Adapting Vineyards to a Challenging Climate

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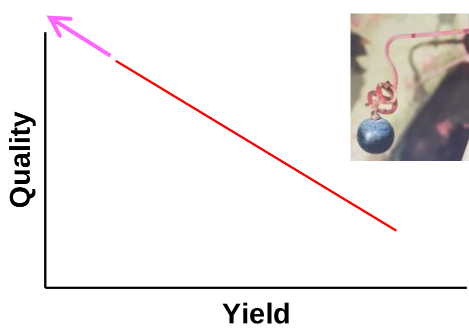
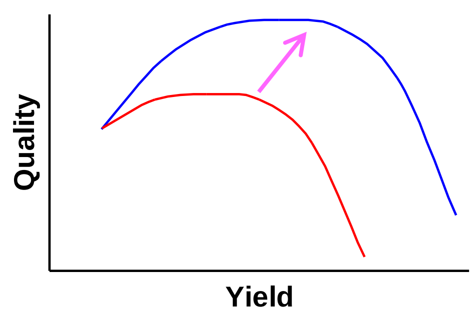
Yield and fruit quality: Is less better?

The **classical** view:



Zero yield → Best quality

The **scientific** view:



Optimum yield → Best quality

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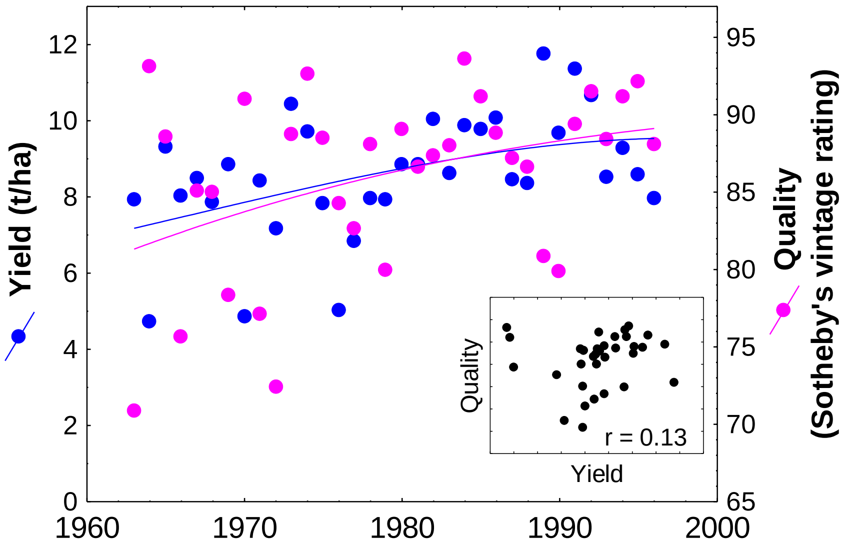
Yield *or* fruit quality: It isn't necessarily so…



- No correlation: Yield and quality vary independently
- Both yield and quality have increased over time
- Annual variation has decreased over time
- Heavy crop yield
  → Ripening delay
  → Good or bad?

CA North Coast (Napa, Sonoma), mean harvest Brix: 20.5 (1971) → 24.2 (2001)

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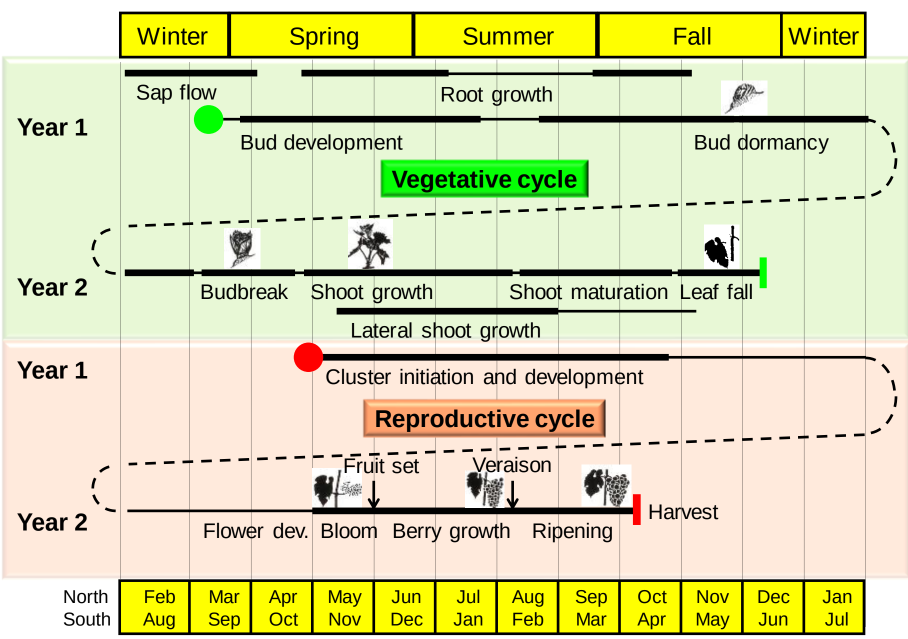
Grapevine yield formation: A 2-year affair



- Two growth cycles
  - ➢ Vegetative
  - ➢ Reproductive
- Both cycles run over 2 years
  - ➢ Yield forms over 2 years
- Viticulture: Farming for two seasons at once

Dry & Coombe (2004)

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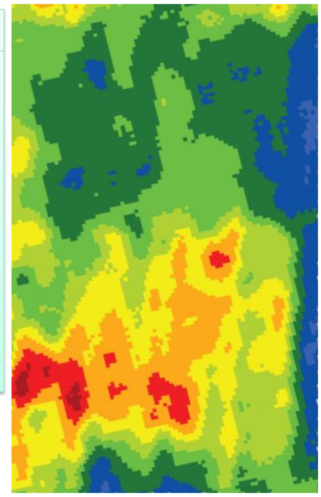
Yield: A product of yield components

Yield component	Time of determination	Management options
Vines/area	Vineyard establishment	Planting density
Buds/vine	Winter pruning	Training system, pruning level
Shoots/bud	Budbreak	Pruning level
Clusters/shoot	Bud formation	Canopy management, nutrition, irrigation
Flowers/cluster	Bud formation, budbreak	Irrigation(?)
Berries/cluster	Fruit set	Irrigation, nutrition, canopy management
Berry weight	Budbreak to maturity	Pruning, irrigation, nutrition



- Vineyard yield = Multiplication of yield components (2 years!)
- Genotype × environment interaction → Yield variation
- Spatial variation (within, between vineyards) and temporal variation (between years)
- Hierarchy of yield component variation: Vine number < bud number < shoot number < berry weight < cluster number < berry number

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Yield: From potential to harvest

- Pruning level → Number of fruitful **shoots**
- Bud fruitfulness → Number of **clusters**

Yield potential

  Optimum: Long days (Riesling, Muscat, Concord…), high light (>⅓ full sun), moderate temperature (20–30°C), adequate(!) water & nutrients, open canopy

- Budbreak → Number of **flowers**

  Optimum: High nutrient reserve status, cool air (10–15°C), warm & moist soil

- Bloom/fruit set → Number of **berries**

  Optimum: Large leaf area, warm air (25–30°C) & above

- Cell division/expansion → Berry **weight**

Yield

  Optimum: Seed(s), moderate temperature (25–30°C) & above (*early* stress is more limiting than *late* stress)

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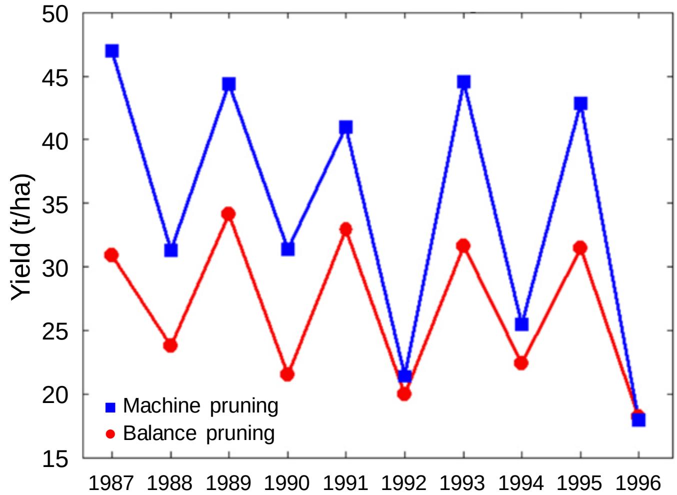
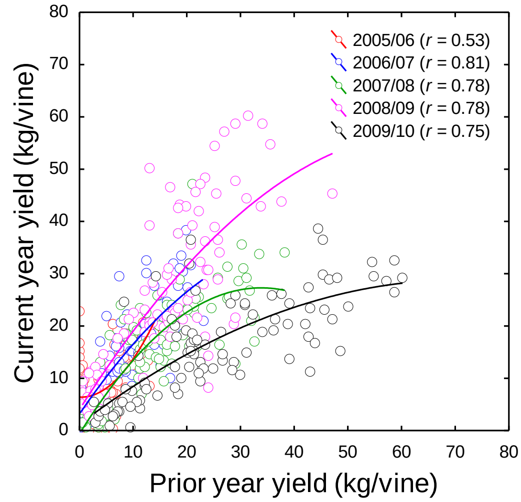
Biennial bearing: Fact or fiction?





- More severe pruning → Lower yield, but does not improve yield fluctuation
- Bigger vines have higher yield potential

Wample (1996); Keller et al. (2021)

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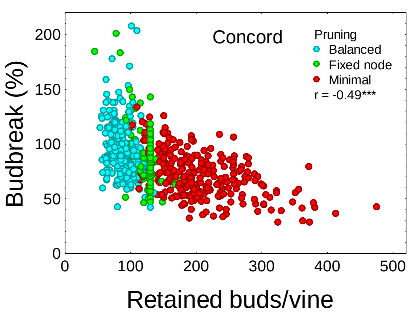
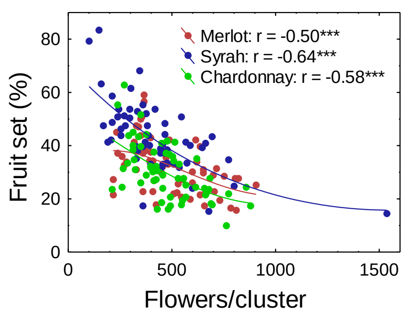
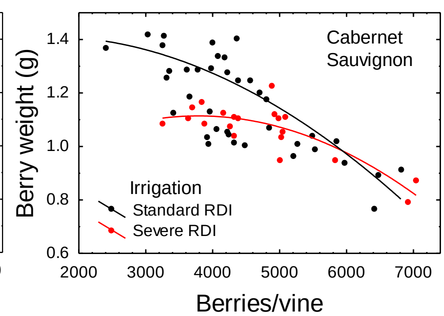
Yield formation: Vines compensate







- More buds per vine → Lower budbreak → Shoots?
- More flowers per cluster → Lower fruit set → Berries?
- More berries per vine → Lower berry weight

Yield component compensation:

Change in one yield component → Less than proportional effect on harvest yield

Keller et al. (2004, 2008)

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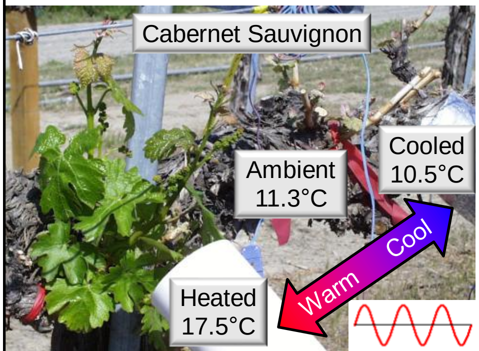
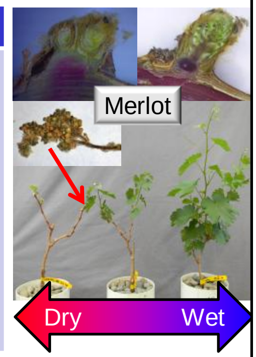
Budbreak: Temperature and water limit yield



T_{max}/T_{min} (°C)	16/6	18/6	23/11
Budbreak (DOY)	**124**	**117**	**106**
Flowers/cluster	406	457	339
Leaf area/flower (cm^2)	1.3	2.5	9.9
Fruit set (%)	20	32	45
Berries/cluster	**65**	**129**	**141**
Berry weight (g)	**0.7**	**0.9**	**1.0**
TSS (°Brix)	26.0	25.9	24.5
TA (g/L)	6.4	5.8	5.7
pH	3.5	3.6	3.6



- Budswell: Buds reconnect to canes, initiate vascular tissues → Sap flow
- Budbreak: Shoots grow out, inflorescences form flowers
- High temperature → Rapid shoot and inflorescence growth, high fruit set
- Dry soil → Erratic budbreak, slow shoot growth, cluster abortion, low fruit set
- Water deficit suppresses temperature effect → Yield loss in cool or dry spring

Keller et al. (2010); Galat et al. (2020)

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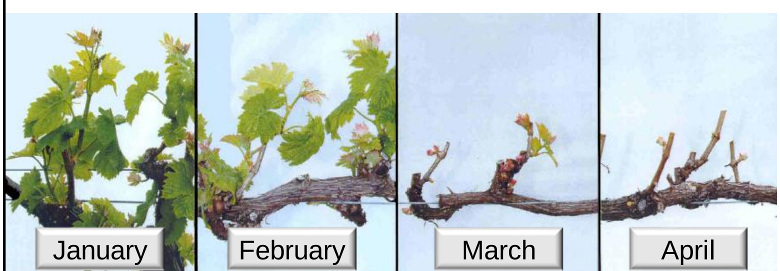
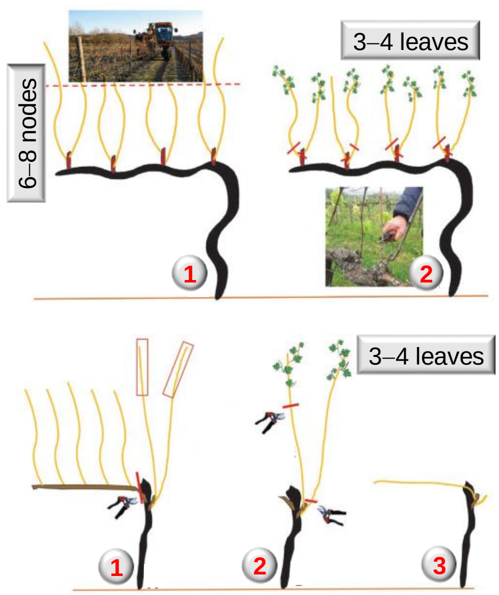
Winter pruning: Time matters (in spring)





- Late spur pruning delays budbreak by 1–4 weeks (apical control)
- Foliar abscisic acid (ABA, dormancy promoter) spray in fall delays budbreak by 1–2 weeks
- Late budbreak delays phenology, but vines can compensate ≤3-week delay in budbreak
- Pre-prune (by hand or machine for spurs, by hand for canes) + follow-up (by hand) after budbreak

Friend & Trought (2007); Poni et al. (2022)

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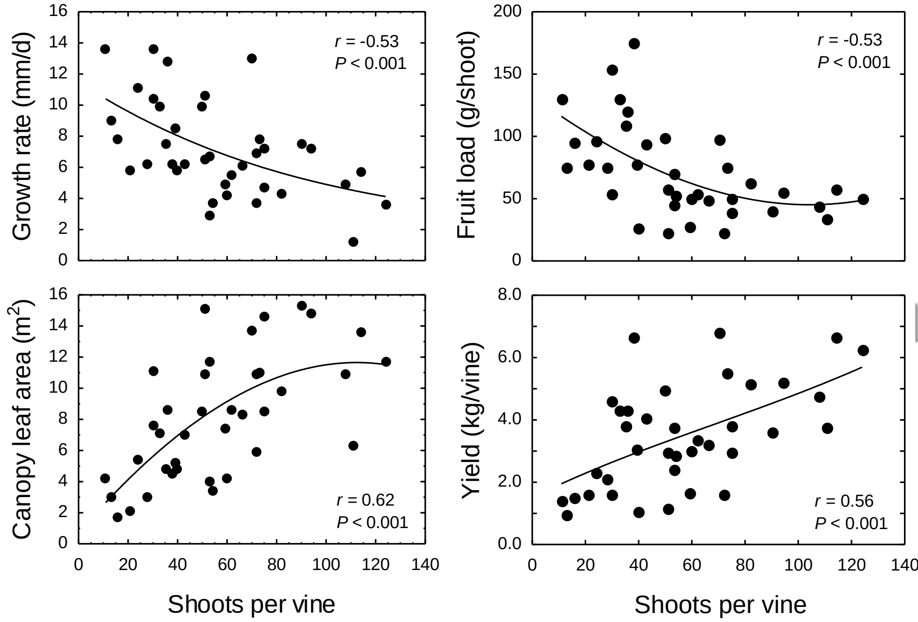
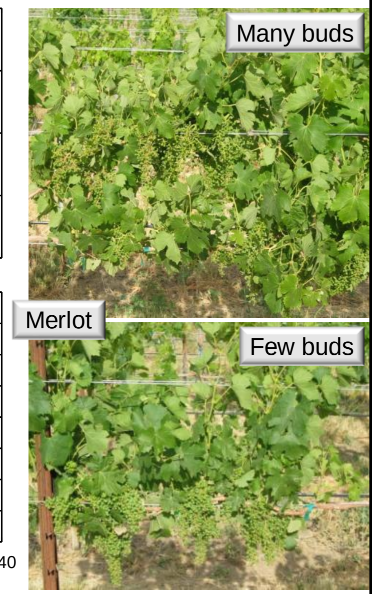
Winter pruning: Bud number matters





Keller et al. (2015)

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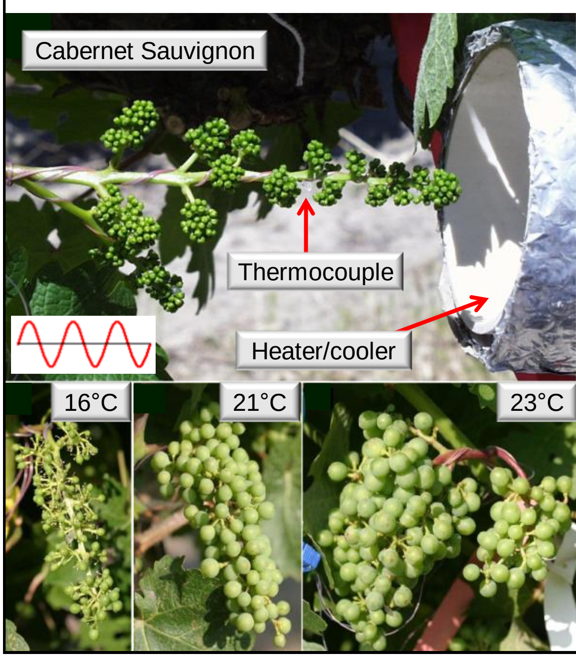
Bloom: Temperature limits yield



T_{max}/T_{min} (°C)	24/9	30/11	32/14
Bloom duration (days)	**24**	**17**	**10**
Fruit set–veraison (days)	62	56	59
Fruit set (%)	20	35	31
Berries/cluster	**81**	**135**	**126**
Berry weight (g)	**0.8**	**0.9**	**1.0**
TSS (°Brix)	23.6	24.2	24.8
TA (g/L)	7.1	5.6	5.3
pH	3.4	3.5	3.6

- Temperature increase from **15** to **35°C**
  → Short bloom time, early fruit set & veraison
  → More, bigger, more mature berries
- **<15** or **>40°C** inhibits pollen germination
  → Poor fruit set, live green ovaries
- **<15** or **>35°C** limits cell division
  → Small berries

Keller et al. (2022)

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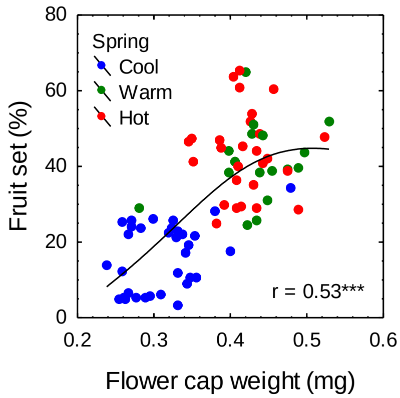
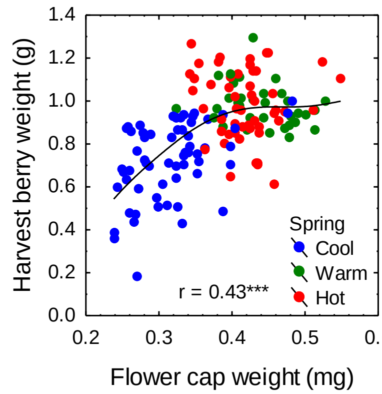
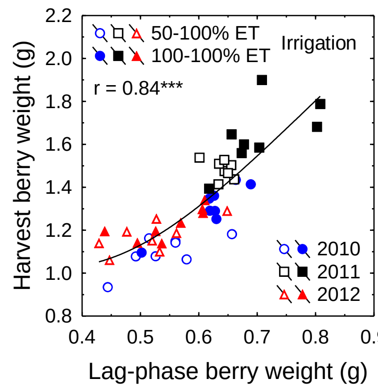
Berry growth: Early events determine final size





Cabernet Sauvignon
Spring temperature



Sauvignon blanc
Preveraison water deficit

- Bigger flowers are more likely to set fruit
- Bigger flowers may become bigger berries
- Harvest berry size is predetermined by veraison

It's difficult to manipulate berry size during ripening

Keller et al. (2010); Keller (2025)

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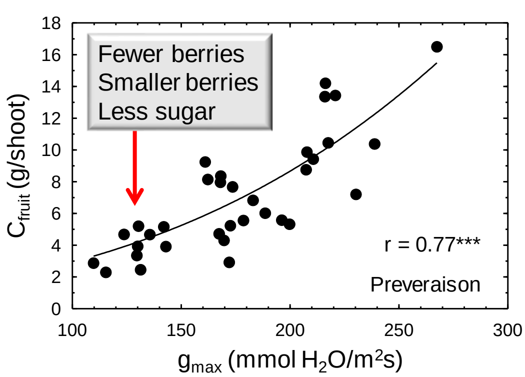
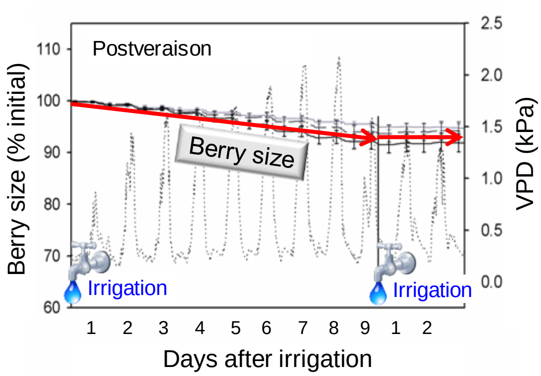
Berry growth: Water limits yield





- Water stress → Vine water status (Ψ_{leaf}) declines → Stomata close (g_{max}) → Photosynthesis declines → Less carbon for fruit (C_{fruit})
- Water stress during bloom → Poor fruit set → Fewer berries
- Water stress before veraison → Smaller berries
- Water stress after veraison → Lower TSS, berry shrinkage

Yield loss

Keller et al. (2006, 2015)

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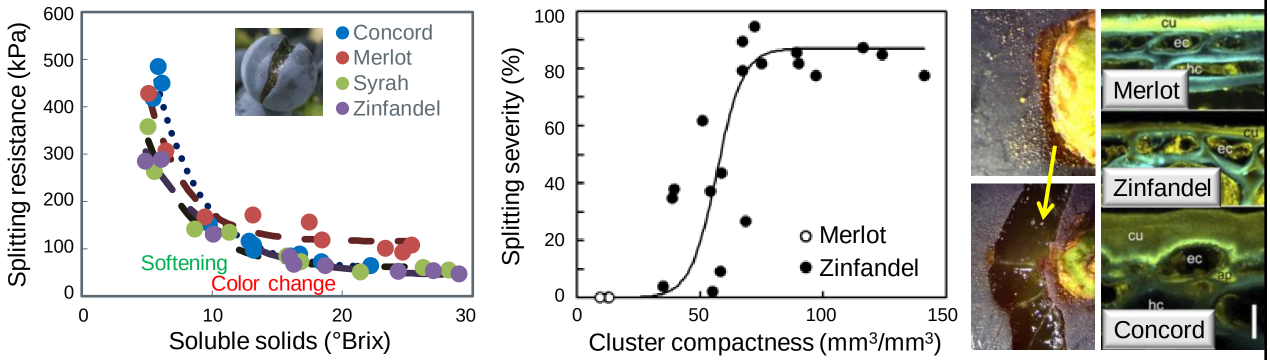
Too much (or too little) water: Berry splitting



- Water stress before veraison, then irrigation, or water excess after veraison (rain, sprinkler irrigation, high humidity) → Splitting from microcracks
- Dehydrated berries do not split → Delay harvest after rain
- Thick skin (cuticle) does not prevent splitting
- Compact clusters, large berries → Higher splitting susceptibility

Chang et al. (2019, 2020); Chang & Keller (2021)

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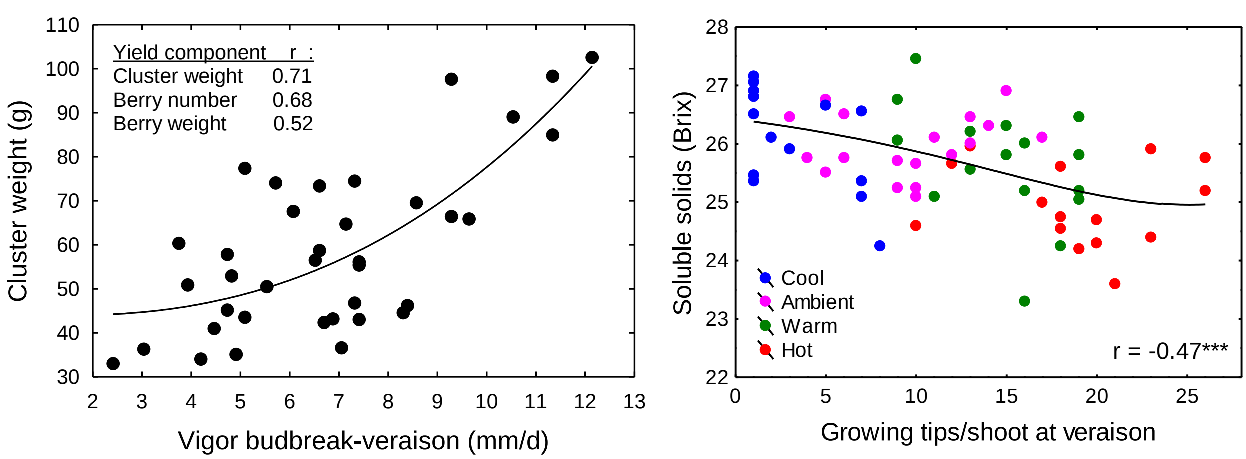
Shoot vigor and yield go hand in hand



- Growth of shoots, flowers, and berries may be coupled: Higher early vigor → More berries/shoot, bigger berries → Higher yield
- Late shoot growth (laterals) may compete with berry ripening → Less sugar
- Control vigor to control berry number and size, and quality

Keller et al. (2010, 2015)

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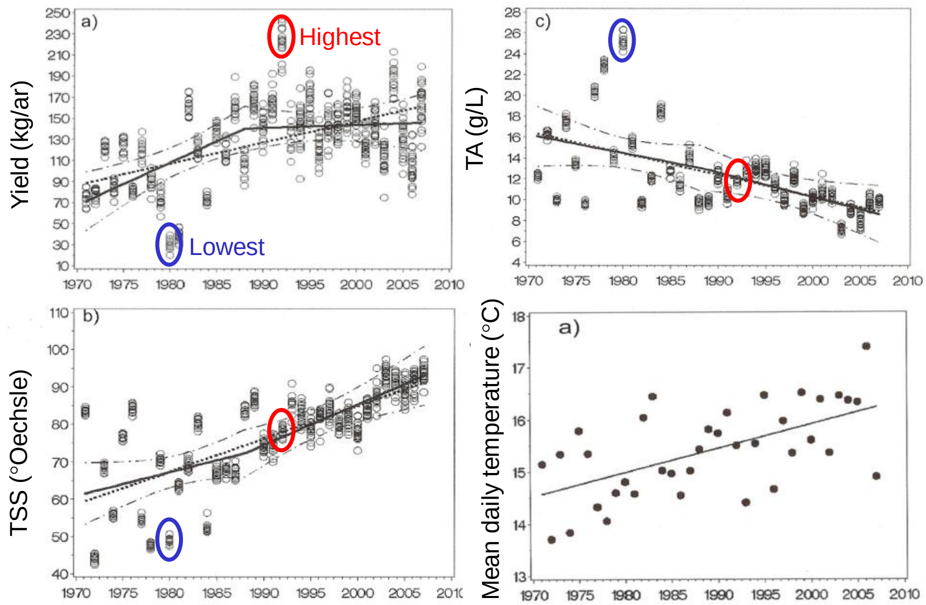
Yield and quality: Another look



- 30 Riesling clones
- 16 locations across Rhineland-Palatinate (Germany)
- 37 years (1971–2007)

Laidig et al. (2009)

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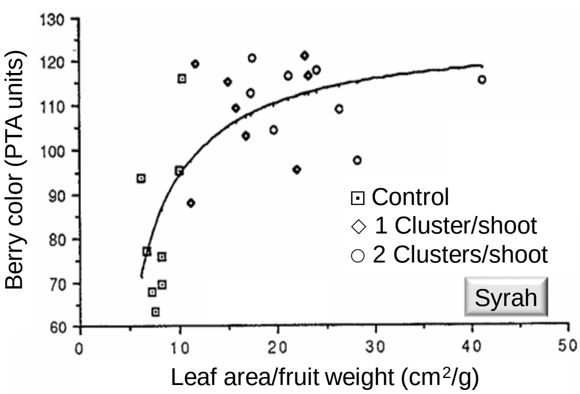
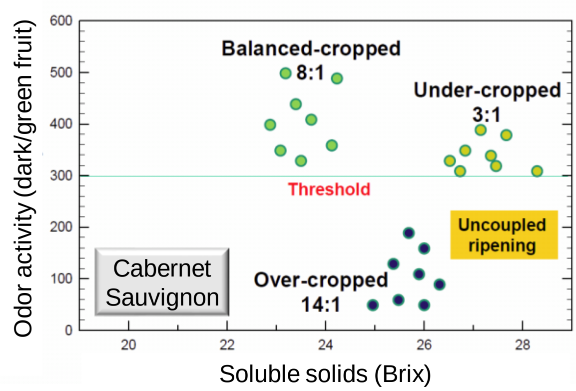
Yield and quality: Tasting is believing





- Need 10–15 cm^2/g of fruit → 1 Leaf feeds 5–10 berries
- Optimum crop load: Yield to pruning weight ratio = 5–10
- Under-cropping and over-cropping → Uncoupled flavor ripening

Dokoozlian (2012)

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The ideal vine: A starting point for vine balance

• Shoots/canopy length	15/m
• Shoot length	90–120 cm (~15 nodes)
• Lateral shoots	5–8 nodes/shoot
• Pruning weight	300–600 g/m
• Cane weight	20–40 g
• Leaf area/fruit weight*	10–15 cm^2/g
• Yield/pruning weight*	5–10
• Canopy gaps	~30%
• Sun-exposed clusters	>50%

Balance pruning:
- 30 buds/kg pruning weight
- 15 buds/m of canopy

*Measures of crop load

Smart and Robinson (1991)

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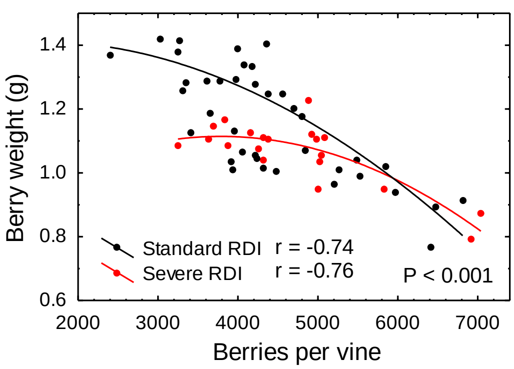
Crop load: Challenges into solutions



Ground speed 2.6 km/hr, shaking 425 rpm → Berry thinning

- Higher crop load (sink÷source ratio) → Delayed ripening → Beneficial for white wine and in warm seasons
- More berries per vine → Smaller berries → Beneficial for red wine
- Mechanization: Combine machine pruning (more shoots → more berries) with machine thinning (berry thinning → loose clusters) and harvesting (cool at night)

Keller et al. (2008); Keller (2023)

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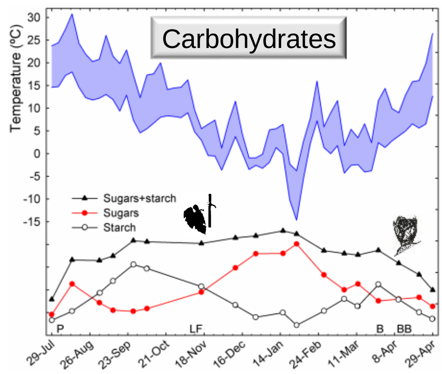
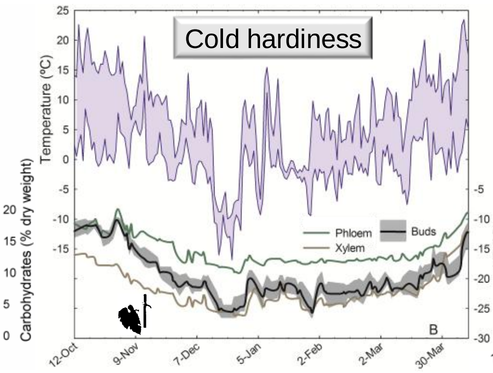
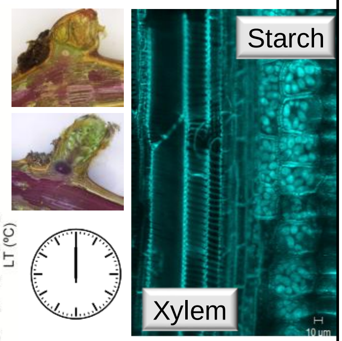
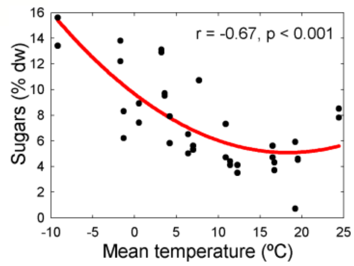
More than fruit: Sugar for winter survival









- Dormancy: **Callose** seals phloem and buds → Bud dehydration (80% → 45% water)
- Cold temperatures: **Starch** converts to sugar to depress freezing point → Cold acclimation
- Warm temperatures: **Sugar** converts to starch to prevent cell flooding → Deacclimation (reversible before budswell)

Eifert et al. (1961); Keller (2025)

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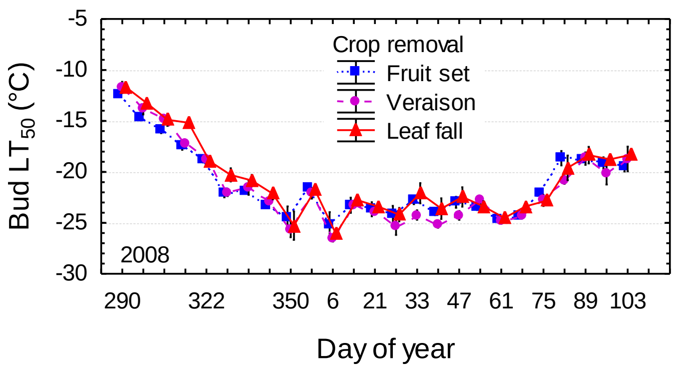
Crop load and hang time: Little threat to winter survival



Harvest at veraison

Harvest after first frost

- Cabernet Sauvignon cropped at 7.5–9.2 t/ha over 4 years
- “Harvest” after fruit set or at veraison → Feedback inhibition of photosynthesis, early leaf senescence, similar carbon reserves in canes as “no harvest”
- No clear influence of fruit ripening (crop load, hang time) on cold hardiness, except if irrigation is withheld → Dry soil → Root injury

Keller at al. (2014)

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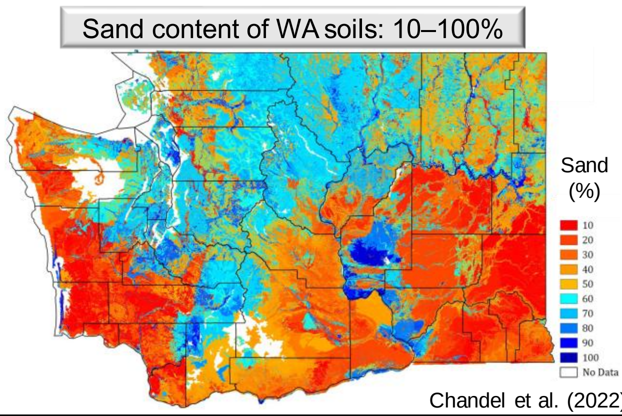
Vineyard nutrition problem: Soils are variable

HiRes Vineyard NUTRITION

- Nutrient availability in vineyards varies greatly over space and time
- One-size-fits-all approach to fertilizer application:
  - ➢ Economically inefficient (oversupply vs. undersupply)
  - ➢ Detrimental to grape quality and environment (nutrient losses)



Chandel et al. (2022)

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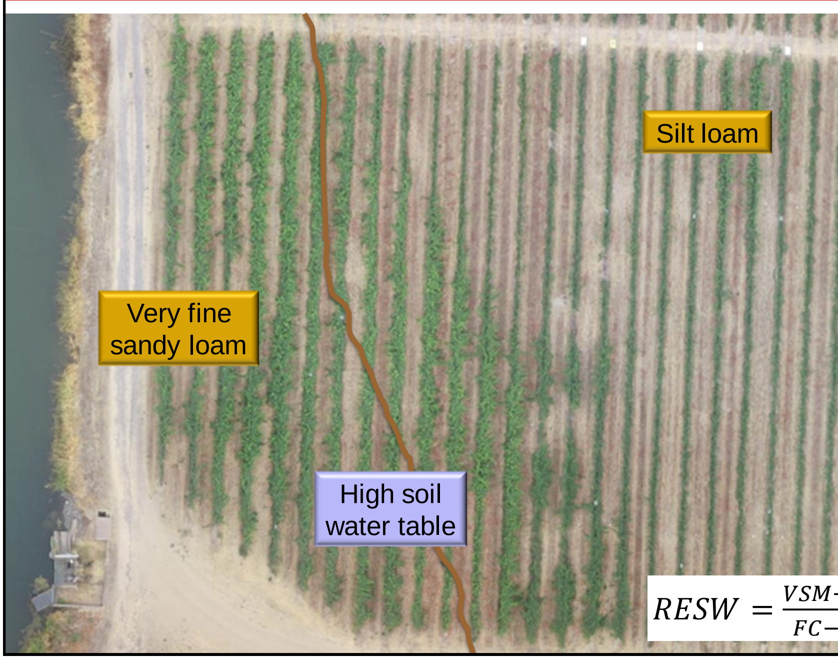
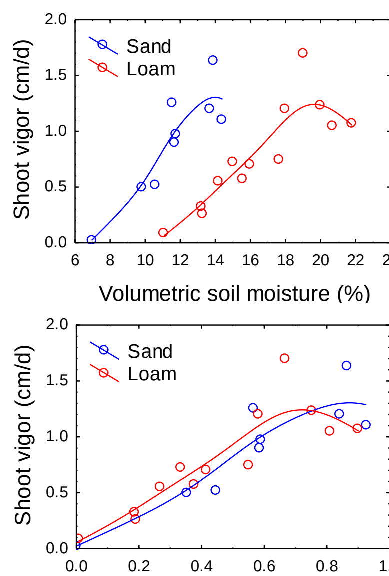
Soil variability translates to vine variability



$$RESW = \frac{VSM - PWP}{FC - PWP}$$



Keller (2023)

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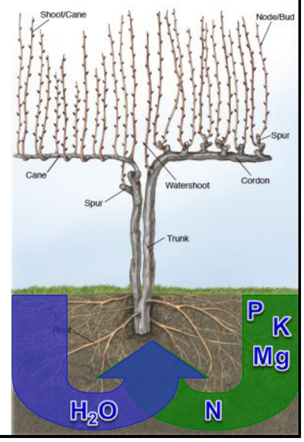
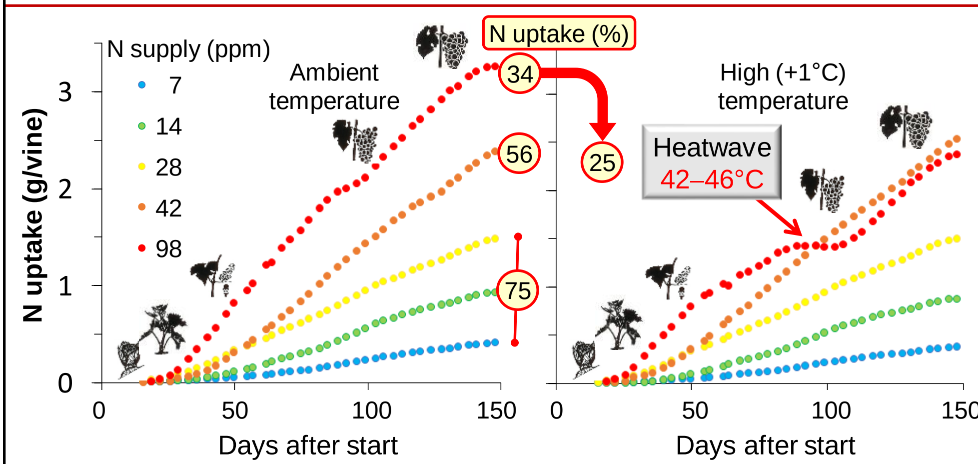
Vineyard nutrients: Availability and uptake

- Nutrients are concentrated in surface soil, dissolved in water
- Nutrient availability is linked to soil water (diffusion, mass flow)
- Movement by **diffusion** (*in* water, concentration gradient) usually dominates, but transpiration favors **mass flow** (*with* water, water potential gradient)
  → Rapid transpiration enhances nutrient uptake
- P, K, Ca, Mg availability is relatively constant
- N availability varies widely in space and time (µM – 100 mM)
  → Roots grow in nutrient-rich zones
- Different nutrients are often in different locations
  → Leaching: $\mathbf{NO_3^-}$ >> $\mathbf{K^+}$ >> $\mathbf{H_2PO_4^-}$
  → Shallow roots take up immobile nutrients (**P**, **K**, **Mg**,…)
  → Deep roots take up mobile nutrients (**N**)
- Mycorrhizal fungi extend root zone

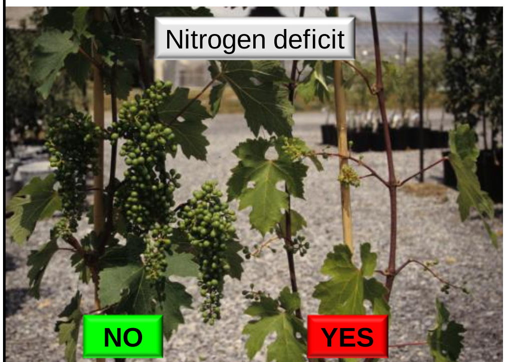


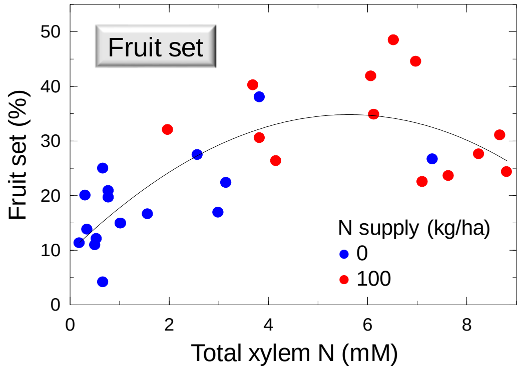
Nutrient uptake: A seasonal affair

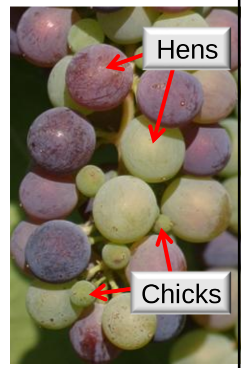


- Vines can take up nutrients throughout the growing season
- Growing roots required: Uptake starts around 5/6-leaf stage
- Canopy growth, fruit and reserve needs drive N uptake
- **N fertilizer** supply: Avoid too much too early (small doses)

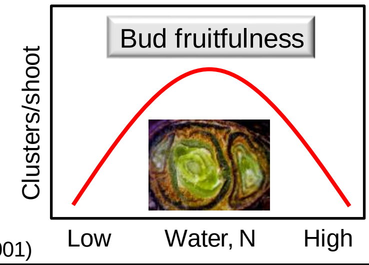
Nutrient stress: Expect low yield







- N deficit exacerbates water deficit (drought stress)
  Low N → ABA → Stomata close at higher Ψ_{leaf}
- Macro- or micronutrient deficit → Poor fruit set
- N deficit or excess → Low bud fruitfulness
- B, Zn, Mo deficit → "Hens & chicks" (big and tiny berries)



Keller & Koblet (1995); Keller et al. (2001)

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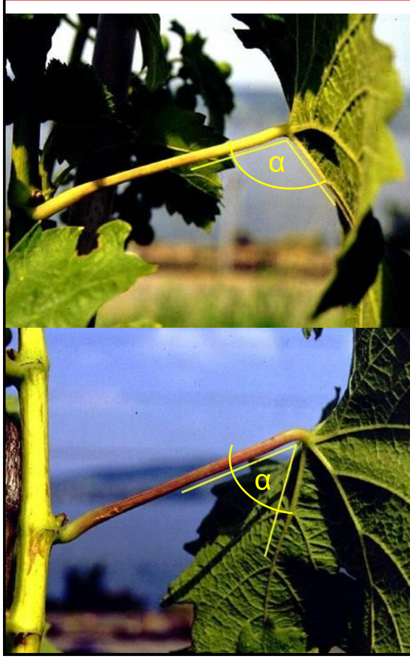
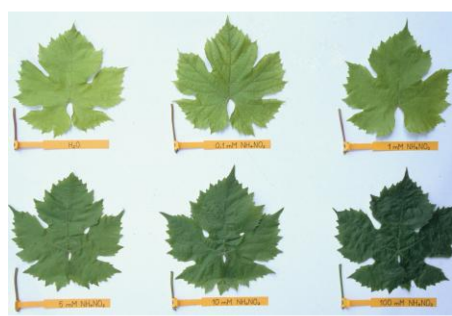
Nitrogen deficit: Pale leaves, red petioles

7
N
Nitrogen
14.0067



- Common with cover crops
- Root growth ⬀
- Shoot growth ⬂⬂
- ABA ⬀, cytokinins ⬂
- Leaf photosynthesis ⬂
  → Energy overload
  → Antioxidant system ⬀
  → Chlorophyll ⬂
  → Sugar, starch ⬀
  → Anthocyanins ⬀
- Leaf senescence
  → Nutrient recycling to sinks (young leaves,…)

- Pale leaves
- Acute angle
- Red petioles



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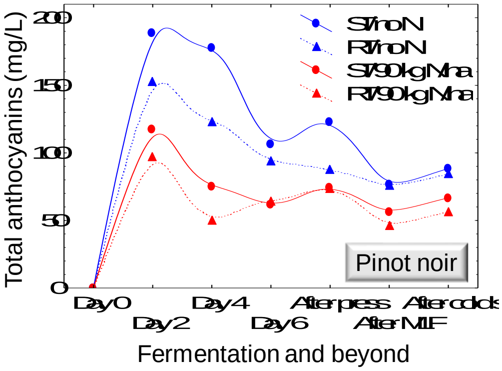
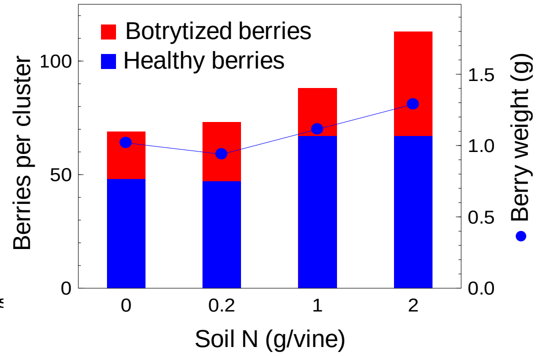
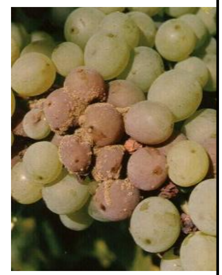
Heavy N supply: Recipe for poor fruit quality







High N supply leads to:

- Higher vigor + yield (compact clusters) → Dense canopy, competition
- NO_3^- interferes with phenolics production
- Lower skin tannins, anthocyanins, higher proportion of malvidin
- Reduced pathogen resistance, higher disease risk

Keller et al. (1999)

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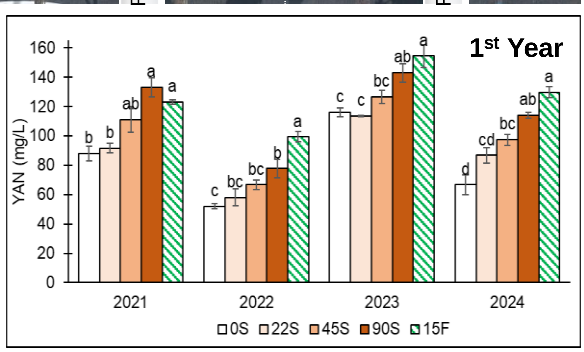
Foliar N: Boosting YAN and reserves in low-N vines

- Apply **soil N** (UAN32) through bloom and/or **foliar N** (urea) at veraison
- More soil N → More fruit YAN, but foliar N more effective, especially in low-N vines
- Foliar N carryover effect (reserve pool): Higher next-year vigor in low-N vines
- ^{15}N: Apply N to clusters only to boost YAN



Davadant (2025)

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Potassium deficit: Glossy leaves

19
K
Potassium
39.098

- Common on lime-rich (high-pH) soils
- Root growth ↘
- Shoot growth ↘
- Phloem loading ↘ (sugar trapped in leaves)
  → Photosynthesis ↘ (feedback inhibition)
  → Fruit set ↘
  → Ripening ↘
  → Storage reserves ↘
- Berry shrinkage (not berry/sour shrivel)
- Xylem sap flow ↘ → Drought stress symptoms?
- Leaf senescence
  → Nutrient recycling to sinks (More fruit → More severe deficit)
- Powdery mildew vulnerability ↗

- Glossy leaves
- Leaf cupping
- Necrotic margins

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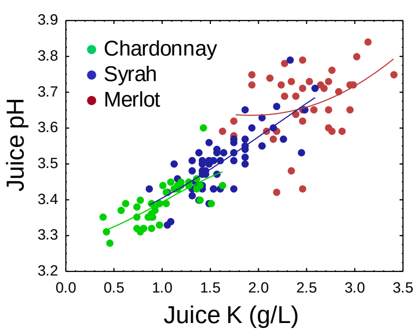
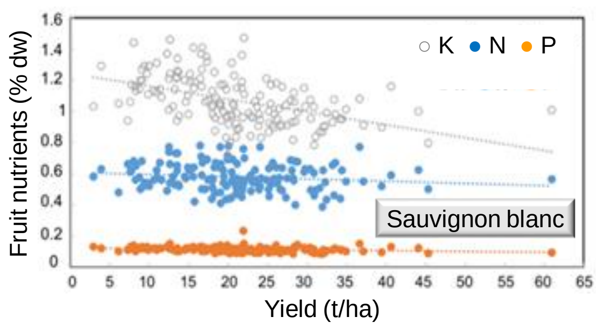
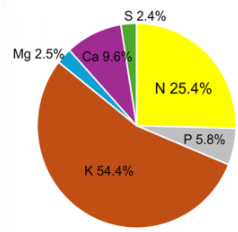
Potassium: The pH conundrum







Berry nutrients

- K is most abundant macronutrient in grape berries (as K^+)
- Both TA and K drive juice pH variation at harvest (→ K^+ replaces H^+)
- Cultivars differ in juice TA and K → Cultivar differences in pH
- Higher yield → Less K in berries (-0.1–0.2% per 10-t yield increment) → Lower pH
- Pomace recycling may return 10–20% of fruit K to vineyard (more for white grapes)
- Juice pH is not very responsive to soil K (More K → More malate)

Keller et al. (2012); Shcherbatyuk et al. (2026)

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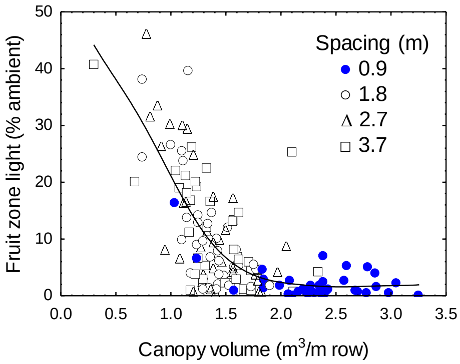
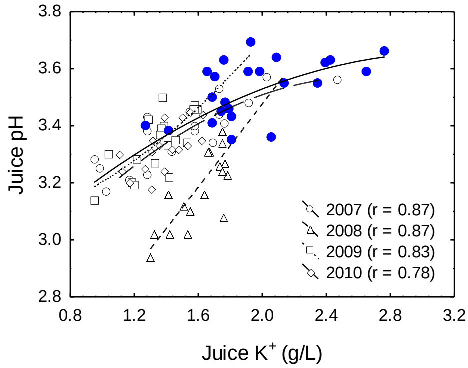
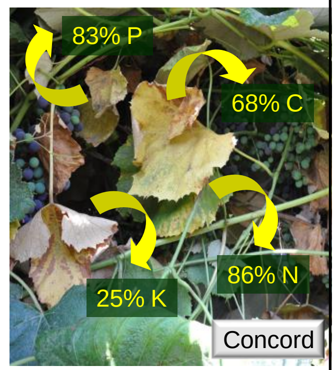
Shade and K: Leaf death raises berry K







- 0.9-m vine spacing: Competition for light → Shade avoidance response
- Vines invest in leaf production at the expense of fruit production
- Lower budbreak, bud fruitfulness, and fruit set → 38% yield penalty (relative to spacing at 1.8, 2.7, 3.7 m)
- K recycling from dying leaves to clusters → High juice pH

Keller et al. (2021)

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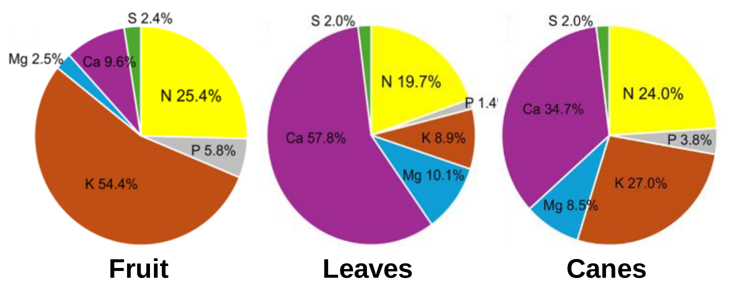
Nutrient requirements: From thresholds to budgets

Nutrient (kg/ha)	Organ	Wine grapes	Juice grapes
N	Fruit	20–30	50
	Leaves	7–10	24
	Canes	3–6	-
P	Fruit	5–7	12
	Leaves	<1	3
	Canes	<1	-
K	Fruit	45–60	106
	Leaves	2–5	11
	Canes	3–7	-
Mg	Fruit	2–3	6
	Leaves	3–4	6
	Canes	1–3	-
Ca	Fruit	6–9	12
	Leaves	17–29	46
	Canes	4–8	-
S	Fruit	2–3	6
	Leaves	1	2
	Canes	<1	-
Yield	(t/ha)	13–22	30



- **Fruit:** Nutrient removal at harvest is driven by yield (K > N > P, Ca > Mg, S), modulated by cultivar, season, fertilizer (0 → 90 kg/ha: +15% N, K)
- **Leaves:** Nutrient loss in fall is non-negligible (Ca > N > K, Mg > P, S); driven by canopy size, modulated by frost (Sep → Nov: -50% N, P), wind
- **Canes:** Pruning loss is minor (Ca ≥ K ≥ N)

Micronutrients: <0.2 kg/ha

Shcherbatyuk et al. (2026)

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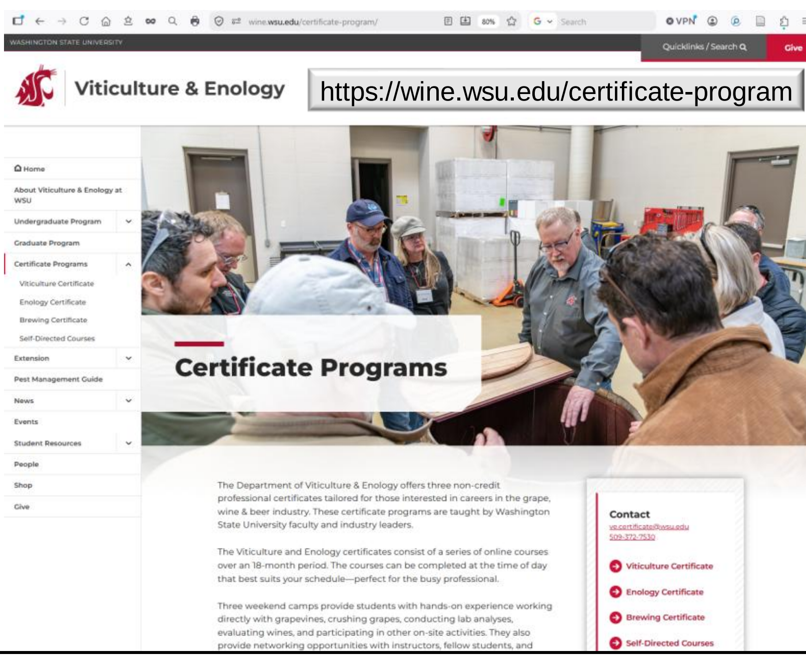
Want to learn more: WSU Certificate Program



- Professional certificates:
  - ✓ Viticulture
  - ✓ Enology
  - ✓ Brewing
  - ✓ Distilling (soon)
- Online learning (2 years)
- Weekend hands-on camps

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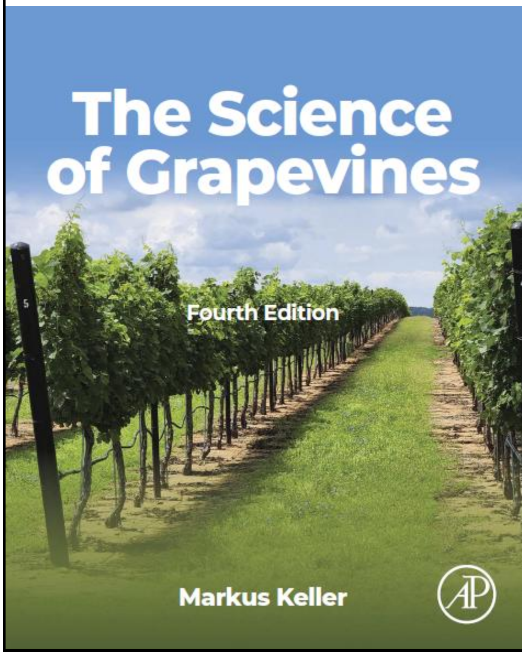
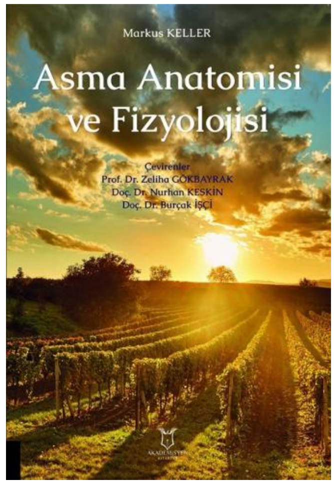
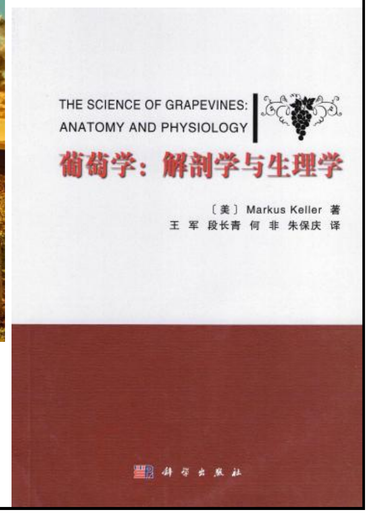
Good news: It’s in the book





Turkish Ed., 2022

Chinese Ed., 2016



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