

THE ESTATE, THE WAGE FLOOR AND WHAT IS ACTUALLY IN THE FIELD

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THE ESTATE, THE WAGE FLOOR AND WHAT IS ACTUALLY IN THE FIELD

Physical AI and Logistics Opportunities in Agriculture

US agriculture is counted well at the top and barely at all where a machine has to work. This review prices what Physical AI can take on across the estate, the labour market and the logistics layer, grades every figure in the public record, and finds a sector whose fullest published unit economics come from one grower in one valley in one season.

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Graded USDA, DOL, SEC and operator records

81 numbered sources, each carrying a verification grade

5 tables · verified / reported / self-published / modelled

Market & economic review · not investment advice

The 2022 Census of Agriculture counted 1,900,487 farms on 880,100,848 acres, with the largest 2% of farms holding 42% of farmland and 42% of farms holding 2% ¹. The machine fleet is 3,784,743 tractors and 298,301 self-propelled combines ⁴, of which 88.4% and 86.8% were built before 2018 ^{4,81}. At 2024 new-machine retail rates the 100-horsepower-plus tractor fleet would take about 46 years to replace and the combine fleet about 54 ^{4,13,81}, so autonomy that ships only on new iron arrives slowly and the retrofit path carries the near term. Hired and contract labour is 12.24% of the \$424.14bn census expense base and is concentrated: 23.0% of farms report any hired-labour expense, and 67,320 farms, 3.5% of the total, carry 83.2% of the national hired-farm-labour bill and 66.9% of hired plus contract labour combined ^{2,81}. The wage floor those farms face is being rewritten. USDA discontinued the Agricultural Labor Survey on 28 August 2025 ¹⁵, DOL

moved the Adverse Effect Wage Rate onto BLS OEWS on 2 October 2025 ¹⁸, and the California entry-level H-2A rate falls from an operative \$19.97 to \$13.52, a 32.3% cut ^{23,81}. Deployment is thinner than the marketing. Monarch Tractor ceased operations on 3 April 2026 ³⁸; FarmWise, advanced.farm and Tortuga AgTech all exited within four weeks in March 2025 ^{47,51}. Robotic milking, at 6% of US milk in 2021 ³⁴, remains the largest verified embodied deployment. California still requires an operator at the controls of self-propelled equipment under a 1977 rule ⁵⁴. Modelled at full national adoption, automated weeding across all vegetable acres harvested for sale excluding potatoes and sweet potatoes is worth about \$612M a year, 0.14% of census farm production expenses ⁸¹.

1. Headline numbers

The table below collects the figures this review returns to. Grades follow the Institute's convention, stated in full in section 2. Where a figure is the author's arithmetic on a cited primary it carries index 81 and is graded modelled throughout. Where a row mixes a published value with a derived share, both grades are shown and both sources are cited.

Three entries reframe what follows. The first is the time it would take to turn over the US machine fleet through new-machine sales, about 46 years for 100-horsepower-plus tractors and about 54 years for combines at 2024 retail rates ^{4,13,81}. On the eleven-month 2025 pace those figures are about 69 and about 95 years ^{13,81}. Any autonomy strategy that reaches the field only inside new iron is a multi-decade strategy, which is why retrofit and supervised operation dominate what is actually deployed.

The second is that 67,320 farms, 3.5% of all US farms, carry 83.2% of the national hired-labour bill ^{2,81}. The addressable population for labour-displacing automation is small, identifiable and already known to equipment dealers. The third is that DOL's interim final rule cuts the California entry-level H-2A wage floor 32.3%, from an operative \$19.97 to \$13.52 ^{23,81}. That is the single largest input to every specialty-crop robotics business case, and it moved by a third while the machines were still being built.

Key number	Value	Grade	Source
US farms and farmland, 2022		verified	USDA NASS Census ¹

	1,900,487 farms on 880,100,848 acres; average 463 acres		
Concentration of farmland	Largest 2% of farms hold 42% of farmland; 42% of farms hold 2%	verified	USDA NASS Census ¹
Concentration of sales	105,384 farms with \$1M or more in sales, 5.5% of farms, over 75% of sales	verified; share modelled	USDA NASS Census ⁵ ; share ⁸¹
Machine fleet, 2022	3,784,743 tractors, 1,252,844 at 100+ PTO hp; 298,301 self-propelled combines	verified	USDA NASS Census Table 45 ⁴
Fleet age	88.4% of tractors and 86.8% of combines manufactured before 2018	modelled	Author's arithmetic on ⁴ ; see ⁸¹
Fleet replacement time at 2024 retail rates	About 46 years for 100+ hp tractors; about 54 for combines	modelled	AEM ¹³ and Census ⁴ ; ratios ⁸¹
Installed machinery capital	\$312.06bn, an average of \$164,212 per farm	verified	USDA NASS Census Tables 1, 43, 44 ³
Total farm production expenses, 2022 census	\$424.14bn across 1.9 million farms	verified	USDA NASS Census Table 4 ²
Field-displaceable expense ceiling	\$106.27bn, 25.1% of the census expense base	modelled	Author's arithmetic on ² ; see ⁸¹
Hired plus contract labour	\$51.94bn, 12.24% of census expenses	verified; share modelled	USDA NASS Census Table 4 ² ; share ⁸¹
Concentration of the labour bill	437,310 farms report any hired labour; 67,320 farms carry 83.2% of the hired-	verified; share modelled	USDA NASS Census Table 4 ² ; share ⁸¹

	farm-labour bill, 66.9% of hired plus contract combined		
Machinery and vehicle purchases, 2025	\$32.0bn of a \$490.3bn expenditure total, 6.5%	verified; share modelled	USDA NASS Farm Production Expenditures ⁹ ; share ⁸¹
Hired workers, April 2025 reference week	637,000 direct hires at \$19.52/hr gross; 40.8 hours worked	verified	USDA NASS Farm Labor ¹⁴
Agricultural Labor Survey	Discontinued 28 August 2025 as duplicative; no replacement named	verified	USDA NASS notice; Federal Register ¹⁵
H-2A workers certified, FY2024	370,836, up from 162,156 in FY2015	verified	DOL interim final rule, Exhibit 3 ¹⁸
H-2A positions certified, FY2025	398,258; about 3.4% growth, slowest in the series	reported	DOL OFLC ²⁰ ; growth rate ⁸¹
California H-2A entry wage under the interim rule	\$13.52 against an operative \$19.97, a 32.3% cut	verified; percentage modelled	DOL OFLC workbook and rates page ²³ ; arithmetic ⁸¹
DOL's own estimate of the rule's effect	\$2.46bn a year transferred from H-2A workers to employers	modelled	DOL interim final rule, Exhibit 1 ¹⁹
Independent estimate of the same effect	\$1.5bn, 22% of an estimated \$6.6bn 2025 H-2A wage bill	modelled	Rutledge, Martin, Ayoub and Hall ²⁴
Robotic milking share of US milk, 2021	6%, up from 4% in 2016; 13% of farms holding 150–499 head	verified	USDA ERS ³⁴
Guidance autosteering, 2023	52% of midsize and 70% of large-scale crop farms; operator in the cab	verified	USDA ERS ARMS ³⁵
		verified	

Self-reported precision agriculture use	22% of farms in 2025, down from 27% in 2023		USDA NASS Technology Use ¹¹
Largest cumulative fielded population	Over 50,000 Lely Astronaut milking robots in 40+ countries since 1995	self-published	Lely ³³
Fullest published cost per acre for a field robot	\$267.72 at one farm and \$448.73 at another, same machine, same season	self-published	Western Growers case study ⁴⁶
Apple-harvest robot success in field trial	82.4% in a trained orchard, 65.2% in an older dense one, about 6 s per fruit	verified	Zhang et al.; Zhu et al. ⁵³
California rule on self-propelled equipment	Operator required at the controls; Title 8 §3441(b), a 1977 rule	verified	Cal/OSHA Standards Board ⁵⁴
On-farm share of US grain storage	13.618 of 25.49 billion bushels, 53.4%	verified; share modelled	USDA NASS Grain Stocks ⁵⁷ ; share ⁸¹
Grain modal split, 2022	62% truck, 26% rail, 12% barge, with truck computed as a residual	verified	USDA AMS ⁵⁸
First-mile haul premium	\$7.53/mile at 25 miles against \$4.09 at 200 miles, 84% higher	verified; premium modelled	USDA AMS GTOR ⁵⁹ ; arithmetic ⁸¹
FSMA 204 compliance date	20 July 2028, now set by statute; covers about 12,000 farms, 0.6% of the census count	verified; share modelled	FDA and CRS ⁶⁴ ; share ⁸¹
Modelled national pool, automated lettuce weeding	\$60.3M a year of service revenue; \$85.6M of displaced hand weeding	modelled	Author's arithmetic on ^{46,76,79} ; see ⁸¹
		modelled	

Modelled pool across non-potato vegetables	About \$612M a year, 0.14% of census farm production expenses	Author's arithmetic on 2,76; see 81
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Table 1. Reference figures for US agriculture, its labour market and its logistics layer, with verification grade.

2. Scope, definitions and method

Physical AI in this review means machines that sense, move, manipulate or navigate in a field, an orchard, a parlour or a packhouse and decide onboard what to do next. That covers autonomous and supervised tractors, retrofit autonomy kits, targeted sprayers, laser and mechanical weeders, harvest robots, milking robots, packing-line robots and autonomous carts. It also covers the perception and planning software that turns sensor output into a usable model of a field, because on the current evidence that model is the binding constraint.

Logistics management means the movement and allocation of physical product and physical resources across the farm boundary: first-mile haulage, on-farm and commercial storage, cold chain, packhouse handling, freight mode selection and the traceability records that will attach to all of it from July 2028 ⁶⁴. Farm-input logistics inbound is in scope where it bears on field operations. Retail and consumer handling is out of scope.

Grades are assigned to every figure. Verified means independently replicated, peer-reviewed, or drawn from a regulator, standards body or primary government series such as USDA NASS, BLS, DOL or DOT. Reported means a named analyst house, operator or news organisation stated it, unconfirmed. Self-published means the number comes from a party selling the thing being measured. Modelled means it was computed rather than observed, including every projection.

One tie-break is needed because the two middle grades overlap. Where a figure originates with the party running the programme being measured, including a company's forward-looking target for its own rollout, it is graded self-published regardless of which outlet relayed it. Trade-press repetition does not raise a grade. This bites in one place worth naming: the Western Growers laser-weeding case study ⁴⁶ is published by a grower trade association but its numbers were supplied by the growers operating the programmes, so it is graded self-published here even though it is the most detailed cost document in the sector.

A modelled figure is never written as a measurement in this report. Author's arithmetic carries index 81 and is labelled as such at the point of use. Where two figures appear not to reconcile, the first question asked was whether the comparison is like with like. Section 3 records one case where it is, exactly, and the apparent discrepancy dissolves; section 5 records one where it is not, and the gap is left open.

Method. Two parallel evidence tracks, one on the estate and its economics and one on labour, deployment and logistics, were compiled and merged into 81 sources. Primary government series were preferred and are the backbone: the 2022 Census of Agriculture, NASS Farm Labor and Grain Stocks, AMS transport reporting, DOL Federal Register rulemaking and OFLC disclosure, FDA regulatory impact analysis, and one SEC filing. The 2022 Census Farms and Farmland highlights sheet ¹ was re-read directly from the primary PDF during drafting and every estate figure in section 3 was confirmed against it.

Limits worth stating up front. www.dol.gov returned HTTP 403 to automated retrieval, so the FY2025 H-2A statistics at ²⁰ rest on a search-index extract and are graded reported; flag.dol.gov and govinfo.gov served the AEWWR workbook and the rulemaking directly, and those figures are graded verified and are graded reported on that basis, downgraded from the grade the series would otherwise carry. bls.gov also returned HTTP 403, which is why the OEWS occupational counts reach this report through ²⁵ and are graded reported. extension.iastate.edu returned a bot-challenge page, so the 2026 Iowa custom rates at ⁷³ come from a trade-press relay. The web-search budget available to this compilation was exhausted before several secondary items could be independently re-checked, and the affected items are flagged where used. Nothing in this report is investment advice.

3. The estate and its counts

The 2022 Census of Agriculture counted 1,900,487 farms, down 6.9% from 2,042,220 in 2017 and below two million for the first time in the modern series, on 880,100,848 acres, 39% of all US land area and 20.1 million acres less than in 2017 ¹. Average farm size rose 5.0% to 463 acres ¹. This is a complete enumeration, and its reliability rests on a definition rather than a sample: since 1974 a farm is any place from which \$1,000 or more of agricultural products were produced and sold, or normally would have been sold. The threshold has never been indexed, so the

count includes a very large population of very small operations that will never buy a machine.

The distribution is what governs any fleet argument. In 2022, 42% of farms were under 50 acres and held 2% of farmland, while the largest 2% of farms, those at 5,000 acres or more, held 42% of farmland, up from 35% in 2002 ¹. Farm counts by acreage class were about 802,000 at 1 to 49 acres, 531,000 at 50 to 179, 288,000 at 180 to 499, 120,000 at 500 to 999, 133,000 at 1,000 to 4,999 and 27,000 at 5,000 or more ¹. By sales the concentration is sharper: 105,384 farms with \$1 million or more in sales were 5.5% of farms and over 75% of all agricultural products sold, while farms selling \$50,000 or less were 74% of farms and 2% of sales ^{5,81}. Acreage class and operating scale are not the same thing, and the census does not cross-tabulate acreage against field operations, so a 5,000-acre western ranch and a 5,000-acre Iowa row-crop operation sit in the same row with entirely different machine-hour profiles.

Land use inside the 880.1 million acres was 393 million acres of permanent pasture (45%), 382 million acres of cropland (43%) of which 301 million were harvested, 72 million acres of woodland (8%) and 33 million acres of other uses ¹. The 81-million-acre gap between cropland and harvested cropland covers idle land, cropland used only for pasture, failed acreage and conservation programmes. Only the harvested figure represents land that saw a harvest operation, and it is the correct denominator for per-acre field economics. For 2025 NASS puts principal crops at 311.5 million acres planted and 295.5 million harvested, with corn at 98.8 million planted and 91.3 million harvested for grain, soybeans at 81.2 and 80.4, all wheat at 45.3 and 37.2, all hay at 49.6 harvested and cotton at 7.80 harvested ⁸. The principal-crops total is not a count of distinct land; NASS states it includes double-cropped acres and unharvested small grains planted as cover crops ⁸.

The machine fleet is large and old, and the aggregate is shrinking, though the 100-horsepower-plus class rose 0.5% from 1,246,592 in 2017 ⁴. The census counted 3,784,743 tractors on 1,509,666 farms, of which 1,252,844 were 100 PTO horsepower or more, along with 298,301 self-propelled grain and bean combines, 564,948 hay balers, 55,496 self-propelled forage harvesters, 16,153 cotton pickers and strippers and 3,161,820 trucks including pickups ⁴. Tractors fell 6.3% from 2017 and combines 7.7% ⁴. Counts are units present on the operation, so machines that are retired, cannibalised or seasonally idle are in there, and the census records no engine hours, working condition or utilisation.

NASS publishes no average age for the fleet. What it publishes is a two-bucket manufacture split, and 3,343,915 of the 3,784,743 tractors, 88.4% by the author's arithmetic, were manufactured before 2018 and so were at least five years old at census date; for self-propelled combines the equivalent share is 86.8% ^{4,81}. That split cannot distinguish a six-year-old machine from a forty-year-old one. Farm tractors are not registered or licensed in the United States, so no independent age series exists anywhere.

Set the fleet against new-machine sales and the turnover arithmetic is stark. AEM reports full-year 2024 US retail sales of 22,864 two-wheel-drive tractors at 100 horsepower or more, 4,358 four-wheel-drive tractors and 5,564 self-propelled combines ¹³. Against the census base that is about 46 years to replace the 100-horsepower-plus tractor fleet and about 54 years to replace the combine fleet; on the eleven-month 2025 year-to-date pace those become about 69 and about 95 years ^{4,13,81}. AEM's data is compiled from member companies through proprietary reporting, so it is the industry's own figure for its own sales, and the census classes tractors by PTO horsepower while AEM uses engine horsepower, so numerator and denominator are not defined identically. Both years were declining ones. Retrofit and aftermarket autonomy kits would not appear in a new-machine count at all, which is a large part of why they matter.

Total farm production expenses in the census were \$424.14bn against \$543.1bn of products sold ². The largest lines were feed at \$88.37bn (20.8%), purchased livestock and poultry at \$51.38bn (12.1%), hired farm labour at \$41.81bn (9.9%), depreciation claimed at \$41.26bn (9.7%), fertiliser and lime at \$36.14bn (8.5%), cash rent at \$27.31bn (6.4%), repairs and supplies at \$25.90bn (6.1%), seeds at \$25.58bn (6.0%), chemicals at \$23.61bn (5.6%) and gasoline, fuels and oils at \$18.39bn (4.3%) ². Roughly a third of that base is one farm buying from another, in feed and livestock, and is not a claim on field labour or machinery at all.

The lines a field machine could plausibly touch sum to \$106.27bn, 25.1% of the census expense base by the author's arithmetic: hired farm labour, contract labour at \$10.13bn, customwork and custom hauling at \$10.05bn, fuels at \$18.39bn and repairs and supplies at \$25.90bn ^{2,81}. That is a ceiling on the addressable pool and not an estimate of what is displaceable, because repairs and fuel include livestock and farmstead uses and no census line separates field task from farmstead task. Hired plus contract labour alone is \$51.94bn, 12.24% ^{2,81}.

Three federal totals for the same quantity disagree and no agency publishes a crosswalk. The census gives \$424.14bn for 2022; NASS's own ARMS-based

expenditure survey gives \$452.5bn for the same year, a difference of \$28.4bn or 6.7% ^{2,9}. Geographic coverage is not the explanation and runs the wrong way, because the expenditure survey covers only the 48 contiguous states while the census covers all 50, and the smaller-coverage instrument returns the larger total. For 2025 the same pattern holds between agencies: NASS puts expenditures at \$490.3bn in a July 2026 release ⁹ while ERS forecast \$473.1bn in May 2026 ¹⁰, a gap of \$17.2bn. The instruments, vintages and category structures differ. Which categories carry the gap is stated by neither agency and is not asserted here.

One apparent discrepancy in the same family resolves exactly once the coverage definitions are compared. NASS gives 1,880,000 farms for 2024 in Farms and Land in Farms ⁷ and 1,872,300 in the Technology Use release ¹¹. The Technology Use table footnotes that it excludes Alaska and Hawaii; NASS gives 2024 counts of 1,200 for Alaska and 6,500 for Hawaii, and 1,880,000 minus 7,700 is 1,872,300 exactly ^{7,11,81}. Same series, two coverage definitions, no disagreement. The 2022 census and the annual estimate series likewise differ by 163 farms, 0.009%, because the annual series is benchmarked to the census and the two are not independent measurements ^{1,7}.

A separate definitional gap is larger and also fully established. ERS puts land in agricultural uses at 1.19 billion acres in 2017, comprising 805 million acres of grazing land, 390 million acres of cropland and 6 million acres of farmsteads and farm roads ¹², against the census's 900.2 million acres of land in farms for the same year. ERS counts grazed forest-use land and public-domain grazing; the NASS farm definition excludes grazing land used under government permits on a per-head basis and counts only land attached to an identified operation ^{1,12}. The ERS series is also seven reference years behind current NASS data.

The 2025 farm count is not an observation. NASS estimates 1,865,000 farms on 873,950,000 acres for 2025, states that it did not conduct the June Area Survey that year, and generated the figures with a statistical model built on historic trends and the previous ten years of survey estimates ⁷. The reported coefficient of variation is 0.5% on farm numbers and 0.2% on land in farms, and NASS states explicitly that this excludes error arising from model selection ⁷. Any 2023 to 2025 movement should be read as a trend extrapolation until the 2027 Census benchmarks it. The same release puts 50.1% of farmland on farms with \$500,000 or more in sales, 9.9% of farms, with sub-\$100,000 farms at 78.8% of farms and 25.7% of farmland ⁷, and those are shares of the modelled series.

The people running the estate are ageing on the census's own measure. It counted 3,374,044 producers at an average age of 58.1 years, up 0.6 years from 2017, with producers 65 and over up 12.1% to 1.29 million, 38% of the total, while those aged 35 to 64 fell 9.0% ⁶. Only 42% report farming as their primary occupation and 40% worked off the farm 200 days or more ⁶. Producer counts capture decision makers, not labour input, and part of the flat total reflects a reporting change: the share of farms naming more than one decision maker rose from 54% to 60% ⁶.

Self-reported precision agriculture use fell in NASS's own series, from 27% of US farms in 2023 to 22% in 2025, with state values from 4% in West Virginia to 50% in North Dakota ¹¹. This should not be read as a fall in installed technology. The question bundles GPS guidance, yield monitoring, variable rate application, drones, electronic tagging, precision feeding and robotic milking into one self-reported response; the estimate comes from a stratified sample of about 28,000 operations; NASS publishes no standard errors in this table and states the values are subject to revision after each census ¹¹. A five-point move on a broad question across a farm population that is 74% sub-\$50,000 operations is within the range a wording or sample effect could produce.

4. Farm labour, and what the numbers actually support

NASS counted 637,000 workers hired directly by farm operators during the reference week of 6 to 12 April 2025, up 3% year on year, and 512,000 in the week of 12 to 18 January ¹⁴. Average gross wages were \$19.52 an hour for all hired workers, \$18.58 for field workers, \$18.15 for livestock workers and \$18.43 combined, on 40.8 hours worked ¹⁴. By occupation, crop, nursery and greenhouse farmworkers numbered 262,000 at \$18.20, animal farmworkers 155,000 at \$18.00 and agricultural equipment operators 103,000 at \$19.20 ¹⁴. This is a single-week head count of direct hires only. The survey explicitly excludes contract labour, custom labour, agricultural service workers and Alaska, with Hawaii also excluded from the annual wage tables, so it is not a count of everyone working on US farms, and since 2020 the published numbers are model-based estimates calibrated against the prior year's same-quarter figure ¹⁴.

That series no longer exists. On 28 August 2025 USDA NASS discontinued the Agricultural Labor Survey under the Paperwork Reduction Act, describing the collections as duplicative or no longer necessary ¹⁵. It was the only national survey of agricultural employers on employment, hours and wages, and it was the stated

input to the H-2A Adverse Effect Wage Rate. The notice gives no replacement source. The last full annual series is 2024, at \$19.10 an hour for all hired workers and \$18.42 for field workers ¹⁴.

Seasonality in the direct-hire workforce is large and asymmetric. NASS recorded 496,000 hired workers in the January 2024 reference week against 808,000 in July, a peak-to-trough ratio of 1.63; the short-term component, workers expected to be employed 149 days or less, swings from 49,000 to 190,000, a factor of 3.9 ^{14,81}.

Because the survey excludes contract labour, and contract labour is disproportionately seasonal and harvest-facing, the true amplitude of total farm employment is almost certainly larger than 1.63.

Hired labour is concentrated in a small minority of operations. Only 437,310 farms, 23.0% of all US farms, reported any hired farm labour expense in 2022, and the 67,320 farms spending \$100,000 or more accounted for \$34.77bn, 83.2% of the entire national hired-labour bill ^{2,81}. Unpaid operator and family labour is not an expense and does not appear at all, so the census understates total labour input by an amount it does not measure. Labour is also concentrated by commodity: it is 42% of production expenses for greenhouse and nursery operations and 40% for fruit and tree nut operations, against 12% for all farms, and contract labour is 19.5% of total labour expenses nationally and 34.5% in California ¹⁷.

H-2A has grown into a structural share of that workforce. DOL's own administrative series records workers certified rising from 162,156 in FY2015 to 370,836 in FY2024, with applications certified rising from 9,516 to 21,633 ¹⁸. OFLC reports 398,258 positions certified in FY2025 ²⁰, which against ERS's roughly 385,000 for FY2024 is growth of about 3.4%, the slowest in the series ^{16,20,81}. ERS puts FY2024 at about 385,000 positions with an average certified duration of 5.75 months, giving roughly 184,000 full-year equivalents against 315,500 visas actually issued ¹⁶. That last gap, about 70,000, is unexplained by ERS.

The three federal and quasi-federal counts of the same FY2024 quantity do not agree. DOL's rule gives 370,836 workers certified ¹⁸, ERS gives about 385,000 positions certified ¹⁶ and CRS gives about 363,000 farmworkers approved ²⁶. All three cite OFLC disclosure data, the column headings differ, none publishes the definition or the reconciliation, and dol.gov blocked retrieval of the underlying files during compilation. The spread is about 22,000, roughly 6%. Against ERS's 1.18 million hired farmworkers in 2024, the roughly 184,000 full-year equivalents are about 15.6% of hired farm employment ^{16,81}, though that divides a full-year-equivalent estimate by a QCEW-based head count, which are different units, so it is

an approximation. Philip Martin's separate calculation puts H-2A at 18% of average crop employment in 2025, on a crop-only denominator, and projects over 20% by 2030 ¹⁶.

On 2 October 2025 DOL issued an interim final rule replacing the discontinued Farm Labor Survey with BLS Occupational Employment and Wage Statistics as the basis for the AEWR, setting two skill levels per state across five SOC codes ¹⁸. DOL estimates the rule transfers \$2.46bn a year from H-2A workers to H-2A employers, \$17.29bn over ten years at a 7% discount rate, against \$0.55 million of ten-year cost, annualised at \$0.78 million, consisting entirely of rule familiarisation ¹⁹. That is the rule-maker's own estimate of the effect of its own rule, computed from ARIMA projections of H-2A growth, a 92%/8% skill-level weighting and an assumption of 40 hours a week for 26 weeks per worker; about \$1.29bn of it is the housing adjustment and about \$1.18bn is wage transfer ¹⁹.

An independent calculation by four agricultural economists puts the 2025 H-2A wage bill at \$6.6bn and the methodology's effect at a \$1.5bn reduction, 22%, with state cuts reaching 42% in Louisiana, 40% in North Dakota and 39% in Mississippi, and California falling \$101M on a \$655M base ²⁴. The comparable pair is DOL's wage-only \$1.18bn against the Choices \$1.5bn; the remaining difference follows from the hours and projection assumptions and neither source publishes a crosswalk. The Choices figure is arithmetic on job orders, not observed payroll, and Choices is editorially reviewed rather than peer reviewed ²⁴.

The occupational base the AEWR now rests on is not primarily agricultural. Of the roughly 955,000 US workers OEWS records across the five SOC codes that now set the rate, about 601,440, 63%, are hand packers and packagers, most of them in nonfarm warehouses on the authors' characterisation; OEWS records only 261,690 workers in crop farmworker code 45-2092, 35,420 in 45-2093 and 30,940 in 45-2091 ^{25,81}. The wage floor for US farm labour now depends in part on wages in warehouse occupations. The authors do not publish the industry cross-tabulation supporting the warehouse claim, which is why it is graded reported.

The resulting rates are a step change. The average AEWR under the new methodology, effective 3 August 2026, is \$15.96 an hour, defined in regulation as a simple average of the 45-2092 rates across all states and territories at both skill levels, so it includes Guam, Puerto Rico and the US Virgin Islands and is not employment-weighted ²¹. New York's rates are \$16.17 at Skill Level I and \$19.25 at Skill Level II, falling to \$13.62 and \$16.70 for H-2A workers after the housing adjustment ²¹. In California the field and livestock worker rate becomes \$13.52 at

Skill Level I and \$15.53 at Skill Level II after a \$3.07 housing adjustment, against an operative \$19.97, cuts of 32.3% and 22.2%; across twelve major agricultural states the Skill Level I cut ranges from 22.9% in Arizona to 34.4% in Oregon ^{23,81}. The separate range-occupation AEWR moved on an unrelated basis, rising 3.6% to \$2,132.41 a month on a mechanical Employment Cost Index escalator untouched by the methodology change ²².

Two things about the operative rates deserve stating plainly. As of 3 August 2026, DOL's own page still showed statewide AEWRs with effective dates in December 2024, still described as derived from the USDA Farm Labor Survey, which was discontinued in August 2025 ^{15,23}. And the rates published under the interim rule take effect 17 August 2026 rather than 3 August for entities and states subject to *Kansas et al. v. US Dep't of Labor*, which covers 17 states ²¹. The binding wage floor for US farm labour is currently unsettled, litigated and derived from a survey that no longer runs.

Over the longer run the direction was upward. Real farm wages for nonsupervisory crop and livestock workers rose from \$12.05 an hour in 1990 to \$18.12 in 2024 in 2024 dollars, 1.2% a year over the full period and 1.9% a year over 2014 to 2024, with the farm-to-nonfarm wage ratio rising from 50% to 60% ¹⁶. DOL's own reconstruction of the employment-weighted national AEWR shows it rising from \$10.54 in 2014 to \$16.66 in 2024, 4.68% a year compounded ^{18,81}. DOL heads that exhibit in 2025 dollars, though the 2014 value sits below the nominal 2014 state rates, so the basis is not stated unambiguously in the source. Wage growth persistently above the nonfarm rate is consistent with a tightening market. It is also what a market clearing at a higher price looks like, and the series ends in 2024 because the survey behind it was cancelled.

Whether US agriculture faces a labour shortage is the load-bearing question for every automation business case, and the answer depends on which question is being asked. DOL's interim final rule states that the available data strongly demonstrate a persistent and systemic shortage of qualified and eligible American workers, even absent intensified enforcement ¹⁸. That is an administrative finding about applicant flow at the offered wage, which is a legal test under 8 U.S.C. 1188(a) and does not require a market-wide quantity shortage.

The econometric literature tests something different and finds effects at or below the low end. Hertz and Zahniser, reviewing four national wage datasets, found only the Current Population Survey showing real crop wages higher in 2011 than 2007, and concluded only that there was preliminary evidence of localised shortages in

certain counties in California, Michigan and elsewhere ²⁷; that paper states on its first page that it was presented in an invited session not subject to standard refereeing, and the evidence is fourteen years old. Clemens, Lewis and Postel used the 1964 exclusion of roughly half a million bracero farmworkers as a natural experiment and failed to reject zero labour-market impact on domestic farm wages and employment, finding mechanisation and crop mix moving on paths not explained by exposure to the exclusion ²⁸. A failure to reject zero bounds an effect without establishing its absence, and 1960s agriculture had a different crop mix and mechanisation frontier. Rutledge and Merel estimate that a 10% fall in farm labour supply causes at most a 4.2% reduction in production in the top ten fruit and vegetable counties in California, and state that their estimate is an upper bound because it exploits variation in equilibrium employment ²⁹.

What is better established is that the source population is shrinking. Charlton and Taylor find, on nationally representative panel data from rural Mexico for 1980 to 2010, a significant negative trend in agricultural labour supply of about 150,000 workers a year, driven by nonfarm employment growth, falling birth rates and rising rural education, with higher US wages and border enforcement slowing but not reversing the transition ³⁰. That is a necessary condition for a US shortage and not a sufficient one, since the US response could be higher wages, H-2A substitution, mechanisation or import substitution, and the record shows all four happening at once.

The most widely cited evidence for a shortage is a grower survey. The California Farm Bureau Federation's 2019 survey of 1,071 self-selecting farmers and ranchers found 56% had been unable to hire all the employees they needed at some point in the previous five years, with 86% saying they had raised wages, 61% using a farm labour contractor, more than half adopting mechanisation and about 6% enrolling in H-2A ³¹. It is a voluntary, self-selected survey conducted by the trade association representing the employers whose claim is being tested, with no sampling frame and no published response rate, and the question has no wage attached to it, so it does not distinguish scarcity from unwillingness to pay a market-clearing wage. It is California-only and seven years old.

The 2025 enforcement effect is not measurable from public data. Economic Insights and Research Consulting reported employment in agriculture and related industries falling 155,000, 6.5%, between March and July 2025, noting that employment rose in those months in both 2023 and 2024 ³². That is a private consultancy with a stated position on deportation policy, the comparison is a within-year seasonal

change in a survey series with large sampling error for a small industry, no confidence interval appears in the coverage located, and the result had not been independently replicated. It is recorded here as the only quantified estimate located, not as a finding.

The honest reading for an operator is this. Labour cost is real, large and highly concentrated in about 67,000 farms ^{2,81}. Whether the constraint is quantity or price is unresolved in the public data and now harder to resolve, because the survey that measured it was cancelled in August 2025 ¹⁵ and the wage floor it set has been cut by roughly a third at entry level in the largest specialty-crop state ^{23,81}. An automation business case built on a rising wage floor is currently building on a number that moved sharply downward.

There is also no vacancy rate. JOLTS publishes total nonfarm only, so the single measure used to establish labour scarcity in every other US industry does not exist for farming. Every shortage claim in this literature is made without one.

5. The cost stack per acre

Two land-grant series give the best public per-acre benchmarks for Midwest field operations, and they are built on different bases, so they bracket a price rather than agreeing on one. The 2024 Iowa Farm Custom Rate Survey reports average charges of \$8.35 per acre for a broadcast ground application with a self-propelled sprayer, \$44.05 for corn combining, \$42.00 for soybean combining, \$17.75 for field cultivating, \$24.20 for planting without attachments and \$155.05 for complete custom farming of corn ⁷². The 2026 edition, on 205 responses and about 4,698 rates, gives medians of \$10.50, \$45.00, \$42.00, \$19.00, \$26.00 and \$165.00 for the same operations, with harvest rates expected to rise about 6.5% and pre-harvest rates about 8.5% over 2025 ⁷³. These are what respondents expect to charge or pay, not transacted prices, on a response rate near 16% in the 2024 edition ⁷².

University of Illinois machinery cost estimates for 2025, built with ASABE engineering formulas on new machinery, put the full owning-and-operating cost of one self-propelled spraying pass at \$6.10 per acre, a conventional planter pass at \$24.40, a field cultivator pass at \$15.30, a chisel plough pass at \$19.50 and combining corn at \$54.40 ⁷⁴. These assume machinery bought new at 85% of list and held ten years, seven for combines, diesel at \$3.00 a gallon, labour at \$22.00 an hour and specific annual acreages, and the authors state the estimates exclude any profit allowance and that 5% to 15% should be added when setting a custom rate ⁷⁴.

The same publication is the only public source located that prints list prices alongside per-acre cost: a 310 PTO horsepower tractor at \$623,657 in 2025, up 7.5% from \$579,945 in 2023, a 470 horsepower combine at \$784,500, a 120-foot self-propelled sprayer at \$543,689 covering 8,028 acres a year and a 1,000-bushel grain cart at \$84,250 ⁷⁵.

For the spraying pass, which is the operation autonomous and targeted-application systems are marketed against, the Iowa 2026 median charge of \$10.50 is 72% above the Illinois full-ownership estimate of \$6.10 ^{73,74,81}. For corn combining the relationship inverts: the Iowa median of \$45.00 is 17% below the Illinois estimate of \$54.40 ^{73,74,81}. Different states, different years, different bases. The Illinois figure prices a new machine at list over a stated annual acreage with no margin; the Iowa figure is a self-reported charge on machinery of mixed age, and in the 2024 edition 53% of corn-combining respondents reported machinery one to five years old ⁷². What this establishes is that no single number can be called the price of a field pass, which matters because every autonomy saving claim is denominated against one.

Specialty crops are where the labour is and where the automation claims concentrate. The UC Davis 2023 cost and return study for romaine hearts on the California Central Coast prices two hand-weeding operations at 12.00 labour hours per acre and \$284, or \$142 for a single pass, at a general labour rate of \$23.68 an hour, being a \$16.00 base wage plus 48% payroll overhead ⁷⁶. It is the only public figure located that decomposes a hand-weeding pass into hours and a wage. The same study prices the herbicide alternative at \$110 an acre, being \$80 of material plus a \$30 custom ground application for one banded pass covering 37.5% of the area, and separately lists an automated weeding pass at \$200 an acre as a custom service, recorded as a potential additional growing cost excluded from the budget ⁷⁶. UC cost studies are constructed representative budgets built with a grower and adviser panel, not a survey of invoices, and the study does not say which machine the \$200 refers to or give it a range.

The same budget puts weeding in proportion. Total cost is \$16,793 an acre, of which harvest, cooling and sales are \$9,393, 55.9%, and hand harvest and field pack alone are \$6,800 at \$8.00 a carton on 850 cartons ⁷⁶. Hand weeding at \$284 is 1.7% of total cost per acre; hand harvest is 40.5% ^{76,81}. A machine that eliminated hand weeding entirely on this crop would move total cost by under two points. Hand harvest is 40.5% of cost per acre on this budget and hand weeding is 1.7% ^{76,81}. Section 7 records the harvest-robotics deployment history.

The most detailed public unit economics for a commercial agricultural robot are in the Western Growers case study of two Salinas Valley farms. At Braga Fresh, a \$1.2M LaserWeeder covering 2,350 acres a year cost \$267.72 an acre to run against a stated pre-robot hand-weeding cost of \$900 an acre; residual hand weeding after the machine was \$282.28, total weeding cost \$550, net saving \$350 an acre, or \$822,500 a year per machine, a 39% reduction ⁴⁶. The same document contains the counter-case. At Triangle Farms the machine cost \$448.73 an acre to run, and on direct-seeded organic romaine it cost \$88.73 an acre more than hand weeding alone, with the grower judging a Stout Smart Cultivator and FarmWise's weeding-as-a-service more cost effective on that crop ⁴⁶. That farm's H-2A hand-weeding baseline ranged from \$500 to \$1,800 an acre by crop, so the machine's advantage is a function of which crop it runs on, and the romaine figure is confounded because the machine was thinning as well as weeding. Overall Triangle still reported a 40% reduction across four crops, \$430,277 a year ⁴⁶.

The Braga figures reconcile on their own terms and the throughput assumption is aggressive. The document reports three crews of 25. The \$900 reconciles only if the 90 minutes is per crew, at 37.5 worker-hours and about \$24 an hour loaded, and that reading is assumed in what follows ^{46,81}. The \$102.13 implement line reproduces exactly as \$1.2M over five years and 2,350 acres. Operator labour is \$70.12 of the \$267.72, so 26.2% of the machine's per-acre cost is human labour. And 2,350 acres a year at the stated 0.8 acres an hour requires about 2,940 machine-hours, which is about 27 weeks of running 18 hours a day, six days a week ^{46,81}. No downtime, weather, field-condition or breakdown allowance is stated anywhere in the document. No downtime, weather, field-condition or breakdown allowance appears anywhere in the document, and utilisation is the input the per-acre result is most sensitive to.

One gap in that document is left open here. The case study's crew time per acre falls from 90 minutes to 12 to 15 minutes and crew size from 25 to 18, which at the 15-minute end implies about an 8.3-fold reduction in hand-weeding worker-hours per acre, while the reported hand-weeding cost falls only from \$900 to \$282.28, a factor of 3.19 ^{46,81}. Both figures come from the same document and describe the same operation on the same farm, so the comparison is like with like. The difference could be explained by a change in the number of passes, by crews covering different acreage, or by a wage change, none of which the document publishes. It is recorded as an unexplained gap and not as an error.

The best replicated field measurement of what a robotic cultivator saves is smaller than any of that. A 2022 UC trial in drip-irrigated cantaloupes at the UC West Side Research and Extension Center found a Robovator automated cultivator cut hand-weeding cost by \$37 an acre and a finger weeder by \$54, about 20% against the uncultivated control, while a Sandea herbicide treatment cut it by over \$100, about 45%, and gave the highest yield at 1,306 boxes an acre ⁷⁷. The implied untreated baseline is about \$222 an acre by the author's arithmetic ^{77,81}. One site, one season, one crop, on an extension blog with no confidence intervals, and by end of season weed pressure was equivalent across treatments. The most-quoted efficacy figure in lettuce, a 38% to 45% labour reduction without yield loss attributed to UC Davis work, is a labour-use reduction carrying no machine capital or operator cost on the other side ⁷⁷.

For targeted herbicide application in row crops the vendor and the independent test disagree in size but not in direction. Deere states 59% average herbicide savings across corn, soybean and cotton in 2024 ³⁶. An Iowa State test of See and Spray Ultimate on five Iowa fields in 2024 found 76% average product saving worth \$15.70 an acre, with individual field savings of 90.6%, 87.6%, 87.2%, 71.2% and 43.9% ⁷⁸. The Deere figure is the equipment maker's own for its own customers' machines. The Iowa State figure is a material saving with no machine premium netted off and reached this review through trade press. The 43.9% to 90.6% spread is driven by initial weed pressure, and no national distribution of weed pressure is published, so every average saving claim for targeted spraying is an average over an unpublished distribution.

Sizing the specialty-crop pool from these inputs gives a number smaller than the sector's capital raised. US lettuce covered 301,400 harvested acres in 2024, being head 109,600, romaine 116,600 and leaf 75,200, with a combined crop value of \$4.60bn ⁷⁹. At the UC Davis \$200 custom rate for one automated pass applied once to every harvested lettuce acre in the country, the entire national service revenue pool is \$60.3M a year; the hand-weeding bill it would displace at \$284 for two passes is \$85.6M, which is 1.86% of the lettuce crop value; covering that acreage once a year at the only disclosed machine productivity, 2,350 acres per machine-year, needs 128 machines and \$154M of capital at the only disclosed purchase price ^{46,76,79,81}. Substituting the Braga \$900 baseline raises the displaced pool to \$271.3M, a 3.2-fold swing that comes entirely from which crop system the baseline describes. Extending the \$200 pass across all 3,061,344 non-potato vegetable acres in the 2022 census gives about \$612M a year, 0.14% of census farm production expenses

^{2,81}. These are computed, not observed, and assume 100% adoption and one pass per harvested acre.

Three national per-acre ratios are worth carrying into any business case, with their denominators stated because both are wrong in known directions. Spread across the 301,327,737 acres of harvested cropland, national customwork and custom hauling is \$33.36 per harvested acre, hired plus contract labour is \$172.36, and installed machinery capital is about \$1,036 ^{2,3,81}. Custom hauling and livestock custom work do not attach to harvested cropland, and a large share of hired labour is livestock, greenhouse and packing labour with no acreage at all, so these are upper bounds per crop acre.

Operation	Price per acre	Basis	Grade	Source
Broadcast spray, self-propelled	\$10.50 median	Expected 2026 custom charge, Iowa	reported	Iowa State Extension ⁷³
Broadcast spray, self-propelled	\$6.10	Full owning and operating cost, new machine, Illinois	modelled	U Illinois farmdoc ⁷⁴
Planting, no attachments	\$26.00 median	Expected 2026 custom charge, Iowa	reported	Iowa State Extension ⁷³
Planting, no attachments	\$24.40	ASABE calculation, new machine, Illinois	modelled	U Illinois farmdoc ⁷⁴
Field cultivating	\$19.00 median	Expected 2026 custom charge, Iowa	reported	Iowa State Extension ⁷³
Field cultivating	\$15.30	ASABE calculation, new machine, Illinois	modelled	U Illinois farmdoc ⁷⁴
Combining corn	\$45.00 median, range \$25–80	Expected 2026 custom charge, Iowa	reported	Iowa State Extension ⁷³

Combining corn	\$54.40	top of a published \$32.70–\$54.40 range across combine sizes; the article does not identify the machine or acreage behind it	modelled	U Illinois farmdoc 74,75
Complete custom farming, corn	\$165.00 median	Expected 2026 custom charge, Iowa	reported	Iowa State Extension 73
Hand weeding, conventional romaine hearts	\$142 per pass, \$284 for two	12.00 labour hours/acre at \$23.68 loaded; panel budget	modelled	UC Davis cost study 76
Banded herbicide pass, romaine	\$110	\$80 material plus \$30 custom ground application, 37.5% of area	modelled	UC Davis cost study 76
Automated weeding pass, custom service	\$200	Listed as an excluded potential additional cost; no range, no source given	modelled	UC Davis cost study 76
Hand harvest and field pack, romaine hearts	\$6,800	\$8.00/carton on 850 cartons; 40.5% of \$16,793 total cost	modelled	UC Davis cost study 76; share 81
Hand weeding, certified-organic baby leaf	\$900	Grower-stated pre-robot baseline; 25-person crew at 90 min/acre	self-published	Western Growers case study 46
Laser weeder, fully loaded (Braga Fresh)	\$267.72	\$1.2M machine over 5 years and 2,350 acres/yr;	self-published	Western Growers

			26.2% of it operator labour		case study ⁴⁶
Laser weeder, fully loaded (Triangle Farms)	\$448.73		Same machine, same season, different farm and crop mix	self-published	Western Growers case study ⁴⁶
Residual hand weeding behind the machine	\$282.28		Grower-reported; crew size and hours not decomposed in the document	self-published	Western Growers case study ⁴⁶
Robotic cultivator saving, cantaloupe trial	\$37/acre (Robovator), \$54 (finger weeder)		Replicated UC field trial; about 20% against uncultivated control	reported	UC Weed Science ⁷⁷
Herbicide saving, targeted spray	\$15.70/acre, 76% of material		Five Iowa fields, 2024; no machine premium netted off	reported	Iowa State via Strip-Till Farmer ⁷⁸
National customwork and custom hauling	\$33.36 per harvested acre		\$10.05bn over 301,327,737 harvested acres	modelled	Author's arithmetic on ² ; see ⁸¹
National hired plus contract labour	\$172.36 per harvested acre		\$51.94bn over the same base; includes livestock and packing labour	modelled	Author's arithmetic on ² ; see ⁸¹
National installed machinery capital	About \$1,036 per harvested acre		\$312.06bn over the same base; machinery also serves pasture and livestock	modelled	Author's arithmetic on ³ ; see ⁸¹

Table 2. The per-acre cost stack, with the basis and grade of each figure. Prices from different states, years and bases are not additive.

6. The logistics layer: handling, storage, cold chain and freight

The single largest storage node in US grain is the farm. Total capacity was 25.49 billion bushels on 1 December 2025, split 13.618 billion on farms and 11.871 billion in off-farm commercial facilities, so 53.4% of national capacity sits on the operation itself ^{57,81}. On-farm capacity is estimated from a probability sample of about 73,100 farm operators; off-farm capacity is an enumeration of known commercial facilities ⁵⁷. Off-farm facilities numbered 7,844, down 1% from 7,897 a year earlier and down 2.0% from 8,004 in December 2023. Over those two years average capacity per facility rose 2.3% to about 1.51 million bushels ^{57,81}. NASS publishes no ownership, throughput or dwell-time data by facility, so a falling count with rising average size cannot be decomposed into closures, consolidations and new builds.

Grain moves mostly by truck and USDA does not measure it. For 2022 the modal split of all US grain movements was 62% truck, 26% rail and 12% barge by tonnage on 574.8 million tons, and it inverts by destination: domestic movements were 80% truck and 1% barge, export movements 45% rail, 44% barge and 11% truck ⁵⁸. USDA computes truck tonnage as a residual, subtracting rail estimated from the Surface Transportation Board Carload Waybill Sample and barge from Army Corps Waterborne Commerce Statistics, and the report opens by stating that any effort to measure tonnages by mode is limited by the absence of information on the total volume of truck movements ⁵⁸. The 62% therefore carries the accumulated error of the rail and barge estimates plus any error in production and disappearance data, the Waybill Sample is itself a sample, and no confidence interval is published.

The first mile is the expensive mile, in both grain and produce, by close to the same factor. USDA's grain truck survey for the second quarter of 2026 put the national average at \$7.53 a mile for 25-mile hauls, \$4.84 at 100 miles and \$4.09 at 200 miles, so field or farm bin to local elevator costs 84% more per mile than a 200-mile haul ^{59,81}. In refrigerated produce the weighted average rates for the first quarter of 2026 were \$2.76 a mile under 500 miles, \$2.56 for 501 to 1,500, \$2.49 for 1,501 to 2,500 and \$1.50 for 2,501 and over, an 84% short-haul premium in the same direction ^{61,81}. Both series have coverage problems worth naming. In the grain quarter only the North Central and South Central regions reported, with East, West and Rocky Mountain marked not available for low or no response, so the national average is not a national sample ⁵⁹. And USDA notes that from the first quarter of

2025 the 0 to 500 mile rates from California regions to Los Angeles stopped being reported, which significantly lowered the national average, so the produce short-haul series carries a break ⁶¹.

Federal hours-of-service rules do not apply to much of this movement, and the exemption creates a data hole as a side effect. 49 CFR 395.1(k) removes the whole of the federal hours-of-service part for drivers moving agricultural commodities within a 150 air-mile radius of the source during planting and harvesting periods, with those periods determined by each State, with parallel exemptions for farm supplies inbound and livestock within 150 air-miles of destination ⁶⁰. The electronic logging device mandate sits at 395.8, inside the part that 395.1(k) disapplies, so qualifying operations produce no electronic duty record. That reading of the regulation's structure is this review's and not an FMCSA statement. Because States set the seasons, calendar coverage varies, and at least one State, Washington, has defined the season as 1 January to 31 December ⁶⁰. No national tabulation of State-declared seasons was located.

Fresh produce volumes are reported rather than counted. USDA recorded 7.76 million tons moved by truck in the first quarter of 2026, down 10% year on year, with Mexican-origin shipments at 3.49 million tons, 45% of the reported total and a larger volume than any US origin region ⁶¹. These are shipments compiled from AMS Specialty Crops Market News; volumes not passing through reporting shipping points are absent, so the Mexico share is a share of reported shipments only.

Cold storage is growing, and the growth is in shipper-owned space. Gross refrigerated warehouse capacity was 3.99 billion cubic feet across 931 warehouses on 1 October 2025, up 7.9% from 3.70 billion in 2023, with usable capacity at 3.25 billion, 82% of gross ^{62,81}. Between 2023 and 2025 private and semiprivate capacity rose 29.6%, from 1.18 to 1.53 billion cubic feet, while public warehouse capacity fell 2.3%, from 2.51 to 2.46 billion, taking the public share of gross capacity from 68% to 62% ^{62,81}. NASS defines private and semiprivate space as space an operator maintains to serve its own function as producer, processor or manufacturer, so part of the shift may be reclassification of ownership, and NASS publishes no build-versus-reclassification split.

The trade association's number for the same thing is larger than the whole national total, and the reasons are documented. The Global Cold Chain Alliance's 2025 list puts the combined capacity of its top 25 North American members at 5 billion cubic feet, 25% larger than USDA's entire US figure for the same period ^{62,63,81}. Two

definitional differences cut the same way. NASS counts only facilities cooled to 50°F or lower that normally store food 30 days or more, and excludes wholesalers, jobbers, packer branch houses and fast-turn frozen food processors by design, so modern fast-turn distribution cold storage is outside its frame; NASS also states its totals should be treated as minimums because some firms are unknown to it, and in the 2025 survey only about 374 firms returned usable reports covering about 38% of tabulated capacity⁶². GCCA's figure is North American, so it spans Canada and Mexico, and it is member-supplied⁶³. What is not established is whether GCCA's member-reported capacity is confined to the region, and neither body publishes a crosswalk, so the residual gap cannot be quantified.

The traceability requirement that will generate machine-readable records across this layer has moved to 20 July 2028. The original FSMA Section 204 compliance date was 20 January 2026; FDA proposed a 30-month extension in March 2025 and Congress then directed FDA not to enforce before that same date in the Continuing Appropriations, Agriculture, Legislative Branch, Military Construction and Veterans Affairs, and Extensions Act of 2026⁶⁴. The extension is statutory rather than discretionary, which makes further slippage less likely without precluding it, and FDA held a public meeting on 15 June 2026 on lot-level tracking flexibilities, so substantive requirements may still change⁶⁴.

The rule's reach into agriculture is narrower than its reputation. FDA estimated coverage of more than 323,000 domestic businesses operating more than 484,100 establishments, of which roughly 443,000 are retail food establishments and restaurants and approximately 12,000 are farms, aquaculture operations or growers⁶⁴. Against the 1.9 million farms in the 2022 census, the covered farm population is about 0.6%^{1,64,81}. The list covers produce, cheese, shell eggs, nut butters and seafood; grains, oilseeds and meat and poultry are outside it entirely, meat and poultry because they fall to USDA FSIS⁶⁴. FDA's own regulatory impact analysis put the 20-year annualised cost at a primary estimate of \$570M a year at a 7% discount rate within a range of about \$63M to \$2.3bn, against a primary annualised health benefit of \$780M within a range of \$59M to \$2.2bn⁶⁵. The cost range spans a factor of 36 and the benefit range a factor of 37, so the central estimates carry very little discriminating power, and the figures are in 2020 dollars on a schedule that no longer applies.

Where loss occurs in the chain is measured by three instruments that cover different segments, and adding them is not legitimate. USDA ERS estimated 31%, or 133 billion pounds, of the 430 billion pounds available at retail and consumer

level in 2010 went uneaten, worth \$161.6bn, and stated explicitly that losses on the farm and between the farm and the retailer were not estimated because of data limitations ⁶⁷. FAO's SDG indicator 12.3.1a estimates 13.3% of world food production lost after harvest and before retail in 2023, with Northern America and Europe combined at 10.0% ⁶⁸; that is an imputed index over ten commodities, FAO attributes the 2015 to 2023 movement primarily to revised country estimates rather than real change, and no US-only figure exists in the series. ReFED models the US farm sector at 16.9 million tons of surplus food in 2024, of which 14.8 million became waste and 94.2% was never harvested ⁶⁶. On ReFED's own published numbers the post-harvest residual is 5.4% using its rounded 14 million tons and 5.8% using its 94.2% share, and either way about 0.8 million tons of farm-sector food waste occurs after the crop has been picked ^{66,81}. ReFED's on-farm coverage is produce only, and the unharvested share partly reflects market and price decisions rather than physical logistics failure. The logistics layer this section describes has no USDA loss estimate at all.

The waterway that carries 44% of export grain tonnage is old. ASCE records that 80% of lock and dam infrastructure on the US inland waterways exceeded its 50-year design life in 2024, and that in 2020 locks experienced 9,147 periods of unavailability, of which 2,786 were unplanned, producing an average delay of 172.2 minutes; the system carries roughly 465 million tons a year and moved 210 million metric tons of agricultural exports and imports in 2022 ⁶⁹. ASCE is a professional society that advocates for increased infrastructure appropriations and the report card is a graded advocacy product; the lock statistics are attributed to USACE but the outage data is five years older than the report, and a 172.2-minute average across all locks and causes does not describe the tail events that shut a corridor for weeks.

Concentration in this layer is at the export chokepoint. Farm Action's 2024 compilation puts the four-firm concentration ratio for US port grain elevators at 60%, with the ABCD traders controlling 32 of 54 port elevators, 80% of Center Gulf capacity and nearly 70% of Pacific Northwest capacity, against a four-firm ratio of 45% or more for river elevators, seven firms controlling 85% of river elevators, and a seven-firm ratio of 41% for all domestic grain storage ⁷⁰. Farm Action is an advocacy organisation campaigning against consolidation and the per-figure primary sources are not recoverable from the published document. The substantive point survives the grading: concentration sits at the export terminal and not in aggregate country storage. The compilation also names Bunge and Viterro as separate firms, which they ceased to be on 2 July 2025. The merged company reports 298

commodity storage facilities and 29 port terminals in its Grain Merchandising and Milling segment worldwide, with 19.49 million metric tons of aggregate segment storage and 10.18 million metric tons across all segments in North America ⁷¹. Those counts are global, include leased assets and equity-method investments, and Bunge does not break out US elevator counts or bushel capacity, so they are not additive with the elevator figures above. No post-merger concentration ratio has been published by any source located here.

Node	Measure	What it does not cover	Grade	Source
On-farm grain storage	13.618bn bushels, 53.4% of the 25.49bn national total	Throughput, turns, ownership, dwell time	verified; share modelled	USDA NASS ⁵⁷ ; share ⁸¹
Off-farm commercial grain storage	11.871bn bushels across 7,844 facilities; about 1.51M bu average	Rice-only, peanut, tobacco and seed facilities are excluded by design	verified; average modelled	USDA NASS ⁵⁷ ; average ⁸¹
Grain modal split, 2022	62% truck, 26% rail, 12% barge on 574.8M tons	Truck is a residual; USDA states no truck volume data exists	verified	USDA AMS ⁵⁸
Grain truck rates, Q2 2026	\$7.53/mi at 25 miles; \$4.09 at 200 miles; 84% first-mile premium	Only North Central and South Central regions reported that quarter	verified; premium modelled	USDA AMS ⁵⁹ ; arithmetic ⁸¹
Agricultural hours-of-service exemption	No federal HOS within 150 air-miles during State-declared seasons	No ELD record is generated; no national tabulation of State seasons	verified	49 CFR 395.1(k) ⁶⁰

Refrigerated produce truck rates, Q1 2026	\$2.76/mi under 500 miles; \$1.50 at 2,501+; 84% premium	Series break from Q1 2025 on California-to-LA short hauls	verified; premium modelled	USDA AMS ⁶¹ ; arithmetic ⁸¹
Fresh produce truck volume, Q1 2026	7.76M tons reported, down 10%; Mexico origin 45%	Volumes not passing reporting shipping points are absent	verified	USDA AMS ⁶¹
Refrigerated warehouse capacity	3.99bn cubic feet gross, 931 warehouses, 1 Oct 2025	Excludes facilities turning inventory more than once a month	verified	USDA NASS ⁶²
Ownership shift in cold storage	Private and semiprivate +29.6%; public -2.3%; public share 68% to 62%	No build-versus-reclassification split published	modelled	Author's arithmetic on ⁶² ; see ⁸¹
Trade-association cold storage total	5bn cubic feet across the top 25 North American members	Member-supplied; spans Canada and Mexico; scope not published	self-published	GCCA ⁶³
FSMA 204 traceability	Compliance 20 July 2028; about 12,000 farms, 0.6% of the census count	Grains, oilseeds, meat and poultry are entirely outside it	verified; share modelled	FDA and CRS ⁶⁴ ; share ⁸¹
FSMA 204 cost	\$570M/yr primary, range \$63M to \$2.3bn	Range spans a factor of 36; 2020 dollars on a superseded schedule	verified	FDA regulatory impact analysis ⁶⁵

Farm-sector food waste	16.9M tons surplus, 14.8M waste, 94.2% never harvested	Produce only; model output, not measurement	modelled	ReFED ⁶⁶
Retail and consumer food loss	31% of 430bn lb available in 2010, worth \$161.6bn	ERS states farm-to-retail loss was not estimated	verified	USDA ERS EIB-121 ⁶⁷
Post-harvest loss, harvest to retail	13.3% globally; 10.0% Northern America and Europe combined	Imputed index; no US-only figure in the series	modelled	FAO SDG portal ⁶⁸
Inland waterway condition	80% of locks past 50-year design life; 2,786 unplanned outages in 2020	Advocacy product; outage data five years older than the report	reported	ASCE 2025 Report Card ⁶⁹
Export elevator concentration	Port elevator CR4 60%; river elevator CR7 85%; domestic storage CR7 41%	Advocacy compilation; per-figure sources not recoverable; predates Bunge-Viterra	reported	Farm Action ⁷⁰
Post-merger trader scale	298 storage facilities, 29 port terminals, 19.49M t segment capacity	Global, includes leased and equity-method assets; no US split	verified	Bunge Form 10-K ⁷¹

Table 3. The logistics layer, node by node, with what each figure actually measures.

7. What is actually deployed

The largest fielded population of embodied autonomy in agriculture is in the milking parlour. Lely states over 50,000 Astronaut robots installed across more than 40 countries on a product line running since 1995 ³³. That is the vendor's own cumulative installation figure across all generations, not units currently in service, with no retirement rate published. The independent measurement of the same phenomenon is smaller and better graded: USDA ERS reports robotic milking produced 6% of US milk in 2021, up from 4% in 2016, with adoption highest on midsized dairies at 13% of farms holding 150 to 499 head ³⁴. The data year is 2021 and the report was published in January 2026, so the series is five years stale at publication.

The next largest deployed population is not autonomy at all. ERS reports guidance autosteering used by 52% of midsize and 70% of large-scale crop farms in 2023, up from single digits in the early 2000s ³⁵. Autosteering is operator-assisted guidance with a person in the cab, and nothing in that series measures driverless operation. The same holds for targeted application. Deere states See and Spray ran on more than 5 million acres in 2025, up from about 1 million in 2024, with a claimed average herbicide saving of 59% ³⁶, and Ecorobotix reports 1,000 ARA precision sprayers sold across more than 30 countries in five years at about 4 hectares an hour ⁴⁹. Both are machines with drivers. The commercially successful products in this sector so far are ones that make a human operator more precise.

Supervised multi-machine operation is the closest thing to fielded autonomy with real acreage behind it. Deere acquired GUSS Automation in 2025 after a joint venture dating to 2022; GUSS states more than 250 machines deployed globally, 2.6 million acres sprayed and over 500,000 autonomous hours ³⁷. GUSS sprayers are supervised, with one operator monitoring several machines from a pickup, so this is crew reduction and not crew removal, and all figures are cumulative with no year-by-year split and no disclosed purchase price. Bluewhite, the leading retrofit vendor for orchards and vineyards, states 150,000 US acres with more than 20 permanent-crop growers and over 75,000 autonomous hours ⁴¹. Earlier company material gives more than 60,000 hectares, about 148,000 acres, across the US and Israel, a near-identical number on a different geographic scope, and no reconciliation is published. Elbit Systems' FUSE subsidiary acquired 100% of Bluewhite on 27 May 2026 with terms undisclosed, and the acquirer's stated rationale is defence and off-road autonomy, so continuity of the agricultural line is an assumption ⁴¹.

The most heavily capitalised US autonomous-tractor startup did not survive. Monarch Tractor filed a California WARN notice covering 102 employees on 19 November 2025, ceased operations on 3 April 2026, and had its autonomy stack, software-defined vehicle platform and electrification IP acquired by Caterpillar, announced 15 April 2026, with no financial terms disclosed ³⁸. The company had reported delivering roughly 500 MK-V tractors, said over 70% of its 2025 revenue came from licensing, and had raised at least \$220 million including a \$133 million round in 2024; its contract manufacturing at Foxconn's Lordstown plant ended when SoftBank bought the facility in August 2025 ³⁹. Total capital consumed is not established: trade coverage of the shutdown gives \$240 million burned and a separate report gives over \$200 million raised over eight years, no source states whether debt, bridge financing or strategic investment is included, and no audited financials exist because the company was private ³⁹.

One piece of that record deserves separate weight because there is nothing else like it in public. Three dealers sued Monarch in federal court, the first in September 2025, and Idaho-based Burks Tractor alleged that ten MK-V tractors bought from early 2024 under nearly \$800,000 of interest-bearing financing failed to operate autonomously and had been represented as fully autonomous without location or time limits ⁴⁰. These are allegations in unresolved civil complaints, not findings of fact, Monarch's defence is not in the public record, and the company ceased operating before the cases concluded. It is the only public instance located where a buyer's account of autonomous field performance contradicts the vendor's marketing on the record.

Retrofit is where the surviving US row-crop position sits. Sabanto states about 300 autonomy retrofit units in operation across the United States and Australia with about 50 employees, and closed an oversubscribed Series B in July 2026 ⁴². Disclosure of interest: the round was led by Leaps by Bayer, the venture arm of a crop-protection seller, with participation by fertiliser producer Yara, so two investors in this autonomy vendor also sell the inputs its machines apply. Unit counts are the company's own and cover kits shipped rather than kits demonstrably in active use. In Australia, SwarmFarm states more than 250 autonomous robots operating across 10 million acres as of November 2025, having reported 145 units, 300,000 operating hours and 2.8 million hectares in February 2025 ⁴³. Neither figure states whether it is cumulative or annual, so the two cannot be reconciled, both trace to the company, and SwarmFarm operates under Australian regulation, so the deployment does not transfer as a US legal precedent.

Weeding robotics has the most marketing and the least disclosed economics. Carbon Robotics reported more than 150 LaserWeeder machines on over 100 farms in 14 countries in November 2025, expanding to 15 countries by July 2026, on \$177 million raised and about 260 employees ⁴⁴. The company publishes no price, no acres per hour and no fleet utilisation; its product page claims up to 80% cost reduction, a one to three year payback on equipment lasting seven to ten years, and 5% to 50% yield increases ⁴⁵. None of those can be converted into a cost per acre by a reader. The only purchase price located anywhere in public material is the \$1.2 million in the Western Growers case study, which reflects a 2022 or 2023 transaction ⁴⁶.

Europe's longest-running field-robot maker shows what the unit volumes actually support. Naio Technologies has delivered more than 350 robots across five continents cumulatively since 2011, yet revenue fell from EUR 3.96 million in 2021 to EUR 2.4 million in 2024; it entered French judicial recovery in June 2025 and was relaunched with EUR 6.4 million from Mirova, Bpifrance and the Occitanie region's ARIS fund, retaining 21 jobs and targeting 100 robots a year and EUR 11 million revenue by 2030 ⁴⁸. Cumulative deliveries say nothing about how many still operate, and the 2030 figures are the restructured company's own plan.

The harvest-robotics record is a list of exits. Abundant Robotics put its entire apple-harvesting IP and assets up for sale on 29 June 2021 citing an inability to build market traction; advanced.farm closed, laid off its team and scuttled a 2025 Washington apple harvest in March 2025 after failing to raise the \$5 million to \$10 million it said it needed over two seasons; and Tortuga AgTech, with 150 robots in a commercial harvesting fleet after deploying \$50 million over eight years, sold its IP, assets and engineering team to vertical-farm operator Oishii on 24 March 2025 ⁵¹. FarmWise, which raised about \$95.7 million from 2016, announced a wind-down on 18 March 2025, ceased operations on 1 April and had its assets acquired by Taylor Farms on 4 April ⁴⁷. Disclosure of interest: Taylor Farms was simultaneously a customer running two Vulcan units over more than 2,100 acres and an investor in FarmWise's \$45 million Series B in 2022, so the reported grower-side savings and the rescue of the company come from the same party. Two more closures bound the sector's capital efficiency: Small Robot Company entered liquidation on 1 February 2024 having raised \$13.18 million across six rounds, and Iron Ox ceased operations after raising \$102 million ⁵². None of these produced an audited statement of what was built or what it cost.

The only independent performance measurements located for harvest robotics come from peer-reviewed field work. A single-arm apple harvester achieved 82.4% successful harvests in a young well-pruned orchard but 65.2% in an older dense orchard at about 6 seconds per fruit, and a dual-arm successor scored 0.807 and 0.797 across two commercial Michigan orchards at 5.97 seconds per cycle, 28% faster than the single-arm baseline ⁵³. These are research prototypes at Michigan State and USDA-ARS, not commercial machines, and neither paper reports a cost per acre. Success is measured against fruit the vision system identified, so fruit never detected does not enter the denominator and whole-tree recovery is not reported. The 17-point drop between a trained orchard and an ordinary one is the single most transferable number in this section.

Material handling is a solved-adjacent case that is often cited as evidence for crop work and should not be. Burro states more than 750 robots deployed globally with over 240,000 autonomous miles and 800,000 hours logged, and Petitti Family Farms went from 10 units to a committed 25 during 2025 ⁵⁰. Those figures are cumulative and span agriculture, industrial and other outdoor settings. Transporting material in a nursery is a structured, repetitive task on prepared surfaces, and it does not evidence autonomy in crop-contact work.

Packhouse automation has the largest disclosed installed base in the sector and the least coverage. New Zealand's Hawk Technology reports 50 robotic apple-packing machines installed in the United States with 250 more on order, after building a few hundred for the domestic market, each handling more than 165 fruit a minute across 12 inspection zones and replacing up to two labour units per packing lane ⁵⁶. All figures are the manufacturer's, relayed in an interview, orders are not installations, and the company states demand exceeds its manufacturing capacity. In-shed and packhouse work is indoors, on prepared surfaces, under controlled lighting, at fixed product presentation. Packhouse work runs indoors, on prepared surfaces, under controlled lighting, at fixed product presentation, which is why these machines reach commercial volume. No public dataset tracks their installed base.

System	Who	What it is	Status	Grade
Robotic milking	Lely	Astronaut automatic milking robot,	Over 50,000 cumulative installations in 40+ countries; not	self-published ³³

			product line since 1995	units in service	
	Robotic milking, independent measure	USDA ERS	ARMS-based adoption estimate	6% of US milk in 2021, 4% in 2016; 13% of 150–499 head farms	verified 34
	Guidance autosteering	USDA ERS	Operator-assisted guidance, driver in the cab	52% of midsize and 70% of large-scale crop farms in 2023	verified 35
	Targeted spraying	Deere See and Spray	Camera-triggered nozzle control, operator in the cab	Over 5M acres in 2025, about 1M in 2024; 59% claimed herbicide saving	self-published 36
	Targeted spraying, independent test	Iowa State	Five Iowa fields, 2024	76% average material saving, \$15.70/acre; 43.9% to 90.6% spread	reported 78
	Precision sprayer	Ecorobotix ARA	Towed sprayer pulled by a conventional tractor with a driver	1,000 units sold in 30+ countries over five years; about 4 ha/hour	self-published 49
	Supervised orchard spraying	GUSS Automation (acquired by Deere, 2025)	One operator monitors several machines from a pickup	250+ machines, 2.6M acres, 500,000+ autonomous hours, cumulative	self-published 37
	Autonomy retrofit, permanent crops	Bluewhite (acquired by Elbit FUSE, 27 May 2026)	Retrofit kit for existing orchard and vineyard tractors	150,000 US acres, 20+ growers, 75,000+ hours;	self-published 41

			scope figures unreconciled	
Autonomy retrofit, row crops	Sabanto	Retrofit kits for conventional row-crop tractors	About 300 units shipped, US and Australia; investors also sell the inputs applied	self-published 42
Purpose-built autonomous platform	SwarmFarm Robotics (Australia)	Small autonomous platforms carrying third-party implements	250+ robots, 10M acres claimed Nov 2025; cumulative-or-annual not stated	self-published 43
Purpose-built electric tractor	Monarch Tractor	MK-V driver-optional electric tractor	Ceased operations 3 April 2026; IP acquired by Caterpillar, terms undisclosed	verified 38
Monarch commercial record	Monarch Tractor	Company statements made while seeking a buyer	About 500 tractors delivered; over 70% of 2025 revenue from licensing	self-published 39
Monarch dealer litigation	Burks Tractor and two others	Federal complaints from September 2025	Ten tractors, about \$800,000 financed, alleged not to operate autonomously	reported 40
Laser weeding	Carbon Robotics	LaserWeeder, towed, operator present	150+ machines, 100+ farms, 15 countries; no price or throughput published	self-published 44

Laser weeding economics	Braga Fresh and Triangle Farms	Grower-supplied figures in a trade-association case study	\$267.72 and \$448.73 per acre, same machine and season, two farms	self-published 46
Mechanical weeding, field trial	UC West Side REC	Replicated trial, drip cantaloupe, 2022	Robovator saved \$37/acre, about 20%; herbicide saved over \$100	reported 77
Field robotics, long-running vendor	Naio Technologies	Small autonomous weeding platforms since 2011	350+ cumulative; judicial recovery June 2025, relaunched with EUR 6.4M	reported 48
Autonomous material transport	Burro	Autonomous carts on prepared surfaces	750+ robots, 800,000 hours, cumulative across all sectors	self-published 50
Robotic apple packing	Hawk Technology	Packhouse robot, 12 inspection zones	50 US installations, 250 on order; up to 2 labour units per lane	self-published 56
Robotic apple harvest	Michigan State and USDA-ARS	Research prototypes, single-arm and dual-arm	82.4% and 65.2% success by orchard type, detection-conditional denominator; dual-arm figures rest on an arXiv preprint	verified 53
		Apple and strawberry	All three exited between	

Commercial harvest robotics	Abundant, advanced.farm, Tortuga	harvesting ventures	June 2021 and March 2025	reported ⁵¹
Automated weeding service	FarmWise (acquired by Taylor Farms, 4 April 2025)	Weeding-as-a-service, Vulcan machines	Wound down after about \$95.7M raised; buyer was investor and customer	reported ⁴⁷
Field robotics closures	Small Robot Company, Iron Ox	UK weeding robots; US indoor growing	Liquidation Feb 2024 after \$13.18M; Iron Ox closed after \$102M	reported ⁵²

Table 4. Deployment ledger: what is documented, and at what verification grade.

8. The regulatory position, and the standards that are missing from it

The binding constraint on driverless field equipment in the largest specialty-crop state is a 1977 rule. California Title 8 section 3441(b) requires an operator at the controls of self-propelled equipment ⁵⁴. Petition 571 from the Association of Equipment Manufacturers in 2019 and petition 596 from Monarch Tractor, filed 15 December 2021, were both denied, 596 on a 4-3 vote on 16 June 2022, with Cal/OSHA stating the dataset was too small to conclude that autonomous safety was equivalent to a human operator ⁵⁴. On 20 November 2025 the Standards Board declined to vote on its own advisory committee's recommendation, and the draft has been characterised as a DMV-derived multi-stage pathway; that account comes from AEM, the trade association representing the manufacturers seeking the change, and is graded reported on that basis ⁵⁵. A Cal/OSHA memorandum of August 2024 reportedly allows driverless operation where no field workers are present, which narrows the constraint without removing it ⁵⁴.

Two things follow. The state with the largest hand-labour bill and the highest wage floor is the state where crewless operation is hardest to permit, which is why the commercially viable products there are supervised rather than driverless. And a company petitioning a state safety regulator for a rule change, being denied, and then ceasing operations three and a half years later is a documented sequence in

this record ^{38,54}, though the causal weight of the denial is not established and is not asserted.

There is no federal registration category for driverless off-road agricultural equipment and no state operates one. Farm tractors are not registered or licensed in the United States at all ⁴. That absence explains several of the measurement gaps in section 11: no age series, no hours series, no fleet turnover series independent of manufacturer sales reporting, and no way to count how many autonomous machines are in commercial service.

On the road, the governing instrument is an exemption. 49 CFR 395.1(k) disapples the entire federal hours-of-service part for drivers moving agricultural commodities within 150 air-miles of the source during State-declared planting and harvesting periods ⁶⁰. Because the electronic logging device mandate sits at 395.8, inside the disappplied part, qualifying operations generate no electronic duty record, so the movement is both lightly regulated and unmeasured. States set the seasons and at least one, Washington, has defined the season as the full calendar year ⁶⁰. No national tabulation of State-declared seasons was located, which means the calendar coverage of the exemption is not publicly established.

The wage floor is the most active regulatory front and it is unsettled. DOL replaced the discontinued USDA Farm Labor Survey with BLS OEWS as the AEWR basis by interim final rule on 2 October 2025 ¹⁸; rates under that methodology were published 3 August 2026 ²¹; they take effect 17 August 2026 rather than 3 August for the 17 states covered by *Kansas et al. v. US Dep't of Labor* ²¹; and DOL's own page still displayed operative statewide rates with December 2024 effective dates, described as derived from a survey that no longer exists ²³. The range-occupation AEWR moved separately on an Employment Cost Index escalator untouched by the change ²². An interim final rule is exposed to litigation and nothing in the public record establishes what the rate will be in twelve months.

On traceability, the compliance date for FSMA Section 204 is now 20 July 2028 and is set by statute rather than by agency discretion ⁶⁴. The requirement will create machine-readable critical tracking events at first receivers for produce, cheese, shell eggs, nut butters and seafood, covering roughly 12,000 farms, about 0.6% of the census farm count ^{64,81}. Grains, oilseeds, meat and poultry are outside it. FDA is still consulting on lot-level tracking flexibilities, so the substantive requirements may change before the date ⁶⁴. For an operator, the date matters more as a forcing function on record structure than as a compliance cost, because it establishes for

the first time a defined event vocabulary at the point where field product enters the handling chain.

No agricultural equivalent of FMCSA roadside inspection data or FAA service difficulty reports exists. There is no mandatory reporting of in-field failure or downtime for agricultural machinery of any kind, autonomous or conventional. The baseline reliability an autonomous system would have to beat, and the cost of a machine stopping mid-operation inside a weather window, are therefore not measurable from public data at all.

No machinery-safety standard is load-bearing anywhere in this section, and that is itself the finding. ANSI/ASABE agricultural equipment safety standards and ISO 18497 on highly automated agricultural machinery exist, but no US regulator incorporates either by reference for driverless field equipment, and no federal body collects in-field failure data against them. A machine can therefore be sold into US fields without any public conformity claim a buyer could check.

9. The field record an autonomous system must act on

The fellow's project statement names the scientific problem as giving embodied systems a usable model of the physical operating environment and the judgment to act on it when conditions get messy ⁸⁰. In agriculture that decomposes into six problems, none solved and each measurable. Where the telecom sibling report found a plant registry that was wrong, agriculture presents something different: for most of the quantities an autonomous planner needs, there is no registry at all.

Three of the inputs such a model needs are simply absent from the public record: a national field register, a count of machine passes per acre, and engine hours on the installed fleet. Each is stated with what would settle it in section 11, and none is restated here. What follows is the part of the gap that the deployed record does measure, and measures badly.

The detection denominator governs how every published harvest-robot success rate should be read. Every published harvest-robot success rate, including the 82.4% and 65.2% in the Journal of Field Robotics work, is computed over fruit the vision system detected; fruit never detected does not appear in the denominator ⁵³. True whole-tree recovery requires hand-stripping the tree after the robot pass and counting what remains, which the published field evaluations do not do. A system reporting 82% success on the 70% of fruit it found is not comparable to one

reporting 75% across all of it, and nothing in the literature reports the second number. This is the agricultural form of the abstention problem: a vendor accuracy figure means very little without the fraction of the task the system declined to attempt.

The machine lost 17 points of success rate between a well-pruned young orchard and an older dense one, on the same machine in the same study ⁵³. That is the measurement in this report. It says the performance of a field autonomy system is a property of the training system as much as of the robot, and that the orchards where the machines work are the ones that were built for them. That points at a different commercial question from the one the sector asks. Instead of asking what a robot costs, an operator should ask what it costs to make a block legible to a machine, and over how many seasons that investment amortises.

Reliability is unmeasured and it is the input the economics are most sensitive to. The Western Growers case study prices hardware and over-the-air service plans at \$88,000 and \$83,000 a machine-year, being \$37.45 an acre over 2,350 acres and \$74.91 an acre over 1,108 acres, and records no unplanned downtime at all ⁴⁶, and its 2,350 acres a year requires about 27 weeks of running 18 hours a day, six days a week at 0.8 acres an hour ^{46,81}. No vendor publishes a mean time between failures, a service-call rate or an aborted-pass rate for any fielded agricultural robot. Since the entire published business case rests on near-continuous utilisation, this is the number the sector's economics actually turn on and nobody has it.

Connectivity is measured at the wrong place. NASS reports that 85% of farms have internet access, but that is a farm headquarters measure, and a farm office with fibre says nothing about connectivity at the far end of a section. No federal agency publishes cellular or broadband availability weighted by cropland acre. Measuring it would require joining FCC Broadband Data Collection coverage polygons to cropland raster layers, which nobody publishes as a combined statistic. The operational consequence is direct: a machine that depends on a link to decide whether to continue working has an availability ceiling that no public dataset establishes, which argues for onboard decision-making in the same way the sibling report's radiating-structure case did ⁸⁰.

The Charlot Lab position applies here without modification. Each attribute in a field model should carry a value, an uncertainty, a provenance and an age, and every autonomous work order should carry an explicit predicate over those attributes that must hold for the plan to remain valid. When the predicate fails in the field, the correct output is abstention and escalation. That makes refusal a first-class,

measurable output, and it gives procurement a second metric alongside accuracy: the abstention rate, meaning the fraction of the task the system declined to attempt, with performance reported on the remainder. Nothing in the agricultural robotics literature reports that denominator today.

10. Where the value sits, ranked

Ranking by the size of the addressable pool, the quality of the evidence and what is technically and legally available now produces an ordering that inverts the emphasis of the venture record. The two applications with the strongest evidence involve no field autonomy at all, and both are indoors. Autonomous field tractors, which absorbed the most capital and produced the most failures, rank seventh.

The table below is the practical output of this review for an operator or an investor. Sizes are drawn from the cited sources and, where marked, from the author's arithmetic on them. None of the readiness assessments is a recommendation to buy or not to buy a specific product, and several of the largest pools in agriculture cannot be sized at all, which is recorded rather than estimated.

Rank	Opportunity	Size of the addressable pool	Best evidence	Readiness
1	Parlour and in-shed automation	6% of US milk in 2021, up from 4% in 2016; 13% of farms holding 150–499 head	USDA ERS ³⁴ ; Lely ³³	Deployed at scale for three decades; the only embodied application with a verified federal adoption series
2	Packhouse and grading automation	Not sized in any public source; up to two labour units per packing lane claimed	Hawk Technology ⁵⁶	Deployed and expanding; no installed-base series exists for US produce handling
3	Targeted application on existing iron	5M acres in 2025 on one product line; 76% material saving measured on five	Deere ³⁶ ; Iowa State ⁷⁸	Available now, driver in the cab; savings vary 43.9% to 90.6% with

			fields at \$15.70/acre		unpublished weed pressure
4	Guidance and autosteer	52% of midsize and 70% of large-scale crop farms already using it	USDA ERS ³⁵	Mature; the remaining headroom is on small farms that hold 25.7% of farmland	
5	Supervised multi-machine operation in permanent crops	250+ GUSS machines over 2.6M acres; 150,000 acres claimed by one retrofit vendor	GUSS/Deere ³⁷ ; Bluewhite ⁴¹	Available where state rules permit; crew reduction, not crew removal	
6	First-mile handling and elevator turn time	First mile costs 84% more per mile than a 200-mile haul in both grain and produce	USDA AMS ^{59,61} ; arithmetic ⁸¹	A measurement problem before it is an automation problem; no public turn-time series exists	
7	Autonomous row-crop field operation	\$10.05bn of customwork and custom hauling nationally, undecomposed by operation	USDA NASS Census ² ; Sabanto ⁴²	Retrofit path only; the purpose-built leader ceased operations in April 2026 ³⁸ and California still requires an operator ⁵⁴	
8	Weeding robotics in specialty crops	\$60.3M/yr service pool in lettuce; about \$612M across non-potato vegetables at full adoption, 0.14% of census farm expenses	Author's arithmetic on ^{46,76,79} ; see ⁸¹	Deployed and small; the only published per-acre economics are grower-supplied from two farms in one valley ⁴⁶	
9	Traceability and record	FSMA 204 covers about 12,000 farms from 20	FDA and CRS ^{64,65}	A statutory forcing function with a fixed	

	capture at first receipt	July 2028; FDA prices it at \$570M/yr, range \$63M to \$2.3bn		date; the record structure matters more than the compliance cost
10	Robotic harvest of tree and soft fruit	Not sized; hand harvest is 40.5% of romaine hearts total cost, the largest single line in specialty crops	UC Davis ⁷⁶ ; Zhang et al. ⁵³	Research stage; every commercial attempt located has exited ⁵¹

Table 5. Physical AI and logistics opportunities in US agriculture, ranked by evidenced value and current availability.

11. What is not known

The following are the open questions this review could not close. Each is stated with what would settle it, because several are answerable by an operator or a land-grant extension service using instruments that already exist.

Machine passes per acre per year, by crop and region. Nothing in the census, the Crop Production series or ARMS records how many times a field is traversed in a season ^{2,8}, which is the natural denominator for any per-pass automation saving. An ARMS module asking operators to report tillage, planting, application and harvest passes per crop acre would produce it, as would aggregated OEM telematics, which no manufacturer publishes.

Engine hours and annual utilisation on the installed fleet. The census counts 3,784,743 tractors and 298,301 combines and records no hours ⁴, and farm tractors are not registered in the United States, so no odometer-equivalent series exists. Without it the fixed-cost base that a machine-sharing or autonomy service would displace cannot be computed. An engine-hour question on the census form, or an OEM telematics disclosure standard, would close it.

Average age of the tractor and combine fleet. The census publishes only a two-bucket manufacture split ⁴, which cannot distinguish a six-year-old machine from a forty-year-old one. Adding manufacture-year bands to the census machinery table would settle it.

The split of hired and contract farm labour by field task. The \$41.81bn hired-labour line and the \$10.13bn contract-labour line are not decomposed into harvest, weeding and thinning, irrigation, pruning, livestock handling or transport, nor between crop and livestock enterprises². Every crop-specific automation business case needs this decomposition and none of it is published. ARMS collects enough operator detail to support a task module if one were added.

Hand-weeding and hand-thinning passes per acre per year, by crop. Every automation savings claim in specialty crops is denominated in the cost of a hand-weeding pass, and no source publishes how many passes a typical acre receives. The UC Davis budget assumes two for romaine hearts⁷⁶; the Western Growers case study does not state a pass count at all⁴⁶. In California, every pesticide application is already reported at field level, so a crew-hour and pass-count return could be added to an existing filing.

Acres on which hand weeding is actually performed. NASS publishes acres by crop and by organic status but not by weed-control practice, so the addressable acreage for weeding robotics is unknown even in principle. A weed-control practice question on the census vegetable schedule would produce it.

Machine productivity, utilisation and downtime for commercial agricultural robots. Braga Fresh's 2,350 acres per machine-year at 18 hours a day, six days a week is the only figure located anywhere in public, it comes from one grower's first year, and no vendor publishes fleet utilisation, downtime, aborted passes or the field conditions that stop work⁴⁶. Every operator running a machine already holds this data in its own logs.

Whole-tree fruit recovery for harvest robots. Every published success rate is computed over fruit the vision system detected⁵³. Measuring true recovery requires hand-stripping the tree after the robot pass and counting what remains, which no published field evaluation does.

A national register of field boundaries. FSA's Common Land Unit data for named producers is statutorily withheld, so the number and size distribution of discrete managed field units in the United States is not public. Every coverage-path and fleet-routing argument rests on it.

Connectivity weighted by cropland acre. NASS reports farm internet access at the headquarters¹¹; nothing measures service at the far end of a section. Joining FCC

Broadband Data Collection coverage polygons to cropland raster layers would produce it and no federal agency publishes the combined statistic.

In-field failure and downtime rates for agricultural machinery of any kind. There is no mandatory reporting analogous to FMCSA roadside inspection data, so the baseline reliability an autonomous system must beat, and the cost of a machine stopping inside a weather window, are not measurable from public data.

The number of autonomous tractors in commercial service in the United States. No manufacturer publishes autonomy-kit activations by year and no state operates a registration category for driverless off-road equipment ^{4,54}.

How many agricultural robotics companies have ceased operations and how much capital they consumed. Closures surface only when a WARN notice, a federal complaint or an asset sale forces disclosure ^{38,47,51,52}, and asset acquisitions are announced as strategic wins. Building the register would mean systematically pulling state WARN filings, Chapter 7 dockets and UCC-3 terminations against agricultural NAICS codes.

The number of distinct individuals who performed hired farm work in a given year. NASS counted 637,000 in one week ¹⁴ and ERS reports 1.18 million UI-covered jobs ¹⁶, and neither is a person count. Linking employer-reported W-2 or state UI wage records to NAICS 111, 112 and 115 at person level would produce it; that data exists inside SSA and state agencies and is not published.

Job openings, hires and quits for agriculture. JOLTS publishes total nonfarm only, so the measure used to establish labour scarcity in every other US industry does not exist for farming. Extending JOLTS to NAICS 11 would close it.

The share of farm employment BLS OEWS actually covers, by state. This became load-bearing on 2 October 2025 when the AEWRS moved onto OEWS ¹⁸, and no agency publishes the ratio of OEWS-covered agricultural employment to total agricultural employment for any state.

Realised wages and hours under H-2A contracts. The entire \$1.5bn to \$2.5bn debate about the 2025 methodology change is conducted on job orders ^{19,24}. Nobody publishes the payroll actually disbursed. A statistical release derived from Wage and Hour Division case files, or a mandatory employer payroll report, would settle it.

A reconciliation between the three federal totals for annual US farm production expenses. USDA publishes a census figure, an ARMS survey figure and an ERS

sector-account figure that differ by tens of billions of dollars for the same year ^{2,9,10}, and no agency publishes a crosswalk. A line-by-line bridge table from ERS and NASS would produce one.

Throughput and ownership at grain elevators. NASS publishes capacity for 7,844 off-farm facilities but not bushels handled, turns per year or utilisation, and does not record who owns them ⁵⁷. A throughput question could be added to the existing enumeration, which already contacts every known facility; ownership would require joining state warehouse-licence registers and the USDA Warehouse Act licence list to corporate parent records.

Farm-to-retail food loss in the United States. ERS states that losses on the farm and between the farm and the retailer were not estimated because of data limitations ⁶⁷, FAO reports only a combined Northern America and Europe figure ⁶⁸, and ReFED models produce only ⁶⁶. Shrink and condemnation reporting at first receivers, packhouses and distribution centres, sampled by commodity on a definition compatible with the existing Loss-Adjusted Food Availability series, would close it.

Truck turn time and queue length at country elevators and packhouses during harvest. No public series measures how long a load waits to be received, which is the specific congestion that first-mile automation would address. Timestamped scale-ticket data from a sample of facilities across a full harvest would produce it, and the facilities already generate it.

12. Risk register

Wage-floor reversal, high likelihood and high impact on the business case. The California entry-level H-2A rate falls 32.3% under DOL's interim final rule ^{23,81}, and comparable cuts run from 22.9% in Arizona to 34.4% in Oregon. Automation displaces expensive labour more readily than cheap labour. A machine justified against a \$19.97 floor is a different proposition against \$13.52, and the litigation exposure means the settled number is not knowable today ^{21,23}.

Loss of the measurement base, high likelihood and high impact. USDA discontinued the Agricultural Labor Survey on 28 August 2025 ¹⁵, which was the only national survey of agricultural employers on employment, hours and wages. The real-wage series ends in 2024 and cannot be extended ¹⁶. Any operator that intends to measure whether an automation programme worked will have to build its own baseline, because the federal one stopped.

Vendor-sourced economics, high likelihood and moderate impact. The only per-acre figures in circulation for field robotics, \$267.72 and \$448.73, are grower-supplied to a trade association, cover two farms in one California valley in one season, and record no unplanned downtime ⁴⁶. Carbon Robotics publishes no price, throughput or fleet utilisation and claims up to 80% cost reduction ⁴⁵. Deere's 59% herbicide saving is measured against a baseline Deere defines ³⁶. An operator that adopts these as its own business case inherits all of it.

Utilisation shortfall, moderate likelihood and high impact. The published laser-weeding economics require about 27 weeks of running 18 hours a day, six days a week ^{46,81}. Weather, field conditions, breakdowns and crop calendars are not modelled anywhere in the document. A machine achieving half the assumed hours has roughly double the per-acre implement cost, which is enough on its own to invert the Braga result toward the Triangle Farms result.

Vendor discontinuity, high likelihood and high impact. Monarch ceased operations with an unresolved dealer-litigation record and no public provision for existing MK-V owners ^{38,40}; FarmWise, advanced.farm, Tortuga, Abundant, Small Robot and Iron Ox all exited ^{47,51,52}; Naio went through judicial recovery ⁴⁸; Bluewhite was acquired by a defence contractor whose stated rationale is off-road and defence autonomy ⁴¹. A buyer of agricultural autonomy is currently taking counterparty risk on a sector where exit is the modal outcome, and support obligations do not survive it reliably.

Regulatory blockage in the highest-value state, moderate likelihood and high impact. California requires an operator at the controls under a 1977 rule, two petitions have been denied, and the Standards Board declined to vote on its own advisory committee's recommendation on 20 November 2025 ^{54,55}. The state with the largest hand-labour bill is the one where crewless operation is hardest to permit.

Crop-system mismatch, high likelihood and moderate impact. The same machine cost \$267.72 an acre on organic baby leaf and \$448.73 on a different farm, and on direct-seeded organic romaine it cost \$88.73 an acre more than hand weeding alone ⁴⁶. Hand-weeding baselines at one farm ranged from \$500 to \$1,800 an acre by crop ⁴⁶. The economics are a property of the crop system, and a national average across crops has no meaning.

Measurement invisibility, high likelihood and moderate impact. Three federal instruments disagree about total farm production expenses by \$17bn to \$28bn for the same reference year ^{2,9,10}, and the 2025 farm count is a model output that NASS

states carries model-selection error it does not quantify⁷. Any automation effect at national scale would be smaller than the disagreement between the agencies measuring it, so an operator will need instrumented, matched-cohort measurement designed in from the start.

Interest entanglement in the evidence base, high likelihood and moderate impact. Taylor Farms was investor, customer and acquirer of FarmWise⁴⁷; Deere ran a joint venture with GUSS before acquiring it and publishes GUSS's cumulative figures³⁷; Sabanto's lead investor and a co-investor sell the crop-protection and fertiliser inputs its machines apply⁴²; the Braga Fresh figures were published by an innovation centre that promotes the technology and offers an ROI spreadsheet alongside them⁴⁶. Every headline number in this sector should be read against who benefits from it.

Data-generation gaps compounding into autonomous action, moderate likelihood and high impact. There is no public field register, no pass count, no engine-hour series, no reliability series and no acre-weighted connectivity measure^{1,4,11}. A system that plans work from a model built on none of these will act confidently on inputs nobody has validated. The mitigation is the uncertainty-and-abstention discipline in section 9 and not better models.

13. Scenarios to 2032

Scenario A, retrofit and supervision carry the value. New-machine turnover is too slow to matter on this horizon at about 46 and about 54 years for tractors and combines^{4,13,81}, so autonomy reaches the field through retrofit kits and supervised multi-machine operation of the GUSS and Bluewhite type^{37,41}. Targeted application on driver-operated machines continues to scale because it needs no regulatory change and no crew removal^{36,49}. Indoor and in-shed automation grows fastest and attracts the least attention^{33,56}. Savings appear as crew reduction and input reduction in the ranges the independent evidence already supports: about 20% of hand-weeding cost from mechanical cultivation⁷⁷, 76% of herbicide material on five measured fields⁷⁸, one operator supervising several machines³⁷. This is the base case on current evidence. Discriminating indicator: no US grower publishes an audited multi-season enterprise budget for autonomous field work by the end of 2029.

Scenario B, the wage floor holds down and the business case reprices. The interim final rule survives litigation, the AEWR settles near the OEWS-derived levels, and

the California entry-level rate stays around a third below where it was ^{21,23,81}. Labour-displacing capital is repriced against a materially cheaper crew, and the machines that survive are the ones justified by throughput, timeliness and input savings rather than by wage displacement. Under this scenario targeted application and packhouse throughput do well and weeding robotics does badly, because weeding robotics is the application whose entire case is denominated in a hand-labour rate. Discriminating indicators: the settled AEWR after litigation; whether Carbon Robotics or a successor publishes a price and a throughput figure; whether H-2A certified positions continue growing at the 3.4% recorded in FY2025 ^{20,81} or reaccelerate.

Scenario C, autonomy becomes a bought service on the concentrated estate. The 67,320 farms carrying 83.2% of the national hired-labour bill ^{2,81} and the 105,384 farms making over 75% of sales ⁵ adopt, and the remaining 1.8 million operations do not. Autonomy is sold by the acre through the customwork channel, which was worth \$10.05bn in 2022 across 391,283 farms ², rather than as capital equipment to individual operators. This resolves the utilisation problem that breaks the published economics, because a service provider running a machine across many farms can reach the hours the business case assumes where a single grower cannot. Discriminating indicators: a land-grant custom rate survey adds a line for autonomous or automated field operations; a service provider publishes acres per machine-year across more than one farm; equipment dealers begin listing autonomy as a service SKU.

A downside branch runs across all three. The sector's exit record is dense and recent: Monarch, FarmWise, advanced.farm, Tortuga, Small Robot, Iron Ox and Naio all failed or restructured between February 2024 and April 2026 ^{38,47,48,51,52}. If that continues, buyers rationally discount the value of any autonomy purchase by the probability the vendor is gone before the machine is amortised, which raises the required saving and slows adoption independently of whether the technology works. The indicator to watch is whether any pure-play US field-robotics company reaches profitability on disclosed figures, which none has.

Three facts hold across all three scenarios. New-machine turnover runs at about 46 years for 100-horsepower-plus tractors and about 54 for combines ^{4,13,81}. The labour bill is concentrated in about 67,000 farms and is legible to anyone who wants to find them ^{2,81}. And the measurement base that would let anyone tell whether any of this is working got smaller in August 2025 ¹⁵.

14. Conclusions, and a measurement programme an operator can run

The economic opening is real and the primary sources agree on its shape. Labour and the field-adjacent expense lines are a quarter of the census expense base at \$106.27bn ^{2,81}, the labour half of that is concentrated in 3.5% of farms ^{2,81}, and the machine fleet those farms run is old enough that 88.4% of tractors predate 2018 ^{4,81}. What the evidence does not support is the mechanism the market has been selling. Autonomy delivered inside new machines reaches the fleet on a 46-to-54-year cycle ^{4,13,81}. Autonomy delivered as a purpose-built field robot has produced an exit record with more entries than the deployment record ^{38,47,51,52}. The applications that work are indoors, supervised, or attached to a machine that still has a driver ^{33,34,36,37,56}.

The value that is actually documented is smaller than the sector's capital raised and it sits in specific places. Robotic milking is the only embodied agricultural application with a verified federal adoption series behind it, at 6% of US milk ³⁴. Targeted application has an independent measurement, 76% material saving worth \$15.70 an acre across five Iowa fields, with a 43.9% to 90.6% spread that no national weed-pressure distribution can resolve ⁷⁸. Modelled at full national adoption, automated weeding across every non-potato vegetable acre in the United States is worth about \$612 million a year, 0.14% of census farm production expenses ^{2,81}. The documented value is real. It is also roughly an order of magnitude below the capital the sector raised against it, on the figures in section 7.

Six steps follow, in order. None requires a vendor commitment.

First, read the hour meters. Before any autonomy decision, record annual engine hours on every machine in the fleet and compute acres per machine-year by operation. No public series exists ⁴, the data is on the dashboard, and every subsequent calculation is denominated in it.

Second, produce a pass count per crop acre. Tillage, planting, application and harvest passes by field and by season. This is the denominator for every per-pass saving claim and no federal dataset carries it ^{2,8}.

Third, decompose the labour line by task. Hired and contract labour split between field, packing, livestock and administration, and within field between harvest, weeding and thinning, irrigation and pruning. The census reports a single aggregate

², the automation case lives entirely in the decomposition, and payroll data will produce it.

Fourth, price the crop system and not the machine. The same laser weeder cost \$267.72 an acre at one farm and \$448.73 at another in the same season, and on one crop it cost more than hand weeding alone ⁴⁶. Ask what a block costs to make legible to a machine, over how many seasons that amortises, and what the machine does on the worst block on the operation rather than the best.

Fifth, write two metrics into every procurement: performance stated per task against a named reference measurement, and abstention rate, meaning the fraction of the work the system declined to attempt with performance reported on the remainder. A harvest robot reporting 82% success on the fruit it detected ⁵³ is not comparable to one reporting 75% of the fruit on the tree, and nothing in the public literature reports the second figure.

Sixth, hold capital that depends on a wage differential until the AEWR settles. The California entry-level rate has moved 32.3% ^{23,81}, the rule is an interim final rule exposed to litigation, and 17 states sit under a separate court order ²¹.

For the fellowship itself, the most valuable piece of open work visible from this evidence base is a duty-cycle and stoppage census of fielded agricultural robots. Every published unit economic in this sector rests on one number, the 2,350 acres per machine-year that Braga Fresh reported in its first season at 0.8 acres an hour, 18 hours a day, six days a week ^{46,81}. No vendor publishes a per-unit distribution, an idle rate, a service-call rate or an aborted-pass rate, and the Western Growers document that carries the sector's only per-acre figures records no unplanned downtime at all ⁴⁶. The study is: instrument a cohort of grower-owned machines across at least three farms and two crop systems for one full season; read hour meters independently at the start and end; log every stoppage with cause, duration and field condition; and publish the resulting distribution of acres per machine-year, hours per machine-year, and stopped-hours per running-hour, with the per-acre cost recomputed at the observed utilisation instead of the assumed one. It requires a season, hour meters, a logging protocol and grower cooperation. It is within an extension economist's ordinary reach and no land-grant service has done it. It would replace the single most load-bearing assumption in agricultural robotics with a measured distribution, and on the arithmetic in section 5 it would move the published per-acre economics by more than any improvement to the machines

themselves. The second-priority study, should access to an orchard allow it, is whole-tree fruit recovery measured by hand-stripping after a robot pass ⁵³.

Corrections are welcome and will be recorded.

References

1. ¹ USDA NASS, "2022 Census of Agriculture Highlights: Farms and Farmland", ACH22-3, March 2024. https://www.nass.usda.gov/Publications/Highlights/2024/Census22_HL_FarmsFarmland.pdf A complete enumeration, but the count depends on the unindexed 1974 farm definition of any place producing and selling, or normally would have sold, \$1,000 or more of agricultural products. Land in farms excludes grazing land used under government permits on a per-head basis. Re-read directly from the primary PDF on 5 August 2026 and every estate figure in section 3 was confirmed.
VERIFIED
2. ² USDA NASS, 2022 Census of Agriculture, Volume 1 Chapter 1, Table 4, Farm Production Expenses. https://www.nass.usda.gov/Publications/AgCensus/2022/Full_Report/Volume_1,_Chapter_1_US/st99_1_004_004.pdf Includes \$2.99bn of landlord expenses. Feed and purchased livestock are largely intra-sector transfers. No line separates field task from farmstead task, or crop from livestock enterprise.
VERIFIED
3. ³ USDA NASS, 2022 Census of Agriculture, Volume 1 Chapter 1, Tables 1, 43 and 44. https://www.nass.usda.gov/Publications/AgCensus/2022/Full_Report/Volume_1,_Chapter_1_US/st99_1_042_044.pdf Market value of machinery is self-assessed by the operator on the census form and is not appraised; no published methodology reconciles operator estimates against dealer or auction values.
VERIFIED
4. ⁴ USDA NASS, 2022 Census of Agriculture, Volume 1 Chapter 1, Table 45, Selected Machinery and Equipment on Operation. https://www.nass.usda.gov/Publications/AgCensus/2022/Full_Report/Volume_1,_Chapter_1_US/st99_1_045_046.pdf Counts are units present on the operation, including machines retired, cannibalised or seasonally idle. No engine hours, condition or utilisation is recorded, and manufacture date is binned into two buckets only.
VERIFIED
5. ⁵ USDA NASS, "2022 Census of Agriculture Highlights: Farm Economics", ACH22-1, February 2024. https://www.nass.usda.gov/Publications/Highlights/2024/Census22_HL_FarmEconomics_FINAL.pdf Sales classes are nominal and unindexed, so class migration between censuses reflects price inflation as well as real growth; 2022 was an unusually high commodity-price year.
VERIFIED

6. ⁶ USDA NASS, "2022 Census of Agriculture Highlights: Farm Producers", ACH22-2, February 2024. https://www.nass.usda.gov/Publications/Highlights/2024/Census22_HL_FarmProducers_FINAL.pdf Producer counts capture decision makers, not labour input. The share of farms naming more than one decision maker rose from 54% to 60% between 2017 and 2022, so part of the flat total is a reporting change.

VERIFIED

7. ⁷ USDA NASS, "Farms and Land in Farms 2025 Summary", February 2026. https://www.nass.usda.gov/Publications/Todays_Reports/reports/fnlo0226.pdf NASS states it did not conduct the June Area Survey in 2025 and generated the figures with a statistical model on historic trends and ten years of prior estimates. The reported CV of 0.5% on farm numbers and 0.2% on land excludes model-selection error, which NASS states explicitly. Not benchmarked until the 2027 Census.

MODELLED

8. ⁸ USDA NASS, "Crop Production 2025 Summary", January 2026. https://www.nass.usda.gov/Publications/Todays_Reports/reports/cropan26.pdf The principal-crops total is not a count of distinct land: NASS states it includes double-cropped acres and unharvested small grains planted as cover crops, and substitutes harvested for planted acreage for all hay, tobacco and sugarcane.

VERIFIED

9. ⁹ USDA NASS, "US Farm Production Expenditures 2025", NASS Highlights No. 2026-5, July 2026. https://www.nass.usda.gov/Publications/Highlights/2026/2025-Farm_Expenditures-Highlights.pdf An ARMS estimate covering the 48 contiguous states, not a census; NASS publishes no sample size or standard errors in the highlights sheet. The same survey family put 2022 at \$452.5bn against the census's \$424.14bn for the same reference year, and no crosswalk is published.

VERIFIED

10. ¹⁰ USDA ERS, Farm Sector Income Forecast, 19 May 2026. <https://www.ers.usda.gov/topics/farm-economy/farm-sector-income-finances/farm-sector-income-forecast> Every figure is a forecast, revised several times a year. ERS constructs a sector account rather than summing operator returns and its category names do not map onto either the census or the NASS expenditure survey.

MODELLED

11. ¹¹ USDA NASS, "Technology Use (Farm Computer Usage and Ownership)", August 2025. https://www.nass.usda.gov/Publications/Todays_Reports/reports/fmpc0825.pdf A stratified sample of about 28,000 operations excluding Alaska and Hawaii. No standard errors are published in this table and NASS states values are subject to biennial revision and revision after each census. The precision-agriculture question bundles guidance, yield monitoring, variable rate, drones, tagging, precision feeding and robotic milking into one self-reported response.

VERIFIED

12. ¹² USDA ERS, "Major Uses of Land in the United States 2017", EIB-275, September 2024, and ERS Amber Waves, December 2024. <https://www.ers.usda.gov/amber-waves/2024/december/ers-data-series-tracks-major-uses-of-u-s-land-with-a-focus-on-agriculture> The latest edition is for reference year 2017, seven years behind current NASS data, and ERS notes that census reclassification of cropland pasture breaks comparability with earlier editions.

VERIFIED

13. ¹³ Association of Equipment Manufacturers, US Ag Tractor and Combine Report, December 2024 and November 2025, via GlobeNewswire. <https://www.globenewswire.com/news-release/2025/01/10/3007860/0/en/AEM-United-States-Ag-Tractor-and-Combine-Report-December-2024.html> Compiled from member companies through proprietary reporting, so it is the industry's own figure for its own sales. The census classes tractors by PTO horsepower and AEM by engine horsepower, so any replacement ratio has a numerator and denominator that are not identically defined. Retrofit autonomy kits do not appear in a new-machine count.

SELF-PUBLISHED

14. ¹⁴ USDA NASS, Farm Labor, releases of 20 November 2024 and 21 May 2025 (ISSN 1949-0909). <https://esmis.nal.usda.gov/sites/default/release-files/x920fw89s/0v839z45n/sx61gj70t/fmla0525.txt> A single-week head count of workers hired DIRECTLY by operators; contract, custom and agricultural service workers are excluded by design. Sample target about 18,000 operations, down from 38,000 in 2021 partly for declining participation. Since 2020 the published numbers are model-based estimates calibrated to the prior year's same quarter. Gross wages exclude perquisites such as employer-provided housing.

VERIFIED

15. ¹⁵ USDA NASS, "Notice: NASS discontinues select data collection programs and reports", 28 August 2025, and Federal Register, Discontinuance of Information Collections, 3 September 2025. <https://www.nass.usda.gov/Newsroom/Notices/2025/08-28-2025.php> Discontinued the Agricultural Labor Survey (OMB 0535-0109) as duplicative or no longer necessary. The notice names no replacement source for farm employment, hours or wage estimates.

VERIFIED

16. ¹⁶ USDA ERS, Farm Labor topic page, drawing on BLS QCEW, DOL and State Department data. <https://www.ers.usda.gov/topics/farm-economy/farm-labor> QCEW covers only UI-covered employment, and the gross-up to about 1.1 million rests on a DOL assumption that UI covers 80% of agricultural employment, which is an assumption and not a measurement. The gap between about 385,000 FY2024 positions certified and 315,500 visas issued is roughly 70,000 and is unexplained. The real-wage series ends in 2024 and cannot be extended.

VERIFIED

17. ¹⁷ Zahniser, S., Castillo, M. and Simnitt, S., "Farm Labor Expenses: Evidence from the 1997-2022 Census of Agriculture Data", USDA ERS Economic Brief EB-47,

September 2025. https://ers.usda.gov/sites/default/files/_laserfiche/publications/113432/EB-47.pdf The labour-to-expenses ratio has fluctuated between 10% and 13% since 1997 with no clear national trend. QCEW gives \$50.1bn of agricultural wages for 2022 against the census's \$51.9bn, but QCEW for crop and animal production alone is only \$35.2bn, the balance sitting in support-activity NAICS codes.

VERIFIED

18. ¹⁸ US DOL Employment and Training Administration, "Adverse Effect Wage Rate Methodology for the Temporary Employment of H-2A Nonimmigrants in Non-Range Occupations", interim final rule, 90 FR 47914, 2 October 2025, Exhibits 3 and 6. <https://www.govinfo.gov/content/pkg/FR-2025-10-02/pdf/2025-19365.pdf> DOL's column is headed "workers certified"; ERS publishes about 385,000 "positions certified" and CRS about 363,000 "farmworkers approved" for the same year, and none of the three publishes the definition or the reconciliation. Certification is a ceiling on permitted hiring, not workers who arrived. Exhibit 6's historical AEWR series was constructed by DOL by weighting state rates by certified workers and is not a published official series.

VERIFIED

19. ¹⁹ US DOL ETA, interim final rule regulatory impact estimate, 90 FR 47914, Exhibit 1, 2 October 2025. The rule-maker's own estimate of the effect of its own rule, computed from ARIMA projections of H-2A growth, a 92%/8% skill-level weighting and an assumption of 40 hours a week for 26 weeks per worker. The \$2.46bn annualised transfer combines about \$1.29bn of housing adjustment with about \$1.18bn of wage transfer. DOL's projection of 119,000 additional hires and \$0.2bn of annual benefit is unvalidated.

MODELLED

20. ²⁰ US DOL Office of Foreign Labor Certification, H-2A Selected Statistics FY2025 Q4: 398,258 positions certified, quarterly 58,213 / 159,554 / 99,473 / 81,018; Florida 31,781, Georgia 25,014, California 21,241. https://www.dol.gov/sites/dolgov/files/ETA/oflc/pdfs/H-2A_Selected_Statistics_FY2025_Q4.pdf dol.gov returned HTTP 403 to every automated retrieval attempted during compilation, so this rests on a search-index extract rather than a direct read and is graded reported on that basis, downgraded from the grade the primary series would otherwise carry. Should be verified against the primary before onward citation.

REPORTED

21. ²¹ US DOL ETA, "Adverse Effect Wage Rate Updates for Non-Range Occupations", 91 FR 48946, 3 August 2026. <https://www.govinfo.gov/content/pkg/FR-2026-08-03/pdf/2026-15673.pdf> Rates take effect 17 August 2026 rather than 3 August for entities and states subject to *Kansas et al. v. US Dep't of Labor*, 749 F. Supp. 3d 1363 (S.D. Ga. 2024), covering 17 states. The \$15.96 average AEWR is a simple unweighted average across states and territories including Guam, Puerto Rico and the US Virgin Islands, so it is not comparable to an employment-weighted national wage. Based on BLS OEWS May 2025 estimates released 15 May 2026.

VERIFIED

22. ²² US DOL ETA, "Adverse Effect Wage Rate for Range Occupations", 91 FR 2373, 20 January 2026, effective 3 February 2026: \$2,132.41 per month, up 3.6% from \$2,058.31. <https://www.govinfo.gov/content/pkg/FR-2026-01-20/pdf/2026-00940.pdf> Range occupations use a mechanical Employment Cost Index escalator established in 2015 and were untouched by the 2025 methodology change, so the two AEWR regimes now move on unrelated bases.

VERIFIED

23. ²³ US DOL OFLC, H-2A Adverse Effect Wage Rates page (page last updated 3 August 2026) and the 2026-2027 IFR AEWR statewide values workbook, posted August 2026. <https://flag.dol.gov/wage-data/adverse-effect-wage-rates> and https://flag.dol.gov/sites/default/files/2026-08/DOL-OFLC_2026-2027_AEWRs_FINAL_valuesonly.xlsx The operative rates still carry December 2024 effective dates and are still described as derived from the USDA Farm Labor Survey, which no longer exists. Several states carry an asterisk reflecting the preliminary injunction in Kansas v. US Department of Labor. The interim rule is exposed to litigation and the settled rate is not established.

VERIFIED

24. ²⁴ Rutledge, Z., Martin, P., Ayoub, S. and Hall, M., "Potential Wage Bill Implications of the New AEWR Methodology for H-2A Workers", Choices, 2nd Quarter 2026. <https://www.choicesmagazine.org/choices-magazine/submitted-articles/potential-wage-bill-implications-of-the-new-aewr-methodology-for-h-2a-workers> Computed from FY2024 H-2A disclosure data multiplied by contract weeks, anticipated weekly hours and applicable state wages; arithmetic on job orders, not observed payroll. Choices is the AAEA's professional magazine and is editorially reviewed rather than peer reviewed.

MODELLED

25. ²⁵ Rutledge, Martin, Ayoub and Hall, Choices, 2nd Quarter 2026, on the occupational composition of the five SOC codes now setting the AEWR: about 955,000 US workers, 601,440 of them hand packers and packagers (SOC 53-7064); OEWS records 261,690 in 45-2092, 35,420 in 45-2093 and 30,940 in 45-2091. The claim that most hand packers work in nonfarm warehouses is the authors' characterisation and the supporting industry cross-tabulation is not published. bls.gov returned HTTP 403 during compilation, so the OEWS values reach this report through this secondary.

REPORTED

26. ²⁶ US DOL National Agricultural Workers Survey 2020-22, via USDA ERS, and Congressional Research Service IF13083, 11 August 2025: 42% of hired crop farmworkers unauthorised, 95% confidence interval 37% to 47% for 2021-22, with roughly 327,000 unauthorised crop workers derived from the lower bound. NAWS covers crop workers only and excludes H-2A workers, livestock and poultry. Legal status is self-reported in a face-to-face interview, so under-reporting is plausible and

the direction of bias is unknown. dol.gov blocked direct retrieval of the NAWS report during compilation.

VERIFIED

27. ²⁷ Hertz, T. and Zahniser, S., "Is There a Farm Labor Shortage?", American Journal of Agricultural Economics 95(2): 476-481, published online 11 December 2012. <https://www.ncaeonline.org/wp-content/uploads/2021/03/Hertz-and-Zahniser-2012-Is-There-a-Farm-Labor-Shortage.pdf> The paper states on its first page that it was presented in an invited session and that such articles are not subjected to the journal's standard refereeing process, which is why it is graded reported. QCEW carries no occupational detail and heavy suppression at the 6-digit NAICS county level limits the analysis. The evidence is fourteen years old.

REPORTED

28. ²⁸ Clemens, M.A., Lewis, E.G. and Postel, H.M., "Immigration Restrictions as Active Labor Market Policy: Evidence from the Mexican Bracero Exclusion", American Economic Review 108(6): 1468-1487, 2018. <https://www.aeaweb.org/articles?id=10.1257/aer.20170765> A failure to reject zero bounds the effect rather than establishing its absence. The setting is 1960s US agriculture with a different crop mix, mechanisation frontier and wage floor.

VERIFIED

29. ²⁹ Rutledge, Z. and Merel, P., "Farm labor supply and fruit and vegetable production", American Journal of Agricultural Economics 105(2): 644-673, 2023. <https://onlinelibrary.wiley.com/doi/10.1111/ajae.12332> California only and hand-harvested fruit and vegetables only. The authors state their estimates are upper bounds because they exploit variation in equilibrium employment and not exogenous shifts in the labour supply curve.

VERIFIED

30. ³⁰ Charlton, D. and Taylor, J.E., "A Declining Farm Workforce: Analysis of Panel Data from Rural Mexico", American Journal of Agricultural Economics 98(4): 1158-1180, July 2016. <https://onlinelibrary.wiley.com/doi/abs/10.1093/ajae/aaw018> Measures the supply of farm labour from rural Mexico, not the US farm labour market, so it establishes a shrinking source population and not a US shortage.

VERIFIED

31. ³¹ California Farm Bureau Federation with UC Davis, "Still Searching for Solutions: Adapting to Farm Worker Scarcity Survey 2019", released late April 2019. <https://www.ucdavis.edu/food/news/california-farmers-have-raised-wages-still-unable-find-enough-workers> A voluntary, self-selected survey of 1,071 respondents conducted by the trade association representing the employers whose claim is being tested, with no sampling frame, no published response rate and no counterfactual. The question has no wage attached to it. California-only and seven years old.

SELF-PUBLISHED

32. ³² Lynch, R.G., Ettlinger, M. and Sifre, E., "Warning Signs of the Economic Harms from Deportations", Economic Insights and Research Consulting, 9 August 2025.

https://papers.ssrn.com/sol3/papers.cfm?abstract_id=5384966 A private consultancy with a stated position on the policy. The comparison is a within-year seasonal change in a survey series with large sampling error for a small industry, no confidence interval appears in the coverage located, and the result had not been independently replicated.

REPORTED

33. ³³ Lely, Astronaut automatic milking robot product page, accessed August 2026: over 50,000 robots installed across more than 40 countries since 1995. <https://www.lely.com/solutions/milking/astronaut/> Lely sells the machines. The figure is cumulative installations across all generations, not units currently in service, and no retirement or replacement rate is published.

SELF-PUBLISHED

34. ³⁴ USDA ERS, "Precision Dairy Farming, Robotic Milking, and Profitability in the United States" (ERR 113704), chart of note, January 2026. <https://www.ers.usda.gov/data-products/charts-of-note/114194> The data year is 2021 and publication was January 2026, so the series is five years stale at publication. ARMS is a sample survey with sampling error and adoption is not broken out by robot vendor.

VERIFIED

35. ³⁵ USDA ERS, "America's Farms and Ranches at a Glance", December 2024, using ARMS 2023 data. <http://www.ers.usda.gov/data-products/charts-of-note/110550> Autosteering is operator-assisted guidance with a person in the cab. It is not autonomy and nothing in this series measures driverless operation.

VERIFIED

36. ³⁶ Deere & Company statements on See and Spray, relayed in trade press November 2025 and in the Q3 FY2025 earnings call: more than 5 million acres in 2025, about 1 million in 2024, 59% average herbicide saving. <https://roboticsandautomationnews.com/2025/11/05/john-deere-customers-use-autonomous-see-spray-technology-across-5-million-acres-in-2025/> Deere's own figure for its own product. Acres are those the system ran on, not acres audited by a third party, and the saving is against a broadcast baseline Deere defines. The machine has an operator in the cab.

SELF-PUBLISHED

37. ³⁷ Deere & Company and GUSS Automation acquisition announcements, August-September 2025, following a joint venture dating to 2022: 250+ machines deployed globally, 2.6 million acres sprayed, over 500,000 autonomous hours. <https://www.deere.com/en-us/john-deere-news/john-deere-acquires-guss-automation> Figures come from the acquired company and its acquirer, are cumulative with no year-by-year split, and purchase price was not disclosed. GUSS sprayers are supervised, with one operator monitoring several machines from a pickup.

SELF-PUBLISHED

38. ³⁸ California EDD WARN filing by Zimeno Inc. covering 102 employees, 19 November 2025, reported by TechCrunch, and TechCrunch, "Monarch Tractor's collapse ends with an acquisition by Caterpillar", 15 April 2026. <https://techcrunch.com/2026/04/15/monarch-tractors-collapse-ends-in-with-an-acquisition-by-caterpillar/> The WARN headcount, the 3 April 2026 shutdown and the acquisition are documented filings and reporting; deal terms are not public and were identified partly through patent-office assignment records. The disposition of existing MK-V owners and the pending dealer litigation is not addressed in the acquisition.

VERIFIED

39. ³⁹ Monarch Tractor company statements on deliveries, revenue mix and capital raised, via TechCrunch, 19 November 2025. <https://techcrunch.com/2025/11/19/monarch-tractor-preps-for-layoffs-and-warns-employees-it-may-shut-down> Company statements made while seeking a buyer, unaudited and not broken out by model year; 500 is cumulative deliveries, not machines still running. Trade coverage of the April 2026 shutdown gives \$240M burned and a separate report gives over \$200M raised over eight years; no source states its inclusion rule for debt, bridge financing or strategic investment, and no audited financials exist.

SELF-PUBLISHED

40. ⁴⁰ Farm Equipment, "Electric Tractor Innovator Monarch Tractors is Sued by Dealer, Lays Off Staff", November 2025, on three federal dealer suits including Burks Tractor's claim over ten MK-V tractors bought under nearly \$800,000 of interest-bearing financing. <https://www.farm-equipment.com/articles/24747-electric-tractor-innovator-monarch-tractors-is-sued-by-dealer-lays-off-staff> Allegations in unresolved civil complaints, not findings of fact. Monarch's defence is not in the public record and the company ceased operating before the cases concluded.

REPORTED

41. ⁴¹ Bluewhite company material, 2025 (150,000 US acres, more than 20 permanent-crop growers, over 75,000 autonomous hours) and Elbit Systems press release on the FUSE acquisition of 100% of the company, 27 May 2026. <https://www.elbitsystems.com/news/elbit-systems-fuse-acquired-blue-white-robotics-ltd-expanding-its-autonomous-and-robotics> Vendor cumulative figures with no audit and no per-machine breakdown; acquisition terms undisclosed. Earlier material gives more than 60,000 hectares of orchards in the US and Israel, about 148,000 acres, a near-identical number on a different geographic scope, with no reconciliation published. The acquirer's stated rationale is defence and off-road autonomy.

SELF-PUBLISHED

42. ⁴² Sabanto and Leaps by Bayer, Series B financing announcement, July 2026: about 300 retrofit units in operation across the United States and Australia, about 50 employees. <https://www.prnewswire.com/news-releases/sabanto-and-leaps-by-bayer-announce-oversubscribed-series-b-financing-to-scale-autonomous-technology-for-row-crop-farming-302824458.html> Unit count is the company's own and covers kits shipped rather than kits demonstrably in active use. Disclosure of interest: the round was led by Leaps by Bayer, the venture arm of a crop-protection seller, with

participation by fertiliser producer Yara, so two investors in this autonomy vendor also sell the inputs its machines apply.

SELF-PUBLISHED

43. ⁴³ SwarmFarm Robotics figures relayed by Commonwealth Bank of Australia newsroom, 14 November 2025. <https://www.commbank.com.au/articles/newsroom/2025/11/swarmfarm-robots-put-ag-on-global-tech-map.html> Company-supplied figures relayed by a bank's marketing newsroom. February 2025 reporting gave 145 units, 300,000 operating hours and 2.8 million hectares, about 6.9 million acres; neither source states whether the area is cumulative since inception or covered in the stated year, so the two cannot be reconciled. Australian regulation, so the deployment does not transfer as a US legal precedent.

SELF-PUBLISHED

44. ⁴⁴ Carbon Robotics deployment figures via RealAgriculture, November 2025, and company news pages and GeekWire, 2025-2026. <https://www.realagriculture.com/2025/11/carbon-robotics-laser-weeder-targets-organic-corn-and-soybean-acres/> Machine and farm counts originate with the vendor. Separately quoted figures of 230,000 acres and over 100,000 gallons of chemical avoided do not state whether they are cumulative or annual or which fleet vintage they describe, so the two sets of numbers cannot be tied together.

SELF-PUBLISHED

45. ⁴⁵ Carbon Robotics, LaserWeeder G2 product page, retrieved 5 August 2026: up to 80% cost reduction, one to three year payback on equipment lasting seven to ten years, 5% to 50% yield increases. <https://carbonrobotics.com/laserweeder-g2> No price, throughput, deployed unit count or cumulative treated acreage is disclosed, so none of the savings claims can be converted into a cost per acre by a reader.

SELF-PUBLISHED

46. ⁴⁶ Western Growers Center for Innovation and Technology, "Cut Weeding Costs By ~40% With Laser Weeding", Carbon Robotics LaserWeeder case study, March 2024. https://wga.s3.us-west-1.amazonaws.com/cit/2024/cit_case-study_carbon-robotics.pdf The document states its numbers are based on data provided by Braga Fresh and Triangle Farms, the growers operating the programmes, so under this series' tie-break it is graded self-published regardless of the association publishing it; the two evidence tracks compiled for this review graded it differently and the stricter grade is used. Two farms, one Californian valley, one season, unaudited. Braga's crops are certified-organic high-density baby leaf with no herbicide option, the highest-cost weeding case in US vegetables. Throughput is reported as an average of 0.8 acres an hour over an average 18 hours a day, six days a week, with no downtime, weather, breakdown or aborted-pass figure published anywhere in the document. The document offers readers an ROI spreadsheet from the same innovation centre that promotes the technology.

SELF-PUBLISHED

47. ⁴⁷ FarmWise wind-down announced 18 March 2025, operations ceased 1 April 2025, assets acquired by Taylor Farms 4 April 2025; about \$95.7M raised from 2016 per

CB Insights. <https://agfundernews.com/salad-giant-taylor-farms-acquires-beleaguered-ai-powered-weeding-startup-farmwise> Terms undisclosed. Disclosure of interest: Taylor Farms was simultaneously a customer running two Vulcan units over more than 2,100 acres and an investor in FarmWise's \$45M Series B in 2022, so the reported grower-side savings and the rescue of the company come from the same party. The funding total is a database aggregate, not a filing.

REPORTED

48. ⁴⁸ AgTech Navigator, "How Naio Technologies plots its comeback", 11 November 2025, and Future Farming, June 2025. <https://www.agnavigator.com/Article/2025/11/11/how-naio-technologies-plots-its-comeback/> Robot count is cumulative deliveries since 2011 and says nothing about how many still operate. Revenue figures are French statutory accounts as relayed by trade press rather than fetched from the filing. The 2030 targets are the restructured company's own plan and are a projection.

REPORTED

49. ⁴⁹ Ecorobotix press release, March 2026, relayed by Startupticker and GGBa: 1,000 ARA ultra-high-precision sprayers sold across more than 30 countries over five years, about 250 staff, about 4 hectares an hour at 7.2 km/h. <https://ecorobotix.com/en-us/blog/ecorobotix-reaches-milestone-1000-ara-ultra-high-precision-sprayers-sold-worldwide/> Vendor's own sales milestone: units sold, not units in service. The ARA is a towed precision sprayer pulled by a conventional tractor with a driver, so it belongs to targeted application and not autonomy.

SELF-PUBLISHED

50. ⁵⁰ Burro press release with Petitti Family Farms, October 2025: more than 750 robots deployed globally, over 240,000 autonomous miles and 800,000 hours logged; Petitti moved from 10 units to a committed 25 during 2025. <https://burro.ai/petitti-press-release/> Vendor figures, cumulative, spanning agriculture, industrial and other outdoor settings. Material transport in a nursery is a structured repetitive task on prepared surfaces and does not evidence autonomy in crop-contact work.

SELF-PUBLISHED

51. ⁵¹ Abundant Robotics asset sale, 29 June 2021 (The Robot Report); advanced.farm closure, Good Fruit Grower, 20 March 2025; Tortuga AgTech sale of IP, assets and engineering team to Oishii, AgFunderNews, 24 March 2025, after 150 robots and about \$50M over eight years. <https://goodfruit.com/citing-funding-shortfall-advanced-farm-shuts-down-work-on-apple-harvester/> None is a bankruptcy filing, so none produced an audited statement of what was built or what it cost. Tortuga's fleet figure comes from the acquiring party. advanced.farm's apple programme was partly funded by the Washington Tree Fruit Research Commission, whose members were also the intended customers.

REPORTED

52. ⁵² Small Robot Company liquidation, 1 February 2024, after \$13.18M across six rounds with more than 50 employees (The Robot Report, February 2024); Iron Ox

ceased operations after raising \$102M, with some technology now deployed by Inevitable Tech (Crunchbase News, 2024). <https://www.therobotreport.com/agtech-startup-small-robot-company-shutting-down/> Funding totals are database aggregates, not filings. The exact date Iron Ox ceased operations was not established in public material located here and the terms of the technology transfer are not disclosed. Neither company published a machine count at closure.

REPORTED

53. ⁵³ Zhang et al., "An automated apple harvesting robot: from system design to field evaluation", Journal of Field Robotics, 2024, and Zhu et al., arXiv:2506.05714, 6 June 2025. <https://arxiv.org/abs/2506.05714> Research prototypes at Michigan State and USDA-ARS, not commercial machines, and neither paper reports a cost per acre. Success is measured against fruit the vision system identified, so fruit never detected does not enter the denominator and whole-tree recovery is not reported.

VERIFIED (JFR PAPER); REPORTED (ARXIV PREPRINT FOR THE DUAL-ARM FIGURES)

54. ⁵⁴ California Occupational Safety and Health Standards Board, Title 8 section 3441(b) and petition files 571 (AEM, 2019) and 596 (Monarch Tractor, filed 15 December 2021, denied 4-3 on 16 June 2022). <https://dir.ca.gov/oshsb/petition-596.html> Regulation text, petition numbers and the 2022 vote are from the state regulator's own record; Cal/OSHA stated the dataset was too small to conclude autonomous safety was equivalent to a human operator. A Cal/OSHA memorandum of August 2024 reportedly allows driverless operation where no field workers are present, narrowing but not removing the constraint.

VERIFIED

55. ⁵⁵ Association of Equipment Manufacturers, California advocacy update, December 2025, reporting that the Standards Board declined to vote on its own advisory committee's recommendation on 20 November 2025 and characterising the draft as a DMV-derived multi-stage pathway. AEM is an interested trade association representing the manufacturers seeking the rule change, and both the non-vote and the characterisation of the draft rest on its account.

REPORTED

56. ⁵⁶ NewsWire NZ, "Hastings robot maker sends apple packing machines to Washington state as US orders outrun the factory", 29 July 2026, on Hawk Technology. <https://newswire.co.nz/2026/07/hastings-hawk-technology-apple-packing-robots-washington-us-orders/> All figures are the manufacturer's, relayed in an interview. Orders are not installations and the company states demand exceeds its manufacturing capacity. The labour displacement claim is per lane and per machine, with no industry total and no independent verification.

SELF-PUBLISHED

57. ⁵⁷ USDA NASS, Grain Stocks, January 2026 and January 2025. <https://release.nass.usda.gov/reports/grst0126.pdf> On-farm capacity is estimated from a probability sample of about 73,100 farm operators; off-farm capacity is an enumeration of known commercial facilities. NASS excludes facilities storing only rice or peanuts, cottonseed or peanut crushers, tobacco and seed warehouses, and dry

edible bean storage other than chickpeas. No ownership, throughput or dwell-time data is published by facility.

VERIFIED

58. ⁵⁸ Henderson, J., Gastelle, J. and Caffarelli, P., "Transportation of U.S. Grains: A Modal Share Analysis 1984-2022 Update", USDA Agricultural Marketing Service, September 2024. https://www.ams.usda.gov/sites/default/files/media/TransportationofUSGrainsModalShare1984_2022.pdf Covers corn, wheat, soybeans, sorghum and barley only and measures the final movement to domestic markets or export ports, not every leg. USDA states in its methodology that any effort to measure tonnages by mode is limited by the absence of information on total truck volumes, and computes truck tonnage as a residual after subtracting rail from the STB Waybill Sample and barge from USACE Waterborne Commerce Statistics. No confidence interval is published for the truck figure.

VERIFIED

59. ⁵⁹ USDA AMS, Grain Truck and Ocean Rate Advisory, Second Quarter 2026, published July 2026. <https://www.ams.usda.gov/sites/default/files/media/GTOR2ndQtr2026.pdf> Rates come from quarterly surveys of grain elevators conducted by North Dakota State University and the Upper Great Plains Transportation Institute. In this quarter only the North Central and South Central regions reported; East, West and Rocky Mountain were marked not available for low or no response, so the national average is not a national sample.

VERIFIED

60. ⁶⁰ 49 CFR 395.1(k), Agricultural operations, US GPO, Title 49 CFR 2024 edition. <https://www.govinfo.gov/content/pkg/CFR-2024-title49-vol5/xml/CFR-2024-title49-vol5-sec395-1.xml> Removes the whole of the federal hours-of-service part for drivers moving agricultural commodities within 150 air-miles of the source during planting and harvesting periods, with those periods determined by each State. The observation that the ELD mandate sits at 395.8, inside the disappplied part, is this review's reading of the regulation's structure and not an FMCSA statement. At least one State, Washington, has defined the season as 1 January to 31 December; no national tabulation of State-declared seasons was located.

VERIFIED

61. ⁶¹ USDA AMS, Agricultural Refrigerated Truck Quarterly, Quarter 1 2026, published May 2026. <https://www.ams.usda.gov/sites/default/files/media/RTQ1stQuarter2026.pdf> Reported shipments compiled from AMS Specialty Crops Market News, not a census; volumes not passing through reporting shipping points are absent. USDA notes that from Q1 2025 the 0-500 mile rates from California regions to Los Angeles stopped being reported, which significantly lowered the national average, so the short-haul series carries a break. Rates are open market and include broker fees.

VERIFIED

62. ⁶² USDA NASS, "Capacity of Refrigerated Warehouses 2025 Summary", February 2026. <https://release.nass.usda.gov/reports/rfwh0126.pdf> The 54th biennial survey.

NASS counts only facilities cooled to 50F or lower that normally store food 30 days or more, excluding wholesalers, jobbers, packer branch houses and fast-turn frozen food processors by design, and states its totals should be treated as minimum figures because some firms are unknown to it. Only about 374 firms returned usable reports in 2025, representing about 38% of tabulated capacity. NASS publishes no build-versus-reclassification split for the ownership shift.

VERIFIED

63. ⁶³ Global Cold Chain Alliance, "2025 Global Top 25 List of Refrigerated Warehouse and Logistics Providers", 2025: 5 billion cubic feet across the top 25 North American members. <https://www.gcca.org/press-releases/gcca-releases-2025-global-top-25-list-of-refrigerated-warehouse-and-logistics-providers/> GCCA is the trade association of the firms whose capacity it reports and the figures are member-supplied with no independent audit. The list is North American, so it spans Canada and Mexico, and GCCA does not publish whether member-reported capacity is confined to the region. GCCA itself notes the increase reflects mergers and acquisitions among top operators rather than industry-wide growth.

SELF-PUBLISHED

64. ⁶⁴ FDA, FSMA Final Rule on Requirements for Additional Traceability Records for Certain Foods, page current as of 2026, and Congressional Research Service R48925, 29 April 2026. <https://www.fda.gov/food/food-safety-modernization-act-fsma/fsma-final-rule-requirements-additional-traceability-records-certain-foods> Compliance moved to 20 July 2028 by statute in the Continuing Appropriations, Agriculture, Legislative Branch, Military Construction and Veterans Affairs, and Extensions Act of 2026, after an FDA-proposed 30-month extension in March 2025. FDA held a public meeting on 15 June 2026 on lot-level tracking flexibilities, so substantive requirements may still change. Covers produce, cheese, shell eggs, nut butters and seafood; grains, oilseeds, meat and poultry are outside it, the last two because they fall to USDA FSIS.

VERIFIED

65. ⁶⁵ FDA, "Requirements for Additional Traceability Records for Certain Foods (Final Rule) Regulatory Impact Analysis", 87 FR 70910, 21 November 2022. <https://www.fda.gov/about-fda/economic-impact-analyses-fda-regulations/requirements-additional-traceability-records-certain-foods-final-rule-regulatory-impact-analysis> The cost range spans a factor of 36 and the benefit range a factor of 37, so the central estimates carry very little discriminating power. Figures are in 2020 dollars and predate the compliance-date extension, so the timing of the cost stream no longer matches the statutory schedule.

VERIFIED

66. ⁶⁶ ReFED, "Food Waste by Sector: Farm" fact sheet, based on 2024 data, 2025. <https://refed.org/downloads/by-sector-farm-2025.pdf> Model outputs from ReFED's Insights Engine, not measurements, and ReFED states its on-farm estimates cover produce only. Because the estimate is produce-only it says nothing about grain,

dairy or livestock handling loss, and the unharvested share partly reflects market and price decisions rather than physical logistics failure.

MODELLED

67. ⁶⁷ Buzby, J., Wells, H. and Hyman, J., "The Estimated Amount, Value, and Calories of Postharvest Food Losses at the Retail and Consumer Levels in the United States", USDA ERS Economic Information Bulletin 121, February 2014. <https://www.ers.usda.gov/media/7364/eib-121-report-summary.pdf> Reference year 2010, published 2014. ERS states explicitly that losses on the farm and between the farm and the retailer were not estimated because of data limitations, so the logistics layer this report is about has no USDA loss estimate at all. No updated national estimate at this stage coverage was located.

VERIFIED

68. ⁶⁸ FAO, SDG Indicators Data Portal, indicator 12.3.1 Global food losses, key results for 2023. <https://www.fao.org/sustainable-development-goals-data-portal/data/indicators/1231-global-food-losses/en> The Food Loss Index is an imputed index over a basket of 10 commodities benchmarked to a base period, not a direct measurement, and FAO attributes the 2015 to 2023 movement primarily to updated national production data and revised country estimates rather than real change. Northern America and Europe are reported as a combined region, so no US-only figure is available.

MODELLED

69. ⁶⁹ American Society of Civil Engineers, 2025 Infrastructure Report Card, Inland Waterways chapter, March 2025. <https://infrastructurereportcard.org/wp-content/uploads/2025/03/Inland-Waterways.pdf> ASCE is a professional society that advocates for increased infrastructure appropriations and the report card is a graded advocacy product. The lock statistics are attributed to USACE but the outage data is for 2020, five years older than the report, and a 172.2-minute average across all locks and causes does not describe tail events that shut a corridor for weeks.

REPORTED

70. ⁷⁰ Farm Action, Agricultural System Concentration Data, July 2024. <https://farmaction.us/wp-content/uploads/2024/08/8.5.24-Farm-Action-Concentration-Data.pdf> An advocacy organisation campaigning against agricultural consolidation; the compilation is a secondary aggregation whose per-figure primary sources are not recoverable from the published document. It names Bunge and Viterro as separate firms in the seven-firm river elevator group, which they ceased to be on 2 July 2025.

REPORTED

71. ⁷¹ Bunge Global SA, Form 10-K for the year ended 31 December 2025, filed 19 February 2026, Items 1 and 2. <https://www.sec.gov/Archives/edgar/data/1996862/000162828026009842/bg-20251231.htm> Facility counts and capacities are global and include leased assets and the production and storage capacity of certain equity method investments, so they are not a US-only figure and are not additive with US elevator counts. Bunge does not break out US grain elevator counts or

bushel capacity, and no post-merger concentration ratio has been published by any source located in this review.

VERIFIED

72. ⁷² Plastina, A., Johanns, A. and Magwaba, C., "2024 Iowa Farm Custom Rate Survey", Iowa State University Extension Ag Decision Maker File A3-10, March 2024. <https://crops.extension.iastate.edu/files/inline-files/a3-10.pdf> Based on 130 responses and 2,805 rates from a mailing to 801 people, a response rate near 16%. Rates are what respondents expect to charge or pay, not transacted prices; 48% of task rates came from service providers and 32% from service users. Assumes diesel at \$3.92 a gallon.

REPORTED

73. ⁷³ Iowa State University Extension 2026 Iowa Farm Custom Rate Survey, based on 205 responses and about 4,698 rates, relayed by Kent Thiesse, Agweek, 2 April 2026. <https://www.agweek.com/opinion/farm-custom-rates-expected-to-increase-for-2026> extension.iastate.edu returned a bot-challenge page to automated retrieval during compilation, so these figures come from a trade-press relay rather than a direct read of the primary. Rates are expected 2026 charges collected early in 2026 and assume diesel at \$2.89 a gallon.

REPORTED

74. ⁷⁴ Lattz, D. and Schnitkey, G., "Machinery Cost Estimates: Field Operations and Harvesting", University of Illinois farmdoc, August 2025. https://farmdoc.illinois.edu/assets/management/machinery-costs/field_operations_2025.pdf An economic-engineering calculation using ASABE formulas, not observed cost. Assumes machinery bought new at 85% of list and held 10 years, 7 for combines, diesel at \$3.00 a gallon, labour at \$22.00 an hour and specific annual acreages. The authors state the estimates exclude any profit allowance and that 5% to 15% should be added when setting a custom rate.

MODELLED

75. ⁷⁵ Lattz, D., Schnitkey, G., Paulson, N. and Zulauf, C., "Machinery Cost Estimates for 2025", farmdoc daily (15):159, 2 September 2025. <https://farmdocdaily.illinois.edu/2025/09/machinery-cost-estimates-for-2025.html> List prices are collected by the authors and are not attributed to a named dealer or manufacturer price book. Purchase price is assumed to be 85% of list, so no transacted price is published.

REPORTED

76. ⁷⁶ UC Cooperative Extension and UC Davis Agricultural and Resource Economics, "Sample Costs to Produce and Harvest Romaine Hearts Lettuce, Central Coast, 2023". <https://coststudyfiles.ucdavis.edu/uploads/pub/2023/08/04/2023-romheartslettuce-full-final.pdf> UC cost studies are constructed representative budgets built with a grower and pest-control-adviser panel, not a survey of invoices; the hours and wage are panel assumptions. Conventional romaine hearts on the Central Coast, which does not transfer to organic or high-density crops. The study does not say which machine the \$200 automated weeding pass refers to and gives it with no range and no source.

77. ⁷⁷ Stoddard, C.S., "Weed control and cost benefit analysis of automated cultivators", UC Weed Science blog, UC Agriculture and Natural Resources, 18 June 2023. <https://ucanr.edu/blog/uc-weed-science/article/weed-control-and-cost-benefit-analysis-automated-cultivators-and> One site, one season, one crop, on an extension blog rather than in a peer-reviewed paper, with no confidence intervals. Weed pressure was equivalent across treatments by end of season. The Fennimore and Smith studies behind the 38-45% and 45% labour-reduction figures are referred to rather than cited in the source located, and those are labour-use reductions carrying no machine capital or operator cost on the other side of the ledger.

REPORTED

78. ⁷⁸ Houser, Darr and Huffman, Iowa State University test of See and Spray Ultimate on five Iowa fields in 2024, reported in Strip-Till Farmer. <https://www.striptillfarmer.com/articles/5598-isu-precision-spraying-study-157-herbicide-savings-per-acre> Five fields totalling roughly 414 acres by implication from the stated \$6,500 total saving. A saving on herbicide material only with no machine premium netted off, reaching this review through trade press rather than a direct read of an Iowa State publication. The 43.9% to 90.6% spread is driven by initial weed pressure.

REPORTED

79. ⁷⁹ USDA NASS, "Vegetables 2024 Summary", February 2025, and USDA NASS 2022 Census of Agriculture Table 1 for vegetable acreage. https://www.nass.usda.gov/Publications/Todays_Reports/reports/vegean25.pdf The 301,400-acre lettuce total is the author's sum of three separately published crops, head 109,600, romaine 116,600 and leaf 75,200. Acreage fell in 2024, head down 10% and romaine down 11%, so the denominator is shrinking.

VERIFIED

80. ⁸⁰ Ronnie Gomez, project statement, Industrial Research Fellowship, The Charlot Lab, Institute for Physical AI @ Bailey Military Institute, 2026. The fellow's own framing of scope and intended outcomes, used to define the questions this review tests and not as evidence for any quantitative claim.

SELF-PUBLISHED

81. ⁸¹ Author's calculations. Every figure carrying this index is computed from the cited primaries rather than measured, and is presented as modelled. Derivations include: the pre-2018 manufacture share of the tractor and combine fleet; fleet replacement time from AEM retail units against census stock at 2024 and 2025 rates; the \$106.27bn field-displaceable expense ceiling and its 25.1% share; hired plus contract labour at 12.24% of census expenses, the 23.0% of farms reporting any hired-labour expense, and the 83.2% of the labour bill on 67,320 farms; the 3.5% and 5.5% farm-count shares; machinery and vehicle purchases at 6.5% of 2025 expenditures; per-harvested-acre conversions of customwork, labour and machinery capital; the exact Alaska and Hawaii reconciliation between the 1,880,000 and 1,872,300 farm counts; the on-farm share of grain storage and the average capacity

per off-farm facility; the 84% first-mile premiums in grain and refrigerated produce; refrigerated capacity growth by ownership type and the public share; the FSMA-covered farm population as a share of the census farm count; the post-harvest residual in ReFED's farm-sector figures under both of ReFED's own published routes, 5.4% and 5.8%; the H-2A full-year-equivalent share of hired farm employment and the FY2024-to-FY2025 growth rate; the compound annual rate on DOL's reconstructed AEWR series; the California AEWR percentage cuts between operative and interim-final-rule values; seasonal peak-to-trough ratios in the NASS Farm Labor quarterly table; the spray and combining comparisons between Iowa custom rates and Illinois ownership cost; the reconciliation of the Western Growers implement, operator-labour and utilisation lines and the implied hours-against-cost gap; the untreated hand-weeding baseline implied by the UC cantaloupe trial; hand weeding and hand harvest as shares of the UC Davis romaine total; and the modelled national pools for automated weeding in lettuce and across non-potato vegetables. Working was executed and checked programmatically on 5 August 2026.

MODELLED

Market and economic review, not investment advice. Figures carry the verification grade under each reference: **verified** (peer-reviewed or independently replicated), **reported** (a named source stated it, not independently confirmed), **self-published** (the organisation's own figure) and **modelled** (computed here, not measured). A modelled figure is never presented as a measurement. Corrections are welcome and will be recorded.