

Review

Companion Crops as Catalysts for Sustainable Cover Cropping in Vineyards—A Critical Review and Research Agenda

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Abstract

Vineyard cover crops deliver well-documented ecosystem services, yet consistent establishment, especially of perennial grasses and legumes, remains a primary barrier to adoption. This review reframes “companion (nurse) cropping” not as a new crop class but as a facilitative establishment strategy within the broader cover-/service-crop literature. We (i) position our contribution relative to recent syntheses, (ii) synthesize evidence on companion crops practices that reduce cover cropping early failure risk, and (iii) propose a testable research agenda. A focused scoping review of peer-reviewed and extension literature indexed in Web of Science and Google Scholar was conducted using search terms encompassing cover/service crops and nurse/companion/facilitation in viticulture systems. Across climates, fast-establishing cereals (*Avena sativa*, *Hordeum vulgare*, *Secale cereale*, × *Triticosecale* Wittmack) and short-cycle legumes (*Vicia sativa*, *Pisum sativum*, *Trifolium incarnatum*) can reliably “nurse” slower perennials and legumes by providing early groundcover, weeds control, and microclimate buffering when sown at reduced rates (≈25–50% of monoculture) and terminated on time to limit vine competition. Evidence gaps persist for in-row applications, water-use penalties under drought, and long-term effects on yield and grape composition. Companion cropping is argued to be a design principle in vineyard cover-crop programs rather than a separate category. A decision framework and research agenda are presented to quantify establishment reliability, resource trade-offs, and wine-relevant outcomes, and it is recommended that future decision tools make the companion-phase logic explicit to de-risk adoption and align with regional guidelines.

Keywords: cereal–legume mixtures; ecosystem services; establishment success; grapevine competition; microclimate moderation; resource competition; vegetation regulation

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1. Introduction

Viticulture cover cropping, or the technique of growing non-vine plants on the vineyard floor, has emerged as a key component of sustainable vineyard management around the world. Cover crops are integral to vineyard groundcover management, providing ecosystem services that include erosion control, soil carbon and structural improvement, soil water regulation, nutrient cycling, restoring soil compaction, enhanced trafficability, vineyard microclimate buffering, weed suppression, pest and disease management, vigor regulation, and conservation of biodiversity [1–5]. However, cover crop establishment frequently faces substantial challenges, most notably the poor germination and growth rates

of preferred species, particularly legumes and perennial grasses, which make them susceptible to aggressive weeds [6–8]. Cover crop establishment reliability in vineyards remains a primary barrier to adoption. In Spanish vineyards, insufficient duration and intensity of vegetation cover resulted in minimal benefits from cover cropping practice as the biomass produced was inadequate to offset soil disturbance from tillage [9]. Poor early growth exposes soil to erosion and weed colonization, which negates the desired benefits. Thus, viticulturists have a clear incentive to adopt strategies that ensure rapid, uniform, and robust cover crop establishment and this is precisely where companion crops are valuable [5,10]. Companion cropping is an efficient method in which pairs a fast-establishing short-lived species, typically a cereal, sometimes a short-cycle legume, with a slower primary cover crop, usually perennial grasses and legumes, to provide immediate groundcover, protection from harsh sun or wind, weed suppression, and erosion control during establishment [11–13]. Once the primary cover crop has been established, the nursing crop is routinely eliminated (by mowing, tillage, or natural senescence) so that it does not compete in the long run [12].

In viticulture, deliberate cover cropping expanded in the late 20th century following decades of bare-soil management through tillage and herbicides. As researchers and practitioners sought more reliable vineyard groundcovers, they found that mixtures of fast- and slow-growing species reduced risks inherent in monocultures: quick annuals provided immediate cover while slower perennials or N-fixing legumes established. Extension guidelines began recommending low rates of annual grasses with perennials to secure first-year soil cover, since perennials alone establish slowly, leaving soil vulnerable to erosion and weed invasion [14,15]. Although traditional European vineyardists sometimes interplanted cereals or other green plants in young vineyards, reflecting ancient polyculture and sheltering practices, the explicit, research-driven framing of one species as a “nurse/companion” in cover crop mixtures is relatively recent [4]. The ecological principle of facilitation, where one species modifies conditions to benefit another, has long been recognized in natural and agricultural systems and formalized in the ecological literature [13]. By the 2000s, Mediterranean vineyard trials paired fast cereals such as oats with legumes like clover or peas to provide both rapid groundcover and biological N inputs. In Portugal, Monteiro and Lopes [11] showed that cereal-based mixtures reduced soil evaporation and altered vineyard water use while improving groundcover compared to bare or less effective treatments. In southern Spain, oat–vetch (*Vicia sativa*) mixtures (70:30) were tested as “sacrificial” covers to divert rabbit foraging, illustrating how nurse/companion logic can also address pest-management challenges [16]. These examples demonstrate how a principle long applied in forages could be adapted to viticulture for establishment, protection, and system resilience.

The terms cover crops and service crops are used in line with current literature, with companion cropping framed as a facilitative establishment strategy within these categories rather than a separate functional type. This framing, analogous to forage systems, reduces ambiguity and situates the review within prevailing usage. This paper provides a focused synthesis of the establishment phase including companion-enabled mixtures, seeding-rate fractions, termination strategies, and in-row versus inter-row deployment, culminating in a decision framework and research agenda for improving cover crops establishment reliability in vineyards. This emphasis on establishment design complements prior reviews that addressed ecosystem services, agronomic performance, and water relations [1,3–5]. The objectives of this review paper are to (i) align terminology by positioning companion cropping as a facilitative strategy within cover/service-crop practice; (ii) synthesize design principles for establishment, including companion choice, seeding rates, and termination timing; (iii) identify research gaps concerning in-row living mulches, water–nitrogen trade-offs, and vine-relevant outcomes; and (iv) propose testable

hypotheses and breeding targets. The review evaluates current techniques, highlights novel viticultural applications, and provides an updated synthesis of research and practice in this domain.

2. Methods: Focused Scoping Review Approach

The effects of facilitative companion species on establishment success, early-season functions, and trade-offs in vineyard cover-crop programs were evaluated for both inter-row and in-row zones. Literature was retrieved from the Web of Science Core Collection and Google Scholar using Boolean combinations of (“cover crop” OR “service crop”) AND (nurse OR companion OR facilitation) AND (vineyard OR viticulture OR grapes), supplemented with vineyard position terms (alleyway, inter-row, under-vine, in-row, under-trellis), for publications available in these databases up to 13 September 2025. Publication on each target facilitative companion species searched separately using the same databases. Grey literature from extension bulletins was included when methods and contexts were explicitly described. Eligible sources comprised field or greenhouse studies and reviews reporting establishment metrics (stand density, early biomass), weed or erosion proxies, mixture seeding-rate guidance, termination timing, or vine water/nitrogen status. Findings were narratively synthesized against baseline reviews [1,3–5] to minimize duplication and identify research gaps. Findings were structured by outcome and explicitly report where evidence is abundant, moderate, or sparse to guide the agenda above.

3. Companion Crops in Vineyard Cover Crop Systems

3.1. Companion Crop Species

The most common companion crops in vineyard cover systems are fast-establishing cereals and grasses (Table 1). Oats (*Avena sativa*), for example, germinate rapidly in cool soils, producing early biomass that suppresses weeds and stabilizes the soil while slower species such as perennial clovers or grasses establish [14]. In temperate regions, late-summer or fall-sown oats typically winterkill, providing groundcover in autumn and subsequently leaving a mulch that conserves soil moisture and suppresses early spring weeds as legumes resume growth [7]. When spring-sown, oats mature by early to mid-summer and must be terminated before seed set, usually by mowing when intercropped or by disking/roller-crimping if seeded alone [11]. Cereal–legume mixtures consistently enhance biomass accumulation, ecosystem service delivery, and stand stability across nitrogen and termination regimes [17–19], with residues contributing to vegetation regulation (weed control) through competition and mulching [20]. In temperate zones, oats combined with legumes serve either as companion crops facilitating establishment or as short-term green manures. These mixtures often outperform monocultures, even under stressful conditions such as saline soils [21], highlighting the value of rapid oat cover in supporting legume performance. Achieving stable, multifunctional stands requires selecting complementary species and moderating seeding rates so that fast companions provide early cover without overwhelming slower components [22].

Table 1. Companion crop species for vineyards and their main characteristics.

Species (Scientific Name)	Common Name	Growth Traits	Main Roles as Companion/Nurse	Key Considerations
Cereals & Grasses				
<i>Avena sativa</i> L.	Oat	Rapid germination, cool-season, high early biomass	Fast groundcover, weed suppression, soil stabilization, mulch after winterkill	Self-terminates in frost-prone zones; reduce seeding rate to avoid dominance
<i>Hordeum vulgare</i> L.	Barley	Rapid growth, cool-season, moderate shading	Early cover, weed suppression, structural support for legumes, balanced light penetration	Tolerate temperatures down to about −6 to −8 °C, tolerates shading, moderate competition
<i>Lolium multiflorum</i> Lam.	Annual ryegrass	Dense root system, fast establishment	Erosion control, early weed suppression, soil stabilization	Can persist in warm climates; may need timely mowing, winterkills in cold climate; potential of being invasive in some climates
<i>Secale cereale</i> L.	Fall rye	Rapid growth, drought/cold tolerant	Strong weed suppression (allelopathy), erosion control, nitrogen scavenging	Can become overly competitive; terminate early
× <i>Triticosecale</i> Wittmack ex A. Camus	Triticale	Intermediate-fast establishment, high biomass, nutrient scavenger, lodging resistance	Quick cover, weed suppression, structural support	More stress tolerant than wheat but less than fall rye; canopy height shorter than fall rye
Legumes				
<i>Pisum sativum</i> L. (subsp. <i>arvense</i>)	Field pea (Austrian winter pea)	Rapid emergence, vining, large seed	Nitrogen fixation, climbs cereals for support, biomass production	Usually winterkills; paired with oats in mixtures; not suitable for under-vine
<i>Trifolium alexandrinum</i> L.	Berseem clover	Fast-growing annual; erect habit; rapid early biomass; low winter hardiness; low drought tolerance; large seed;	Early groundcover and weed suppression; strong nitrogen fixation; supports establishment in perennial legume mixtures	Frost-sensitive; terminate before seed set; pair with cereals to moderate nitrogen and vigor; monitor re-seeding in warm regions
<i>Trifolium incarnatum</i> L.	Crimson clover	Quick germination, dense canopy, winter annual	Early weed suppression, nitrogen fixation, floral resource; supports establishment in perennial legume mixtures	Often used in mixes with ryegrass/oats
<i>Vicia faba</i> L.	Fava bean/bell bean	Quick germination, large seeds, robust seedlings, tall canopy	Fast cover, strong nitrogen fixation	Can add excess nitrogen (risk of vine vigor); balance with cereals; warm season
<i>Vicia sativa</i> L.	Common vetch	Aggressive growth, vine-like habit	Nitrogen fixation, cover in mixtures with cereals	Needs support; can become competitive if unmanaged; not suitable for under-vine
Other Broadleaves/Brassicas				
<i>Brassica</i> spp. (e.g., <i>Sinapis alba</i> L.)	Mustards	Fast growth, tall canopy	Weed suppression, floral resources, nitrogen cycling	Short cycle; terminate before seed set or can be invasive; not suitable for under-vine
<i>Fagopyrum esculentum</i> Moench	Buckwheat	Very rapid growth (30–40 days), allelopathic, frost- and drought-sensitive	Weed suppression, pollinator habitat	Must terminate early to avoid reseedling; not suitable for under-vine
<i>Raphanus sativus</i> L. var. <i>longipinnatus</i> (L.H. Bailey) Hanelt	Tillage (Daikon or oilseed) radish	Fast-growing annual; large taproot, rapid leaf growth, frost-sensitive	Soil decompaction, nutrient retrieval, canopy cover	Sensitive to heat → bolting; cool-season; winterkills

Cereal companion crops such as barley (*Hordeum vulgare*), fall rye (*Secale cereale*), and triticale (× *Triticosecale* Wittmack) provide complementary functional traits in mixture design. Barley's upright canopy, with moderate shading, facilitates coexistence with under-story legumes by allowing adequate light penetration while still delivering early

groundcover and structural support [23]. Its ability to tolerate moderate shading without major yield loss in intercropping systems reflects a balance between cover provision and minimal suppression of companion species [24]. Fall rye, in particular, is exceptionally winter-hardy and rapidly produces dense spring biomass and fibrous roots that stabilize soil and scavenge residual nitrate; meta-analyses show non-legume cover crops, especially fall rye, reduce nitrate leaching by ~50–70% compared with fallow [25–27]. Weed suppression arises both from physical mulching and allelopathy via benzoxazinoids released from shoots and roots, which inhibit germination and early growth of small-seeded weeds and some cover crops [28–31]. Because fall rye residues often have high carbon:nitrogen, late termination can temporarily immobilize soil nitrogen and slow release to companions; pairing fall rye with a legume or terminating near anthesis mitigates this trade-off [32,33]. In vineyards, vigorous spring rye can also compete with vines for water and nitrogen in dry climates, so mowing or roller-crimping at flowering is recommended to form a stable mulch while minimizing competition [12,23,24]. Deployed as a fall-sown nurse/companion, fall rye protects soil over winter, provides scaffolding for vining legumes (e.g., vetch or pea), suppresses weeds, and when terminated after vine flowering can preserve spring soil moisture and nitrogen relative to permanent grass covers such as tall fescue [12]. Triticale, a wheat-rye hybrid, combines the high biomass production and nutrient-scavenging capacity of fall rye with the grain quality and tillering potential of wheat, establishing rapidly, suppressing weeds, and tolerating marginal soils, while offering greater lodging resistance and disease tolerance than fall rye [34]. Ruiz-Colmenero [35] demonstrated that barley and fall rye service crops can reduce runoff and soil erosion, provided they are managed with timely mowing to prevent nutrient competition, without negatively affecting grape yields. Cereal-legume mixtures have consistently demonstrated higher multifunctionality than monocultures across diverse environments [11]. These mixtures also exhibit structural complementarity, with cereals providing a physical framework that supports trailing or vining legumes, enhancing stand stability and performance [17,18].

Annual ryegrass (*Lolium multiflorum* L.) is a common nurse-companion grass because it establishes rapidly in cool conditions, creating dense early cover for erosion control and weed suppression and sheltering slower legume seedlings; in cold climates it often winterkills [36]. In Mediterranean regions, where winterkill is unreliable and some ecotypes persist, timely mowing or termination is needed to prevent dominance; competitiveness and persistence vary with genotype and environment [18,37]. The species can become a weed, and herbicide-resistant biotypes are documented in New Zealand and Portugal [38]. It can be sown in early fall or spring to exploit cool, moist conditions for rapid emergence [39].

While cereals are the most prevalent companion crops, fast-growing annual legumes can also act as nurse companions. Large-seeded species germinate quickly and provide short-term biomass for early cover and nitrogen inputs. Field pea (*Pisum sativum* L. subsp. *arvense*; also called Austrian winter pea when grown over winter) emerges rapidly and produces vining biomass that can climb cereals such as oats where the cereal supplies physical support while the pea fixes nitrogen [7,40]. Commercial “oat-pea” mixes are common and typically winterkill in cold climates, leaving nutrient-rich residues [40]. Fava bean (*Vicia faba*) likewise establishes quickly and forms a tall canopy [14,41]. Crimson clover (*Trifolium incarnatum*) and berseem clover (*Trifolium alexandrinum*) are annual clovers that establish rapidly, produce early biomass that aids weed control, and supply biologically fixed nitrogen; their residues mineralize relatively rapidly, supporting early-season nitrogen availability [42–44]. Crimson and berseem clovers are ideal companion crops for slow growing perennial clovers such as white clover for under-vine cover cropping (personal experience).

Beyond cereals, grasses, and legumes, other fast-establishing species can serve as companion crops (Table 1). Brassicas such as tillage radish (*Raphanus sativus* var.

longipinnatus) and mustards (*Brassica* spp.) germinate rapidly in cool conditions and quickly provide groundcover before summer heat or winter frosts [45,46]. In mixtures, tillage radish can act as a nurse companion for perennial grasses and clovers: its broad canopy shelters slower seedlings, and spring-sown stands are typically mowed before seed set [47,48]. Its deep taproot alleviates shallow compaction and scavenges nutrients from depth, enhancing soil physical and fertility conditions [49]. In temperate regions, optimal sowing is early spring or shortly after the summer solstice to exploit cooler temperatures for leaf and root development; high early temperatures trigger premature bolting, diverting biomass from storage-root formation and diminishing soil-penetrating efficacy [46,49].

Buckwheat (*Fagopyrum esculentum* Moench) is another fast-growing cover crop, often used during warmer periods due to its ability to establish and provide significant ground coverage within approximately 30–40 days post-seeding [50]. Although less commonly used in vineyard systems due to its sensitivity to frost and drought, buckwheat can serve effectively as a short-term companion crop particularly in inter-rows when establishing perennial covers in late spring or early summer in humid environments [51]. Its rapid growth cycle, along with allelopathic effects from phenolic compounds that regulate germination and enhance competitive suppression, makes buckwheat a suitable option; provided it is terminated before seed maturation to prevent unwanted reseeding [52].

3.2. In-Row vs. Inter-Row Applications

Vineyard cover cropping can be applied both between vine rows (inter-row) and directly under the vines (in-row), with differing considerations for companion crops in these distinct zones. Traditionally, vineyard cover crops have been predominantly implemented in inter-row spaces, maintaining bare soil under vines to minimize competition. Recently, however, interest has grown in using in-row cover crops, particularly in organic and regenerative viticulture systems, for weed control and vine vigor management [2].

Inter-row spaces provide ample room, adequate sunlight, and convenient access for direct seeding, making them suitable for companion cropping. Viticulturists widely regard this practice as beneficial, and it has been successfully implemented in various viticultural regions, such as California [14,41]. Typically, inter-row companion crops are managed by mowing during the spring, reducing competition with vines and mitigating frost risk. Mowing in mid-spring can effectively thin out dominant companion crops, enabling slower-growing species to receive sufficient light and nutrients for continued growth. Trials conducted in the Okanagan Valley, Canada demonstrated that radish or oats, when used as companion crops alongside perennial grasses and clovers, provided continuous cover after midsummer mowing, significantly improving overall establishment success compared to scenarios without companion crops [47,48]. In cool-temperate Central Europe (Germany, Austria, Hungary), inter-row alleys are the main deployment zone: autumn-sown fall rye, triticale, or barley with white or micro-clover delivers rapid spring cover [31,53].

In-row cover cropping, directly beneath the trellis, poses unique challenges but is gaining interest for its potential to suppress weeds and moderately control vine vigor through mild competition [2]. Typically, this strip (1–1.5 m wide) is left bare in conventional systems through herbicides or cultivation. In organic and biodynamic vineyards, some growers have experimented with establishing living mulches using low-growing cover species [54]. However, environmental conditions under the vine, limited light, weed pressure, and uneven moisture distribution due to drip irrigation, can make seedling establishment difficult [55]. In these challenging in-row environments, the concept of companion cropping may offer advantages. under-vine candidates should be low-stature (≤ 12 – 15 cm) and prostrate, shade tolerant, with shallow, fine fibrous roots to limit deep resource overlap; they should also tolerate periodic drought, avoid twining, reseed minimally, and be easily mown [42,56–59]. For example, sowing a fast-growing species such

as crimson clover or lentil (*Lens culinaris*) alongside a slower-growing microclover (*Trifolium repens* var. Pipolina) may improve overall establishment [60]. Management is key, however: the companion crop must not compete excessively with vines for water or nutrients, especially in unirrigated or drought-prone vineyards [57,61]. The annual under-vine companion crop may be terminated through mowing or natural senescence as summer progresses, leaving behind the perennial species [62,63].

While cereals like oats or barley may function effectively in early stages, they are not suitable choices for in-row and if not carefully managed, their high vigor can deplete soil moisture, interfere with fruiting zone, and negatively impact vine growth [14,64]. Breeding should prioritize dwarf/prostrate architecture, shade tolerance, shallow root systems with low peak evapotranspiration (ET) demand, summer-dormancy ideotypes for dry regions, and reduced seed shattering to limit persistence, following trait-based and intercropping frameworks [59,65–67]. Overall, companion cropping remains most straightforward and widely practiced in inter-row alleyways, but the same ecological principles may be cautiously applied to under-vine management where appropriate.

4. Management Considerations and Trade-Offs

Companion crops can expedite establishment of slower or desired species and provide early groundcover, but they could introduce trade-offs. Without careful management, they may compete with grapevines or the primary cover for water and nutrients [3,11,61]. Early suppression or removal reduces competition and improves vine water status, especially in Mediterranean, water-limited sites [11,68]. Such dynamics have been documented in French vineyards and Central Europe, where ongoing transpiration from unmanaged covers increased water and nitrogen stress, while a mid-spring termination (rolling or mowing) converts the cereal to mulch and reduces competitive pressure [12,53,61,68]. Growers often mow at or shortly after budbreak to remove biomass and, in frost-prone areas, enhance soil heat exchange by lowering the canopy [69]. Fast annual grasses (e.g., ryegrass) are restrained by spring mowing to ~5–10 cm, which limits regrowth and water use [23,56]. Tall cereals such as triticale and fall rye deliver rapid groundcover but, if unmanaged, can shade grape canopies, delay soil warming and ripening, and complicate tractor access; therefore, to avoid these challenges, earlier mowing or selecting winter-killed types helps limit shading and humidity in fruit zones [12,70]. An alternative is to use self-terminating nurse companions. In cold climates, winter-killed oats or forage radish die over winter and usually eliminate pre-budbreak termination [71,72]. In milder climates, short-cycle annuals such as buckwheat or some mustards senesce early or can be ended with a single mowing or cultivation, providing early cover while limiting competition [40,73,74].

Seeding rate is a key lever in companion crop-cover crop design. If the fast component is too dense, it can suppress the slower or target species [75–77]. To avoid dominance, practitioners commonly reduce aggressive nurse components to ~25–50% of their monoculture rate in mixtures [19,78,79], so they deliver early cover without overrunning the stand. For example, oat monocultures are often sown near ~90–110 kg ha⁻¹, whereas as a nurse for alfalfa, substantially lower rates (~10–35 kg ha⁻¹) maintain vegetation regulation and early cover while minimizing legume suppression [75,77,80]. Keeping nurse densities moderate ensures sufficient light and space for slower perennials (e.g., grasses, clovers); excessive early competition increases failure risk [19,81]. Ultimately, successful nurse-companion cropping balances early vigor with restraint so the nurse does not become a competitive impediment itself [19]. First-year yield risk is moderated by staging establishment in alternate inter-rows and completing the remainder once the perennial is anchored, as supported by Tokaj trials showing reliable establishment and strong weed suppression with species-rich cereal–legume mixtures [62,63].

Another important consideration is species selection to avoid unintended persistence through self-seeding. Some companion crops, if not carefully managed, can volunteer and become a semi-permanent or weedy component of the vineyard flora [50]. Annual ryegrass can establish seedbanks and persist in perennial systems; resistant and naturalized populations are documented in California orchards and vineyards [82–85]. Reseeding and volunteer issues are moderated by matching species life cycles and termination timing to local climate. In cold regions, winter-killed or otherwise non-hardy annuals senesce naturally, limiting the need for mechanical control; in milder regions, vigorous legumes such as vetch may reseed and climb trellises, warranting closer monitoring [14]. In organic systems, where chemical options are limited, early mechanical termination (e.g., mowing at flowering before pod set) together with life-cycle-based planning reduces the risk of unwanted persistence [40,50].

From the vine management perspective, not all situations benefit from a traditional companion crop. In high-vigor vineyards, growers sometimes establish competitive cover stands to intentionally devitalize vines through sustained resource competition [2,4,5,54]. In those contexts, a gradual or slow establishment of the desired cover can be acceptable or desirable, though an initial companion phase can still help get the stand established before transitioning to the long-term composition [86].

Irrigation and nutrient management require adjustment when using companion crops. Establishment increases early-season water demand, and in dry periods supplemental irrigation to “water up” the seed zone improves germination and reduces patchiness; inadequate soil moisture at sowing often compromises emergence [3,55,87]. Once established, suitable species can persist largely on seasonal rainfall, with resilience shaped by species traits and climate [10]. Nutrient needs also differ between grasses and legumes: grasses benefit from modest nitrogen inputs to promote tillering and rapid cover, while legumes require adequate phosphorus (and sulfur) for root growth and nodulation; excessive mineral nitrogen suppresses fixation and shifts competition toward grasses [88,89]. Early phosphorus availability supports legume establishment and stabilizes nitrogen dynamics, and small, judicious pre-plant inputs (well below cash-crop levels) can determine whether a stand is patchy or dense, with significant downstream benefits for erosion and weed control [89].

Compatibility with mechanization is generally favorable. A well-established companion crop stand can improve soil structure and surface firmness, easing equipment traffic and reducing mud [90]. Excessive biomass is typically managed by pre-mowing before incorporation to reduce drag and facilitate decomposition [50]. In no-till or perennial systems, mowing and leaving residue as surface cover is a common strategy that also provides soil protection, moderates temperature, and conserves moisture [41]. Proper timing and handling of high-biomass covers are essential to avoid operational difficulties during incorporation and to convert potential challenges into opportunities for efficient residue management [90]. Row spacing influences mechanization where narrow alleys (<2.2 m) limit mower and roller widths and turning radius, favoring low-stature covers and controlled residue height. Under-trellis tools like finger, brush, or knife weeders require stone-free, consistently regrowing stands, while in-row establishment benefits from shallow-seeding or drop-seeding techniques combined with cultipacking [91].

The necessity and utility of companion crops in vineyards are highly context dependent. On fertile, moist soils, a legume cover often establishes without assistance. If unchecked, it can also drive excessive vine vigor. In such cases, some practitioners omit a companion to limit early competition and keep the cover less aggressive [4,5,92]. By contrast, on poor, sandy, or dry soils, a companion crop can determine whether any meaningful cover is achieved. Clovers often struggle until soil structure and organic matter improve. An early companion helps by stabilizing soil, adding organic inputs, and

moderating the microclimate [10]. Across seasons, soil health tends to build under continued cover cropping, and mixture complementarity accumulates. After a few years of a cereal–legume sequence or mix, the seedbank and improved conditions may allow perennial or self-sustaining covers to persist without an annual companion [9,93]. Companion cropping is therefore most critical during transitions, for example, when moving from bare ground to vegetated alleys or when introducing new species.

In irrigated vineyards of semi-arid regions, companion and cover crop biomass can deplete soil water, making species selection and flexible termination strategies critical [3]. When water availability is limited and cover crops compete with vines or disrupt vineyard water management, companion crops used as temporary covers are preferable, as they sustain yields while enhancing soil carbon sequestration and overall soil health. For instance, in the Okanagan Valley, Canada, maintaining permanent cover crops year-round, particularly in the loamy sand soils of the southern valley, without reducing irrigation from flowering to veraison can negatively affect yield quality and increase pest and disease pressure (e.g., leafhoppers and powdery mildew) [94]. Under these conditions, growers are encouraged to establish fall- and winter-sown companion crops that capitalize on residual soil moisture in fall and spring, thereby producing biomass that contributes to vineyard soil productivity and environmental sustainability. According to Liebhard et al. [9], alternating low-intensity inter-row management provides a viable alternative to permanent green cover. Figure 1 presents a seasonal decision framework that links climate, vine phenology, and cover-crop actions for cool-climate, irrigated Northern-hemisphere vineyards (e.g., the Okanagan Valley, Canada). Blue bars show 30-year precipitation normals (1991–2020) and the orange line shows the corresponding mean daily temperature for Penticton, British Columbia, in the central Okanagan Valley; phenological stages are annotated above. The management panel outlines actions for two within-vineyard zones. Inter-row: a winter companion mix of cereals and hardy legumes is sown in September (WCompC), germinates and grows through autumn, and then remains dormant from December to March. Regrowth occurs in April–May (WCompC-Regrowth), followed by termination or suppression or senescence during the peak-competition, dry period in June–August (Nirrig-Term-NCC). The cycle resumes the following September when soil moisture is adequate. In-row: because drip irrigation operates through summer, both annual and perennial covers can be established; here, a perennial legume (e.g., Ladino or micro-clover) is the resident cover. In year 1, a spring companion (e.g., crimson clover or berseem clover) facilitates establishment from April–August (SCompC + Permanent CC), transitioning to the low-stature permanent cover crop in September–November (Permanent CC), then dormancy. In year 2, the permanent cover crop regrows (with optional April overseeding if stands are thin), is maintained from April–November, and then enters dormancy from December to March. By contrast, in cool-humid regions such as the Niagara wine region of Ontario Canada, cover crops can be strategically managed to improve fruit quality, while permanent species with dense ground cover are favored to mitigate the greater risk of soil erosion.

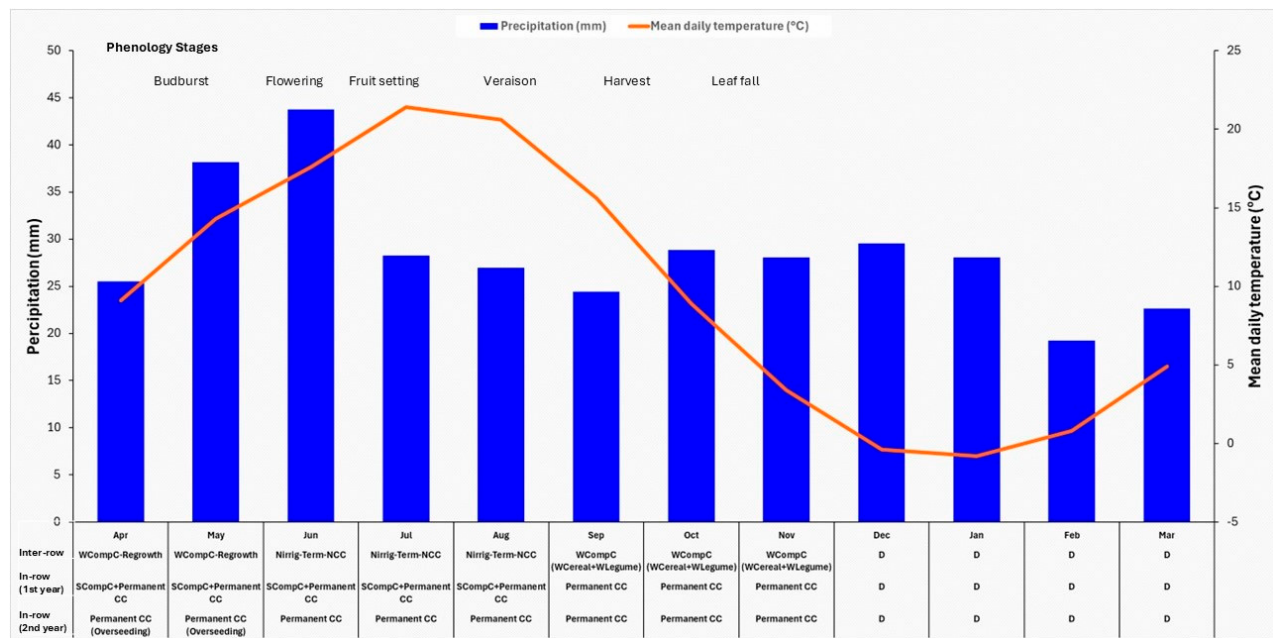


Figure 1. Decision framework for when and how to include a companion phase in cool-climate drip-irrigated vineyards in Northern hemisphere. WCompC-Regrowth, Winter companion crops regrowth; Nirrig-Term-NCC, No irrigation/termination/no cover; WCompC (WCereal + WLegume), Winter companion crops (winter cereal and winter hardy legumes); SCompC + Permanent CC, Spring companion crop + low stature/permanent/winter hardy/non- competitive cover crop; Permanent CC, low stature/permanent/winter hardy/non- competitive cover crop; Permanent CC (Overseeding), over seeding low stature/permanent non- competitive cover crop; D, dormant. Climate data downloaded from Environment and Climate Change Canada [95]. Phenology and cover crop recommendations are based on unpublished data by Dr. M. Sharifi.

5. Critical Synthesis and Research Agenda

Companion cropping typically improves weed control (Table 1), with fall rye and buckwheat performing strongly via allelopathic effects; however, under-vine selectivity and seasonal cohort shifts are underreported [4,5]. Water competition and vine status are context-dependent and only moderately consistent; few studies partition vine verses companion ET or standardize termination thresholds across climates [3,11,12]. Nitrogen effects are mixed and timing-sensitive, with scarce multi-year nitrogen budgets [1,4]. Yield and berry composition tend to be neutral under well-managed programs, but inference is limited by short study horizons and confounding practices [1,5,96]. Biodiversity outcomes are favorable when flowering windows and staged mowing are used, yet endangered-species safeguards are rarely explicit [1].

The evidence base is strong for inter-row erosion mitigation, cereal-driven vegetation regulation, and general ecosystem services in vineyards [1,3–5]. It is moderate for termination-window effects on vine water status, seeding-rate fractions governing dominance verses establishment success, and biomass thresholds related to fire risk. It is sparse for under-vine living mulches with quantified vine/fruit outcomes, event-based erosion/sediment yield, companion-vs-vine ET partitioning, long-term nitrogen and carbon budgets, and endangered-species-compatible management.

From a research and innovation perspective, priority should be given to refining companion–main crop pairings and evaluating their long-term impacts on vineyard systems. Key questions include which companion-cover crop combinations maximize cover crops establishment success, functional complementarity, and resilience across

contrasting soil textures and under both water-limiting and non-limiting conditions. Equally important is understanding how these choices affect vine vigor, yield and yield stability, wine quality trajectories, and sensory endpoints over time [5,90,97]. Furthermore, future research should prioritize climate-specific termination thresholds derived from multi-site trials with standardized stem water potential (Ψ_{stem}) and phenology; under-vine living-mulch trials of short-stature species under drip irrigation, tracking weed control, vine water/nitrogen status and volunteerism; erosion studies using paired-alley rainfall simulations and sediment traps across slope classes; and ET partitioning via lysimetry or sap-flow plus soil-moisture arrays in semi-arid versus humid zones.

Another important trend is the development of decision-support tools to guide species selection and mixture design, with increasing emphasis on integrating companion crop logic alongside local environmental and management conditions. Web-based platforms such as species selectors and simulation tools from Precision Sustainable Agriculture, NC State Extension, the Northeast Cover Crop Council, and the farmdoc cover crop analyzer; already help growers align cover crop and companion species with site-specific goals, climate, and constraints by incorporating functional traits, decomposition dynamics, and water–nutrient interactions to optimize establishment and ecosystem services [55,98]. However, comprehensive decision-support systems tailored specifically to grapevine production are still lacking, underscoring the need to translate research findings into region-specific if–then rules embedded in web-based tools and validated through farmer-participatory trials. There is also active interest in breeding or selecting cover crop varieties tailored for vineyard contexts, such as low-growing cereals that act as non-obstructive companions, faster-establishing legumes, or locally adapted native species that combine persistence with water efficiency. Work in Mediterranean-type and comparable systems has shown that while some native and perennial species establish slowly, once established they contribute to soil quality and water-use efficiency, making a complementary companion phase during establishment a sensible strategy [20,99].

6. Conclusions

Companion cropping in vineyards is an establishment-focused design principle, not a fixed crop category. Pairing slower, high-value species with fast-growing companions accelerates groundcover, shields seedlings, suppresses weeds, and limits early-season erosion. It suits alleyways and, with careful management, the under-vine zone. Success depends on species choice, calibrated seeding fractions, and timely termination. When these align, trade-offs are small and benefits substantial: better soil structure, richer biodiversity, lower herbicide and fertilizer use, and greater climate resilience. To scale adoption, the field needs standardized termination thresholds across climates, clear under-vine protocols, and long-term water and nutrient budgets. These insights should feed grower-friendly decision tools.

In cool-temperate regions, a short companion phase seeded at 25–40% of cereal monoculture rates should deliver $\geq 80\%$ groundcover within 30–40 days. Vine midday Ψ_{stem} should remain within 0.1–0.2 MPa of bare-soil controls at bloom. Trait-matched in-row living mulches (≤ 15 cm stature, shallow roots, high shade tolerance) can keep yield and fruit composition within $\pm 5\%$ of clean-cultivated controls while cutting herbicide or cultivation by $\geq 50\%$. Mixtures tuned to rainfall quartiles can optimize erosion control, vegetation regulation, and nitrogen retention without breaching fire-risk biomass thresholds. Allelopathic residues, such as fall rye, can regulate spring weed cohorts when termination occurs ≥ 2 weeks before shoot elongation.

Breeding priorities follow (i) dwarf or prostrate cereals for under-vine and short companion phases; (ii) low-ET fast-establishing legumes; (iii) traffic-tolerant native or locally adapted species; and (iv) species with predictable life cycles that minimize volunteer

reseedling in under-vine drip irrigation. On slopes ≥ 6 –10%, a cereal companion phase should shorten bare-soil exposure by 2–3 weeks and reduce sediment yield at alley outlets. Early-canopy mixtures (companion ratio $\times$ termination timing) should improve infiltration and dampen runoff peaks while keeping vine performance within target ranges. Standardized groundcover phenology (seasonal cover management factor proxies) should predict erosion well enough to support regional, block-level risk mapping. Coordinated multi-site trials are needed to test these claims. Results should be converted into simple, region-specific rules and web-based tools. Together, these steps would enable robust, scalable adoption of companion cropping aligned with climate resilience, ecological stewardship, and industry sustainability goals.

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