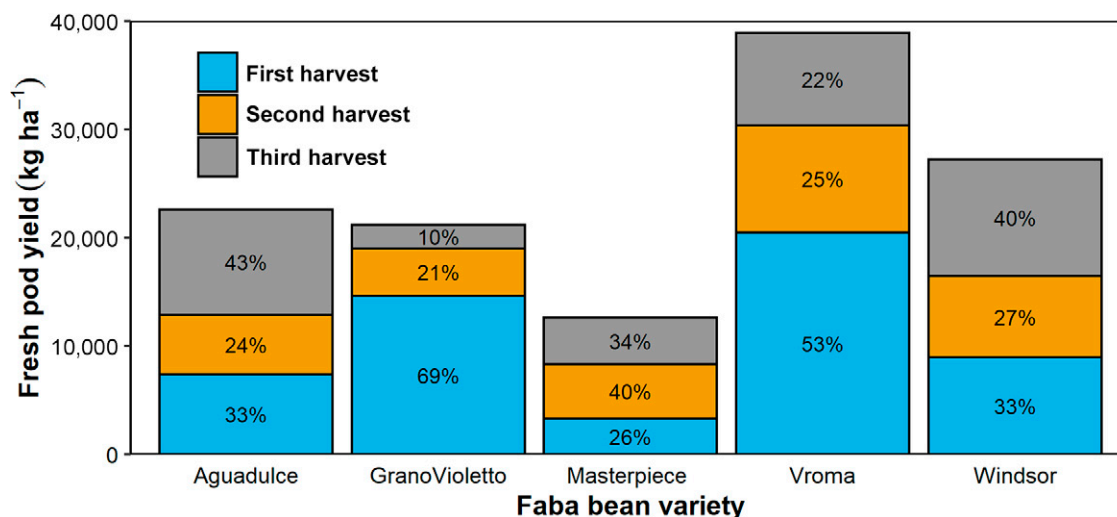


Fig. 1. Comparison of faba bean fresh pod yield from the three time points of the multiple harvest scheme across testing environments (Chico 2020, Chico 2021, and Pomona 2021).

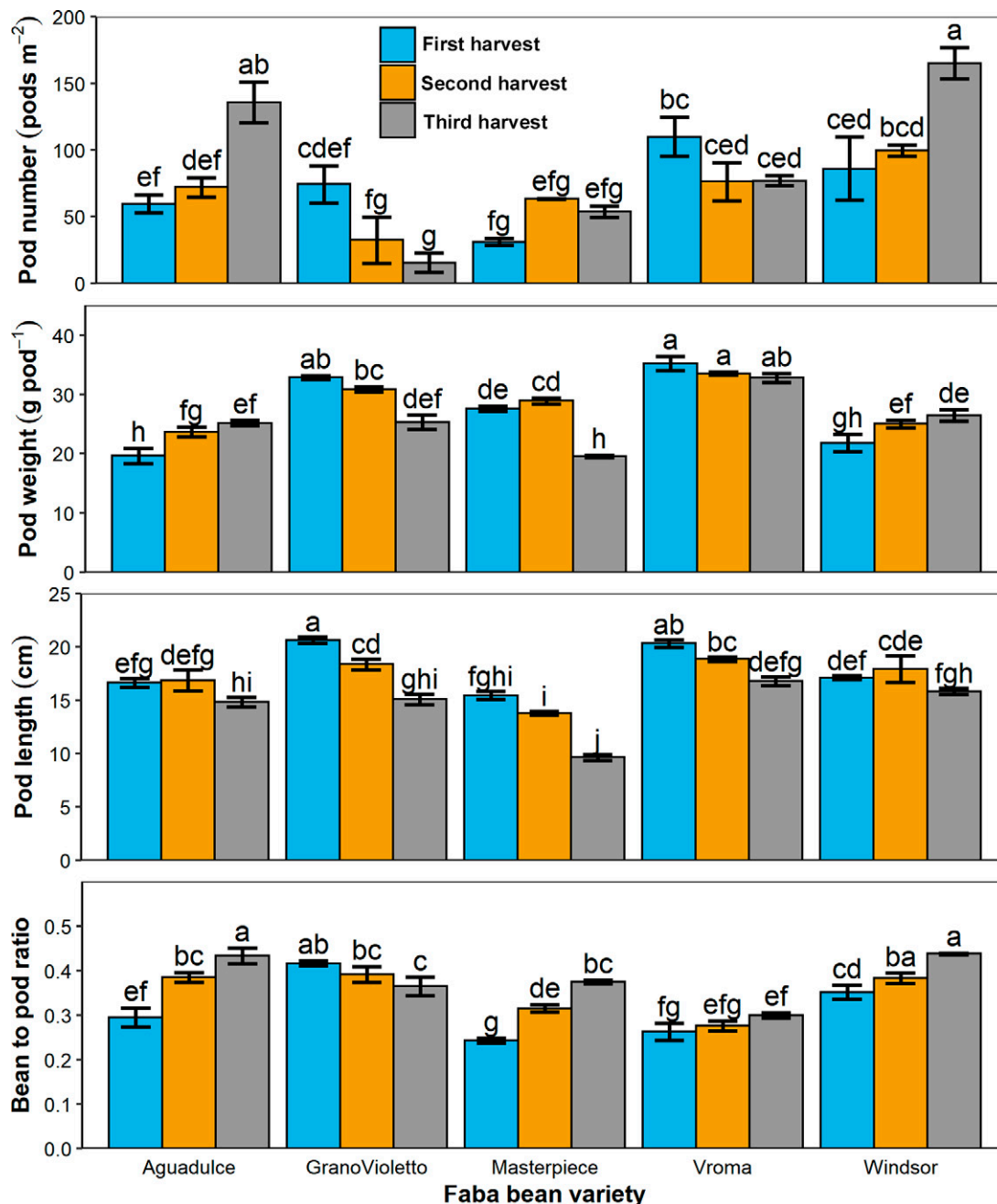


Fig. 2. Comparison of faba bean vegetable quality traits from the three harvests within the multiple harvest scheme in Chico 2020. Least significant difference at $P \leq 0.05$ is used to compare trait means for varieties and harvest numbers within the multiple harvest scheme; means followed by the same letter are not significantly different. Error bars represent standard error.

2020, Chico 2021, and Pomona 2021, respectively. Average C:N ratio of food varieties across harvest schemes was 21 in Chico 2020, 17 in Chico 2021, and 24 in Pomona 2021. The effect of harvesting scheme on C:N ratio was inconsistent across testing environments and faba bean varieties. The high C:N ratio of plant biomass in the multiple harvest treatment in this environment appeared in all varieties except 'Masterpiece', which may have been due to low pod yield and low pod N removal by this variety.

The source of accumulated N in biomass at harvesting (biomass N return) from atmospheric fixation (Fixed-N) and soil N uptake (Soil-N) is presented by testing environment

in Fig. 3. Similar to total biomass N return, the proportion of Fixed-N and Soil-N was different under the experimental conditions. Across harvest schemes and testing environments, $73 \text{ kg} \cdot \text{ha}^{-1}$ of biomass N of the five food varieties at termination was from BNF, and the remaining $37 \text{ kg} \cdot \text{ha}^{-1}$ was the N that plants had taken from the soil. In comparison, the two cover crop varieties accumulated $78 \text{ kg} \cdot \text{ha}^{-1}$ N from BNF and took up $50 \text{ kg} \cdot \text{ha}^{-1}$ N from the soil over testing environments. The highest biomass N return derived from BNF was in Chico 2020 where food (averaged over harvest schemes) and cover crop varieties accumulated 138 and $142 \text{ kg} \cdot \text{ha}^{-1}$ atmospheric N, and 59 , and $76 \text{ kg} \cdot \text{ha}^{-1}$ soil N, respectively. The effect of harvest scheme (i.e., pod removal) on

the source of biomass N was significant in Pomona 2021, where the biomass N return from the multiple harvest scheme returned $59 \text{ kg} \cdot \text{ha}^{-1}$ N less N than single harvest scheme. This variation was especially high in 'Aguadulce' and 'Windsor,' which returned 85 and $105 \text{ kg} \cdot \text{ha}^{-1}$ N less Fixed-N in the multiple harvest scheme than the single harvest scheme.

Discussion

This study sought to explore the potential of fresh faba bean pod production under two harvest schemes and to assess aboveground biomass nitrogen return after vegetable harvest. Our results showed that there are

Table 5. Least square means for vegetable faba bean N traits within environment (Chico 2020, Chico 2021, and Pomona 2021) and harvest scheme (Multiple and Single). Unharvested (None) cover crop varieties are shown for comparison.

Pod harvest	Variety	Pod N removal			Biomass N return			Biomass C:N		
		Chico 2020	Chico 2021	Pomona 2021	Chico 2020	Chico 2021	Pomona 2021	Chico 2020	Chico 2021	Pomona 2021
		kg·ha ⁻¹ N			kg·ha ⁻¹ N					
Multiple	Aguadulce	93 ab	45 ab	45 ab	239 a	53 b	25 b	22	19 ab	33
	Grano Violetto	63 b	59 ab	56 ab	74 b	39 b	14 b	23	13 c	33
	Masterpiece	51 b	16 b	25 b	84 b	82 a	60 a	25	13 c	24
	Vroma	132 a	68 a	99 a	218 a	41 b	33 b	22	22 a	35
	Windsor	127 a	57 ab	43 ab	306 a	56 b	36 b	25	15 bc	36
	Average	93	49	54	184	54	36	23	17	32
Single	Aguadulce	18 c	28 b	24 ab	335 a	79	157 ab	19 b	17	16 bc
	Grano Violetto	56 ab	80 a	58 a	129 b	35	71 b	18 b	16	18 a
	Masterpiece	27 bc	7 c	13 b	143 b	83	105 ab	19 ab	17	17 ab
	Vroma	63 a	35 b	57 a	216 ab	52	89 ab	21 a	17	17 ab
	Windsor	20 c	29 b	18 b	222 ab	83	194 a	21 a	15	14 c
	Average	37	36	34	209	67	123	19	16	16
None	Bell Bean	—	—	—	211	70	79	16	15	15
	Sweet Lorane	—	—	—	224	65	116	17	11	14
	Average	—	—	—	218	68	98	17	13	15

Least significant difference at $P \leq 0.05$ is used to compare trait means for varieties within each harvest scheme and environment; means followed by the same letter are not significantly different.

opportunities to use faba bean as an autumn sown dual-use vegetable and cover crop.

Pairing cultivar choice with management strategy. On-farm management and harvest decisions are often the product of balancing a complex suite of factors including market demands (Griffey et al. 2010), economic return (Carreiro et al. 2022), labor availability (Greene 2018), postharvest requirements (Lobos et al. 2014), and pest pressures (Mesele et al. 2016). Although some of these factors are outside of a grower's control, it is possible to focus on production decisions from preplant to harvest. Because labor accounts for roughly half of vegetable production costs in California's low-input faba bean operations, farmers must gauge the quality of their crop and market trends to determine if a single- or multiharvest approach will add value. These types of economic driven considerations are essential for the success of small- and large-scale vegetable faba bean farms that stand to benefit from selecting the right cultivar for their operation. In the present study, early-flowering faba bean cultivars, including 'Vroma' and 'Grano Violetto', produced high fresh pod yields with a single harvest early in the season, offering a strong "first-to-market" production scheme. This single harvest approach may best align with the needs of producers operating on large farms who need to account for labor costs and harvest priorities (Johnson et al. 2019). The present study also demonstrated that growers seeking yield optimization could select varieties such as 'Windsor' that have consistent fresh pod production over a span of roughly 25 d, making it a popular choice for small-scale farmers.

Fresh pod quality followed a similar trend as pod yield where the interaction of harvest date and cultivar was deterministic of pod length, pod weight, and the bean to pod ratio. Similar impacts of variety and harvest date have been observed for vegetable pod yield and quality in edamame (Moseley et al.

2021). Here, the authors noted that the period between the early reproductive stage and harvest is a strong driver of vegetable pod yield and pod quality. In an ambitious experiment that sought to characterize a panel of faba bean landraces and commercial varieties, De Cillis et al. (2019) similarly uncovered strong genotypic variation for fresh pod and fresh bean quality for traits. These findings were consistent with those of the present investigation that reported significant genotypic variation for pod length and pod number.

Management as vegetable or cover crop for farm optimization. Although the pairing of faba bean variety with a market-driven choice in production system is key to the economic success of a farm, many growers are also interested in the cover crop benefits of faba bean for soil health. Taking a flexible management approach for a low-input and indeterminate legume crop, such as faba bean, gives growers the opportunity to make decisions at two key stages: first pod stage and horticultural maturity. In the present investigation, the quantity of N returned was compared for cover crop varieties and harvested vegetable varieties of faba bean. Here, two cover crop faba bean varieties were ended around the first pod stage, which returned an average of 128 kg·ha⁻¹ N (61% from fixed N and 39% from soil N) to the plant-soil system from aboveground biomass across testing environments. By comparison, a total of 133 kg·ha⁻¹ N (68% from fixed N and 32% from soil N) and 91 kg·ha⁻¹ N (64% from fixed N and 36% from soil N) was returned as aboveground biomass from the single harvest and multiharvest schemes, respectively. These small variations in %Ndff due to the harvesting scheme could be the results of changing plant $\delta^{15}N$ compositions due to varied $\delta^{15}N$ composition of removed pods and remaining biomass (López-Bellido et al. 2010). Further, the amount of biomass N returned from harvested faba bean in the

present study was high. This result is well observed by the sums of pod N removal and biomass N return for the single harvest scheme was 169 kg·ha⁻¹ N and the multiple harvest scheme was 156 kg·ha⁻¹ N compared with that of 128 kg·ha⁻¹ N for the cover crop varieties. Indeed, this result is consistent with N accumulation trends post-flowering in cultivated legumes (Etemadi et al. 2018a; Pampana et al. 2016; Schulze 2003; Zakeri and Bueckert 2015). These studies broadly highlight the reduction in BNF activity during the pod fill stage while the plant experiences changes in the source-to-sink relationship.

In a recent review of faba bean for sustainable cropping systems, Karkanis et al. (2018) outlined the potential benefits of single mechanical harvests and multiple hand harvests. Here, the authors emphasized the benefits of combining superior genetic material with strong agronomic practices to increase crop yield and quality while also contributing to the improvement of soil and environmental health. In the spirit of this concept, Gatsios et al. (2021) observed tomato (*Solanum lycopersicum*) yields after cultivation of cowpea, cultivation of common bean (*Phaseolus vulgaris*), and green manuring of faba bean. The authors found that the highest tomato yields (largely driven by the number of fruit per plant) were achieved when following green manure faba bean (15.8 kg·m⁻²) then by harvested cowpea (14.5 kg·m⁻²) and harvested common bean (11.4 kg·m⁻²). Although the authors did not include cultivated faba bean as a factor in their experiment, the actual impacts on tomato yields following harvested legumes compared with cover crop faba bean is clearly illustrated.

The present experiment demonstrated that harvesting fresh pods from vegetable faba bean varieties can result in greater biomass N return than cover crop varieties. However, the authors caution that the different potentials of food and cover crop varieties for

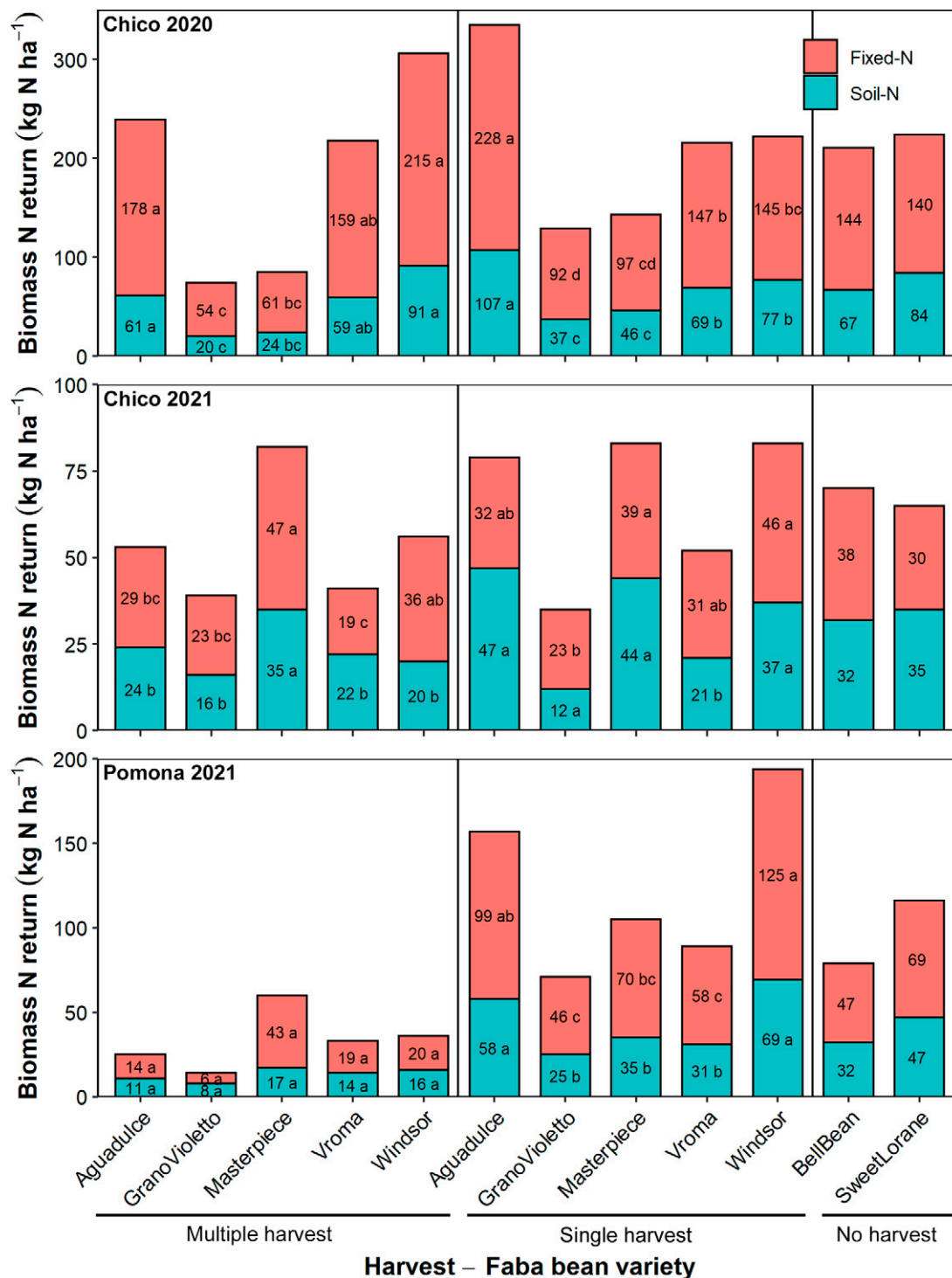


Fig. 3. Biomass N return broken into N derived from fixation and soil uptake in each environment. Means followed by the same letter within each environment and harvest scheme are not significantly different. The two cover crop varieties were not included in the data analysis.

biomass production should be considered in this comparison. Compared with small and medium-size faba bean cover crop varieties, food varieties are large-seeded and known to produce greater biomass yields—a large driver in biomass N return (Boots-Haupt et al. 2022). Genotypic effects on biomass N return were observed among vegetable faba bean varieties in the present study under the single and multiple harvest schemes. For example, ‘Aguadulce’ and ‘Windsor’ had high biomass N return, which was equal to or

greater than the cover crop varieties under the single harvest scheme, whereas ‘Grano Violetto’ consistently produced the lowest biomass N return in all three environments. These findings indicate a strong potential for fresh pod yield and biomass N return benefits derived from crop harvest from a high yielding faba bean variety. However, a grower must still consider the potential economic return of ending the faba bean for cover cropping then cultivating a higher value cash crop (Drewnoski et al. 2018).

Decomposition of plant biomass may also have a pivotal role in the determination of faba bean harvest scheme or termination for cover cropping. A grower must consider factors that include moisture, temperature, termination strategy, and soil tillage to prepare for the following crop (Thapa et al. 2022). In the present investigation, the average C:N ratio of cover crop varieties ranged from 13 to 17 across environments, whereas the average vegetable variety averages ranged from 16 to 19 across environments under the

single harvest scheme and 17 to 32 across environments under the multiple harvest scheme. These C:N ratios are consistent with the existing literature for cover crop biomass (Wendling et al. 2016) and harvested crop biomass (Luce et al. 2014). Much of the variation between the single harvest and multiple harvest faba bean in the present study is likely due to the remobilization of N to the harvested fresh pods (Etemadi et al. 2018a). Previous investigations have reported significant increases in tomato and sweet corn (*Zea mays*) yield to the pairing of cover crop faba bean with agronomic management (i.e., plastic mulching and tillage) that synchronizes cover crop decomposition with needs of the following cash crop (Etemadi et al. 2018c; Galieni et al. 2017). It stands to reason that the vegetable faba bean following a single harvest scheme could provide benefits that are similar to that of the cover crop faba bean. However, there are some concerns of N loss from the plant-soil system due to the low C:N ratio and high aboveground N yield of cover crop faba bean (Karkanis et al. 2018). Although this indeed poses some risk, N loss from faba bean green manure has been shown to be reduced with agronomic practices such as termination method and tillage (Badagliacca et al. 2018).

Biomass from the faba bean varieties that were subjected to one or multiple harvests had higher C:N than the green manure cover crop varieties in the present investigation. Although this may be problematic for some farmers that have major concerns about cover crop biomass residue, this management strategy provides opportunities in regions that regulate N applications. For instance, California's Central Coast Regional Water Board adopted Ag Order 4.0. This regulation places limits on N applications while offering incentives for sustainable agronomic practices such as cover cropping (Carlisle et al. 2022). Under Ag Order 4.0, a C:N minimum limit of 20:1 has been set for cover crops, generally restricting the use of legume cover crops such as faba bean. In scenarios such as this, growers may be able to produce a viable faba bean vegetable crop using a multiple harvest strategy, contribute to soil organic matter, and produce a high yielding cash crop after faba bean.

In conclusion, faba bean shows great potential to achieve dual purpose benefits of cash and cover cropping. The experiment reported significant ($P \leq 0.05$) genotypic variation fresh pod yield, biomass, pod quality traits, biomass N return, and C:N ratio for the vegetable varieties. This result indicates that growers can select cultivars that better fit their production scheme to produce vegetable products and add cover crop benefits. The use of a single harvest on an early- and high-yielding faba bean variety has the potential to produce an economic return from fresh vegetable pods while also having biomass N returns that are comparable to termination of a cover crop on the same date. This prospect is well demonstrated by the vegetable variety, 'Vroma', which produced high average fresh pod yields under the single harvest scheme

(16,178 kg·ha⁻¹) while maintaining high biomass N return (119 kg·ha⁻¹ N). Growers can benefit from this study with a more compatible pairing of variety with harvest scheme to fit their farm management system.

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