WTFRC Technology Roadmap

November 2023

Executive Summary: WTFRC Apples Technology Roadmap 2024-2026

The Washington Tree Fruit Research Commission (WTFRC), founded in 1969, represents tree fruit producers in Washington state, including apple, cherry, pear, and stone fruit growers and packers. Today, the industry is facing numerous challenges - from climate pressures to increasing costs to macroeconomic uncertainties - and recognizes that technology will be key to thriving in an increasingly complex and uncertain future.

This report, focused on apples, presents a technology roadmap for the next two years of research, development, and extension activities. Through deep engagement with over 100 stakeholders across the industry, and in line with the principles shown below, three high priority areas have been selected across three different timelines to impact: Irrigation (near-term), Crop Load Management (mid-term), and Harvest Labor (long-term). Within each area, the existing technology landscape is described, and strategies and example activities have been identified for focus and action in the next two years, and prioritized across the roadmap (i.e., overall priorities).

Selection Principle	Details
Mission alignment.	Alignment to the WTFRC mission to “inspire strategies economic security and sustainability for Washington tr
Balance timeframes to impact.	Focus on near-term (2 year) strategies that will move th laid today to tackle mid- (3-5 year) and long-term (5-10 y
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Technology Roadmap

Priority Area	Strategy	End Goal	Priority
Irrigation	Create and improve incentives for new and existing irrigation service providers to support advanced irrigation technologies.	Eliminate real and perceived service gaps that can limit growers from investing in advanced irrigation technologies.	2
	Increase the availability of third-party data showing the effectiveness of irrigation technologies.	Increase confidence in the effectiveness of existing and emerging irrigation technologies.	2
	Develop a local evidence base for how irrigation technologies can enable the use of non-traditional irrigation techniques that improve fruit yield and/or quality.	Improve apple yield and quality through innovative irrigation techniques.	1
	Document and share irrigation technology strategies that growers are using to reduce costs.	Motivate adoption of irrigation tech by appealing to cost-saving opportunities, and leveraging social proof.	3
	Build capacity and capabilities for the effective use of irrigation technologies.	Improve the confidence and skills of operators across all levels of orchard operations related to effective use and optimal utilization of irrigation technologies.	2
Crop Load Mgmt	Incentivize research on the precision application of plant growth regulators.	Improve the effectiveness of existing chemical thinning tools to reduce labor and input costs.	2
	Advance the availability and effectiveness of crop load modeling tools, with special emphasis on early season prediction.	Farmers have access to high quality data around crop load management as early in the season as possible.	1
	Incentivize research and development work in pruning technology.	Increase the amount of technologists creating tools to advance pruning efficiency.	1

	Advance awareness of, and evidence for, the value of tech-enabled crop load management tools.	Increase crop load management tool exploration and adoption among growers.	3
Harvest Labor	Lower the costs of developing commercially viable mechanical/autonomous apple harvesting solutions.	Increase the amount of collaborations between technology developers, academic researchers, and commercial R&D providers to reduce duplication of efforts in the development of harvest labor solutions.	1
	Educate vendors and developers to ensure harvest labor solutions are designed to work within the operational and financial constraints of existing systems.	Vendors come to market not just with technology that works, but that is also affordable and easily integrated into apple orchards	2
	Help Washington apple growers get "robot ready."	WA apple growers are able to take advantage of emerging harvest labor solutions with minimal negative commercial impacts / trade-offs.	3
	Update WTFRC's RFP processes to efficiently engage the appropriate experts in vetting new research and commercialization proposals.	Ensure that limited resources for harvest labor solutions are appropriately and efficiently distributed, based on a range of required lenses for evaluating technologies (e.g., technical, industry, commercial, etc.) and development teams.	2

Introduction: Industry and Technology Adoption Trends & Barriers

Trends in Washington Apple Production

Broad Trends

The industry is currently going through a down cycle. The current cycle of low prices in the apple sector is not unprecedented, but is also not common in the history of apple production. There are many likely drivers, but a key result is that, though growers are particularly hungry for cost-saving tools now, they are likely also more risk averse than they might be during an era of rising apple prices.

Labor costs continue to rise. Between the wage rate for H2A workers and the additional expenses related to housing and transit, grower expenses related to labor are some of the highest in the US, and growing at a rate of about 6% per year. Additionally, regulatory requirements to ensure worker safety are increasing. One grower reported spending more than $17 million in the last two decades on housing, shuttles, and administrative staff alone. Plus, given the level of the minimum hourly wage, growers are finding it difficult to set a piece rate that motivates increased productivity.

Voices of the Industry
"Global GAP and other regulations, along with rising expenses and wages, are making it harder to stay in business" –Washington Apple Grower "The number one issue is labor efficiency / cost management. 65% of the production cost is labor. Businesses in the state of Washington no longer have control of the cost structure of labor, so the only long term solution is to dramatically reduce the headcount of field workers." - Industry Service Provider

Increased competition within Washington State. The entrance of outside investors into the apple production space in Washington has led to a substantial increase in overall apple production despite the labor and input cost headwinds. This increase, combined with a more challenging export market (US apple exports are off 8 million boxes in 2023), have made for a poor price environment for producers, especially of the most common varieties (Gala, Fuji, and Granny Smith).

Consolidation. Due to a range of factors, from generational transition and access to capital to rising costs, there are fewer, larger producers today than previously. Similarly, the industry has seen increased interest from outside capital sources, e.g., private equity.

Increasingly challenging regulatory environment. Across areas such as food safety, export (phytosanitary conditions), and labor access (particularly through the H2A program), compliance costs are rising which will in turn require increasing amounts of data to manage.

Increased climate volatility. While attribution and names for this vary, and are often politicized, there's recognition that climatic conditions are increasingly volatile and this has associated risks for apple production.

Apple Production Trends

Input inflation cuts into margins. Today, from the moment an apple orchard is first imagined until the time of its first harvest, growers will spend about $65-$70,000 per acre. After that, even leaving aside labor, costs related to crop chemistry, equipment, energy, and other essential inputs will mean the orchard won't begin paying for itself for about 15 years. Some of these factors (like land cost, etc.) are part of longer trends, but others (like crop chemicals), are beholden to volatile markets in which prices fluctuate substantially over short periods of time, significantly increasing grower's price risk.

Newer orchard designs opt for uniformity and 2-dimensionality. Across grower interviews, we did here a near uniform story about a movement towards increased standardization, uniformity, and 2-dimensionality in orchard plantings, in preparation for autonomous equipment that operates primarily by looking at a "wall" and picking the fruit that it can clearly see. Vertical trellises seem to be much more accessible (compared to V trellises) to autonomous equipment, and despite the cost disadvantage, there is a trend towards having a more mixed system to be prepared for mechanized solutions when they come available. Equipment manufacturers and orchard managers are also largely aligning on other key features, like on equipment size that fits the majority of row/tree spacings and bin sizes.

Aging population and the need to make wisdom available to young growers. With an aging population of growers in the Washington apple space, there is increased interest in making more wisdom and expertise available for younger growers, especially when it comes to horticultural issues. An experienced grower can look at a tree and determine its need for more/less water, nutrients, etc., based on decades of experience, whereas younger growers have a harder time making similar evaluations.

Production Technology Trends

Steady tech progress has been made in many areas of apple production. Growers say there have been regular and meaningful improvements in areas of fruit quality, root stock, IPM and nutrients, chemical thinning tools, and varieties, among other things. Though there is still room for marginal improvement in specific areas, there are few gaping holes in technological progress outside the labor space. Significant ROI has been realized by some related to moisture monitoring, plant health/tree stress monitoring, irrigation monitoring, and payroll management software.

More data without the ability to act on it. Many growers noted that there has been a proliferation of tools to help them identify parts of the orchard that are experiencing adverse effects, but there have been far fewer cost-effective tools to facilitate variable rate application of inputs. Also, many of these tools do not deliver the data within a reasonable time frame in which it can be acted on.

Advances made in monitoring/mapping for intensive orchard management. There are existing solutions that are being adopted to improve labor efficiency, such as scanning technology that can help in managing labor during pruning and thinning. Multiple growers are also currently using a semi-custom solution to track and analyze this data. Though affordability is increasing, the current barriers are high costs per scan and a too long turn-around time. Access to high upload/download speeds was also mentioned as a potential barrier to widespread adoption going forward.

Barriers to Current/Future Technology Adoption

Declining profitability of production. An existential barrier, the fact that orchard profitability is such a high hurdle to clear likely means that any tech that requires significant upfront expense or that has a long payback period will be untenable for some major cohort of Washington apple growers. Service-based go-to-market models (e.g., custom harvest with a price per bin rate) will likely be more widely adopted than equipment or tools that must be bought outright.

Lack of uniformity across the apple sector and over time. Growers in the apple sector are a relatively heterogeneous group, and even a single organization will go through periods, within years and between years, in which they operate outside of their standard operating procedures. Plus, each grower has some elements of unique management practices and/or orchard architecture (e.g., row spacing, tree spacing, trellis system, bin size, irrigation system, etc.) meaning that even similarly sized orchards in the same year might operate quite differently. Because of this lack of standardization, efficiency and affordability calculations for a technology or service will vary for different growers in different years.

Specific examples include:

- Some years, it may make sense for growers to absorb a 10% fruit loss related to mechanical harvesting, other years, it may not.
- Some growers have access to senior water rights along the Columbia River while others do not, and therefore have much higher concerns about water availability from year to year compared to other factors.
- Depending on the compensation that exists on a given farm, benefits to improved labor efficiency gained from platforms may accrue to the grower, or they may accrue to the picker.
- Tools like robotic sprayers and mowers are available and, in some cases, affordable today; however, small operations, or operations made of non-contiguous, small orchards, can't take advantage of these tools due to affordability constraints.

Upfront cost efficiency. In the past, technology tools that have been available in the earliest stages of their development have not yet been cost efficient. This kind of technology might be worth trialing, but meaningful adoption will not occur until the total economic value proposition can be realized. This relates to the technology's effective price as well as its reliability. There is a sense among surveyed growers that though many tasks could be accomplished mechanically today (particularly by an autonomous technology), they cannot be done more cost effectively than with human labor. In terms of business models, purchase models (versus service models) have proved untenable when investing in new technologies, and non-passive tech (which requires high levels of interaction) have made even trialing new tools too costly.

Voices of the Industry
"Many of the companies that are presenting technology are on a shoestring and they're selling something that they think is very exciting. And it probably is, but they're not quite there yet. I think many of us have watched this process, where they've got all the answers, and then five years later they're backing out and saying, okay, we're bankrupt. And then the growers have also invested in the process, because of the potential. And so I think many participants are getting a little jaded and insisting that, okay, that looks exciting, but you don't have any track record. I can't really afford to pay you to figure this out."   –Washington Apple Grower

Technology Proliferation & Low Success Rates. Given the proliferation of technology, growers now need to identify all the tech that could have a positive impact in a given operation, have the resources to appropriately explore those options, and have the confidence necessary to invest in piloting or adopting that technology. Fatigue from these increased requirements, combined with cases where the technology failed and/or the company went out of business, represent a possible drag on future interest and adoption rates.

The need to redesign orchard infrastructure in preparation for automation. More planar, 'robot ready' orchard systems often require more management/labor in the nearterm, and are not equally accessible given the growth characteristics of trees/certain varieties. This might mean that there are savings related to picking, and the ability to yield more target fruit, but there's more infrastructure and tree management costs throughout the season. Therefore growers, when making short term investments, must optimize between short term yield and the ability to use autonomous equipment in the future.

A key aspect of this challenge is ensuring that new infrastructure is not only appropriate for automation, but also improves the efficiency of hand harvesting in the meantime. Most growers are open to adopting new trellis systems, but the goal would be for those systems to remain in place for 30-50 years, given the price tag.

Solving for total cost of ownership. Managing grower's existing fleets already involves significant outlay for parts, fuel, and mechanics, and is often a high risk endeavor when the annual productivity of a 10 acre block could be slash considerably by a fan that's offline for an hour in the middle of the night. As the industry looks to increase mechanization and automation, ensuring that there is attention paid to how these new tools will be serviced, repaired, and fueled can not be overlooked.

Perception of difficulty of certain tasks. Especially for tasks like thinning at early stages, there are certain activities that growers perceive as being more difficult to mechanize than handling mature fruits. This could mean that growers (and technologists) show less interest in these solutions and are less vocal about the need for them, which may lead to diminished investment in them over time.

Limited opportunities in new varieties. The apple industry is unique within fresh fruit in having established name-recognized varieties that correspond to higher value products. Over the past decade or two, this has presented an opportunity for growers to increase margins. Today, however, there is variety fatigue among growers, many of whom believe that we've reached "peak-apple-diversity" on the consumer level, and who therefore are uninterested or unwilling to adopt new, unproven varieties, especially if they are perceived to be more difficult to manage horticulturally.

Lack of awareness of the potential of non-obvious technologies. One grower pointed out that one of the technologies that most dramatically impacted the apple industry in the past was cold storage. However, interestingly, "I need to be able to sell apples year round" was not a likely focus for growers prior to cold storage, because it was a simple impossibility. There could be additional opportunities in this vein– unknown unknowns– that could revolutionize the apple industry not because it solves a key existing issue, but because it unlocks a completely unrealized opportunity.

Growing concern about the availability of a tech-literate workforce. As the apple industry looks to a more autonomous/mechanical future, growers worry about having the right people and skills to operate more complicated machines. This concern serves as yet another barrier to purchasing robotic/autonomous equipment, as growers are unsure as to whether or not their employees will be able to maintain and repair their machines. More broadly, there is concern about a lack of entry level people to train up through apple business, casting uncertainty on who the managers and leaders of the apple sector might be in the future.

Further, the skill and education levels of the apple industry workforce can be a limiting factor in communication (e.g., between technology companies and end users; owners to workers; etc.), impacting requirements for user experience and even adoption more broadly.

Methodology and Prioritization Approach

The final technology roadmap was developed with significant input from over 100 stakeholders across the Washington Apple industry. Several engagement techniques were deployed to engage stakeholders (see below), and ultimately to ensure the roadmap represents industry needs and has strong buy-in.

Engagement Technique	**Attendees & Frequency**	**Scope**
Steering Committee	WTFRC and Apple Grower representation Regular meetings throughout the project	Project management Stakeholder coordination Approvals & decision making
Focus Groups	33 attendees across five sessions Variety of perspectives (e.g., growers & packers of different sizes, researchers & industry experts, etc.)	Identify top three priorities
Prioritization survey	Open survey promoted across the industry 63 responses received (see below), representing a variety of perspectives (operation size, location, etc.)	Identify top three priorities

Overall, the following priorities were selected:
- Irrigation (near-term);
- Crop load management (mid-term); and
- Harvest labor (long-term).

The three priorities shortlisted for the roadmap were selected based on the outputs of the activities above, and the following principles:
- **Mission alignment.** Alignment to the WTFRC mission to “inspire strategies and promote collaborative science-based solutions to foster economic security and sustainability for Washington tree fruit growers”
- **Balance timeframes to impact.** Focus on near-term (2 year) strategies that will move the needle for growers, including groundwork that needs to be laid today to tackle mid- (3-5 year) and long-term (5-10 year) priorities.
- **Overcome barriers.** Target specific barriers to technology adoption, as identified via desktop research and interviews

- **Leverage strengths.** Focus on WTFRC strengths (i.e., don't suggest things WTFRC is not well placed to take on)
- **Encourage diverse partners and broad thinking.** Specify outcomes and provide example (but not prescriptive) activities to encourage "out of the box" thinking and attract a diverse range of traditional (i.e., researcher) and non-traditional partners

It is worth noting that the results from the prioritization survey overall reflect the outputs from the focus groups. Specifically, crop load management and harvest/labor were very strongly supported in both, and "climate volatility," "nutrient management," and "abiotic stress management" also received strong interest. One difference between the survey and focus groups results was that "pest management" scored higher, and "irrigation" scored lower, in the survey than in the focus groups. Within the "mid term" timeframe, crop load management scored the highest and was therefore selected.

In the survey, respondents were asked whether they "feel that the top 3 issues on your operation are different from the top 3 issues generally plaguing the industry?" While most respondents agree that labor is the #1 issue, it was noted several times that large and small growers face different constraints and therefore may have different priorities. The project team consulted broadly across the industry to mitigate the risk of creating a roadmap that only applies to large growers.

Finally, additional suggested, but not prioritized, strategies and activities are included in the appendix.

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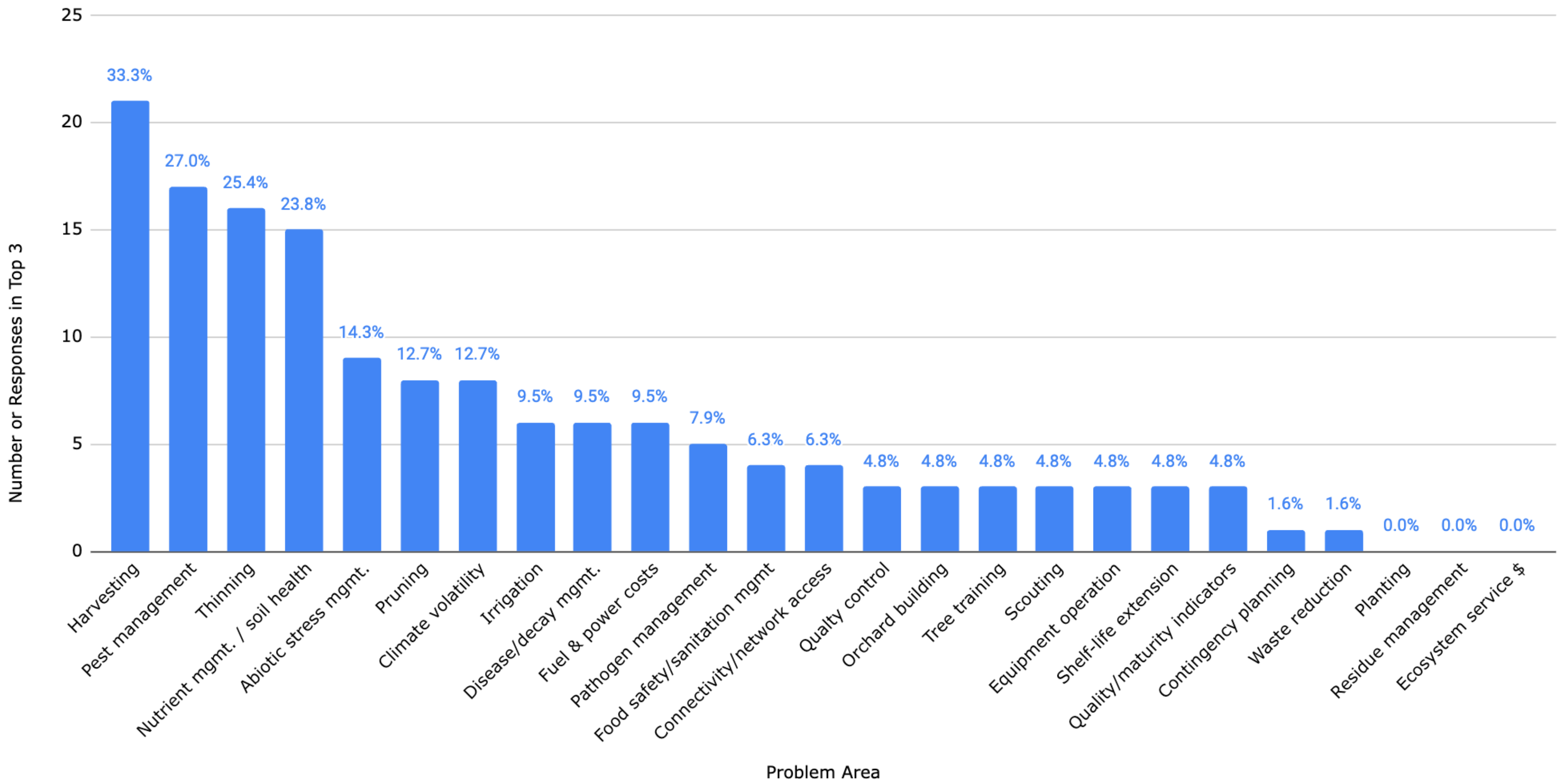
Survey Outputs: Top Industry Priorities



Short-list Priority: Irrigation

Current Irrigation Technology Landscape

The irrigation technology landscape can be broken down into three, heavily-interconnected categories; hardware, optimization software, and control systems. Advanced irrigation hardware is the most widely adopted of the three categories, with adoption rates of associated software following closely behind. Advanced irrigation control systems are becoming more common, but are still not widely adopted.

Voices of the Industry
"It's cool to see some of these new, control technologies being adopted. Being able to run things on your phone from anywhere, and set programs and be able to fine tune your water usage."   –Washington Apple Grower

Irrigation Technology Categories

Irrigation Sensors & Infrastructure: Hardware advances in orchard irrigation continue to help growers reduce costs related to pumping as well as preserve water resources and optimize tree health. Some of these advancements have been made at the irrigation system-level, leading to more optimized systems (e.g., sprinklers, drip, subsurface drip, fertigation, etc.). Other advancements have been made with regards to supplementary tools like soil moisture sensors and alternative energy-powered pumps.

Example offerings include:

- Netafim: drip and micro-irrigation solutions
- Toro: smart controllers and precision sprinklers
- Tule by CropX: in-field sensors
- Dynamax: soil moisture, stem flow gage, and other in-field sensors
- Nelson: Twig-V Wireless Automation System

Irrigation hardware is a category that encompasses everything from pipes and pumps (the essentials of any irrigation system) to state-of-the-art soil probes and automated valves. Given the breadth in this category, every Washington apple grower with irrigation has embraced irrigation hardware tech of some kind. Though there is no specific data available on how widely adopted newer irrigation hardware tools are among Washington apple growers, anecdotally, producers are generally familiar with soil moisture sensors, tree- and fruit-mounted sensors, advanced pumps and nozzles, and pressure monitors. Many are already using these technologies, either via trials or full adoption across part or all of their operation. A more tangential aspect of newer irrigation technology promises to marry the latest in soil mapping with irrigation to enable variations in water application rates across the orchard. However given the current state of technology, to do this would require massive capital investments to redesign irrigation system infrastructure. This is being pursued in other regions where water shortages create additional incentives, but is unlikely to be justified in the near term in Washington orchards.

Generally, since soil moisture sensors have been around in one form or another for nearly a century, there is more conviction that the information they supply is actionable, versus other, newer sensor types. Notably however, soil moisture sensors must also be calibrated to be accurate, an activity which is not always performed.

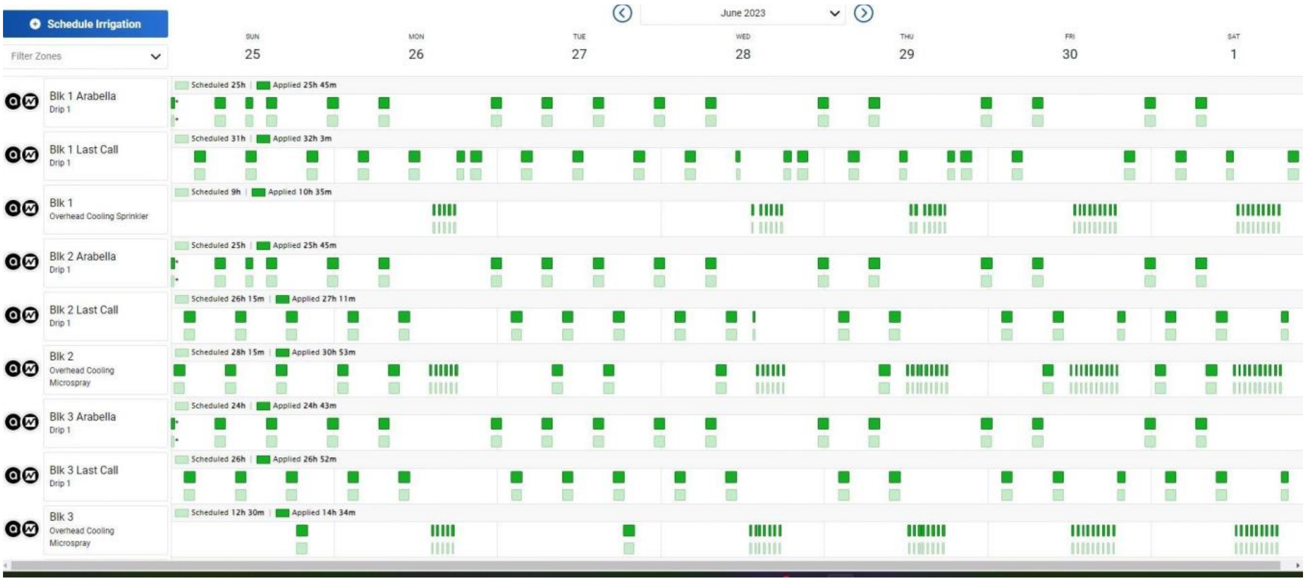
Irrigation Optimization Software: Irrigation software systems allow for the integration of GPS data, aerial and satellite imagery, and other data about crop health and soil moisture levels into the irrigation decision-making process, offering opportunities for growers to use water resources more efficiently. Many of these systems require cloud-based analysis, due to the high quantity of data involved. Data from soil, tree, and fruit sensors can provide real-time information about water needs, allowing growers to make informed decisions about leaving irrigation systems off longer to conserve limited water allocations and/or to fine-tune deficit irrigation schedules to minimize water usage without causing extensive yield damage and/or to optimize fruit quality (i.e. bitter pit management) and fruit size.

Beyond orchard performance optimization, these irrigation tools also collect and record water-use data that could be useful in the future for marketing purposes (e.g., “water smart” apples), for regulatory compliance, and/or to respond to investor demands for the sustainability credentials of orchard operations.

Though many apple growers in Washington do not struggle with water shortages, junior water rights holders and those located in more marginally geographies are sensitive to the volume of water used. Given that many Washington apple growers are not water-limited, over-irrigation is much more common than under-irrigation. Over-irrigation, though it has few direct negative impacts on tree health, can affect a growers ability to run equipment in orchards, can waterlog roots and impact plant health, and most critically, can increase costs through nitrogen leaching, which increases the need for supplemental fertilization over time. By narrowing in on optimum irrigation (and exploring irrigation strategies that allow for more water infiltration into the root zone alone, which tend to be more frequent and for shorter durations), some growers are maintaining more soil nutrients throughout and between seasons, over time leading to less need for supplemental fertilization.

Example offerings include:

- SWAN Systems: Irrigation optimization software (AU)
- Wilber-Ellis Probe Schedule: Irrigation scheduling software
- Semios: Irrigation planning and monitoring software plus data analysis



Screen Capture of a typical irrigation schedule, Courtesy of Semios

Though many irrigation hardware tools that deliver data come with associated software, it is unclear how commonly adopted the softwares/apps are amongst Washington apple growers. Though many growers have access to them, whether they regularly consult the software, or when they do, there is uncertainty about whether they or their irrigators are able to translate that information directly into effective irrigation planning. It is likely that fewer growers are utilizing irrigation software than irrigation hardware, and that the most commonly used features are relatively basic soil moisture models and evapotranspiration data reports.

Advanced Irrigation Control Systems: Irrigation control devices and/or platforms integrate both software and hardware, as well as combine historical weather data, soil moisture sensors, and other inputs like forecasts to optimize irrigation scheduling and in some cases even automate irrigation to manage flows in real-time. Many tools in this category allow for remote monitoring and control via mobile apps or online platforms.

Labor savings is a major value proposition of these systems, especially because, too often, irrigators spend much of their time carrying out rote, laborious tasks like turning valves and manually checking pressure gauges. Though advanced irrigation tools do not eliminate the need for irrigators in the orchard, they can transform the tasks of irrigation from ones focused on doing (e.g., turning values) to monitoring (e.g., verifying that the valve is open, checking irrigation lines, etc). Not only can this reduce the time it takes to manage the irrigation process– freeing up the irrigator to support other tasks in the meantime- it can also allow for improvement in the overall process.

One such improvement is that control systems allow growers to experiment with alternative irrigation strategies like pulse irrigation, which is a process by which trees are irrigated multiple times per day for extremely short durations. This strategy has anecdotally resulted in yield gains in other tree crops,[1] but the main barrier to carrying out pulse irrigation in apple orchards is the amount of labor required to manually operate valves. Systems that allow valves to be turned automatically can allow for experimentation with irrigation plans that might be beneficial in terms of yield and quality, without dramatically raising irrigator-related labor costs.

Example offerings include:

- Phytech: direct plant sensing and data analytics to inform optimized irrigation
- Wiseconn: wireless hardware installed in the field and software for monitoring, control, and automation

Control and monitoring solutions are the most recently commercialized irrigation tools. Anecdotally, these systems are currently not widely adopted, though there is increasing interest, especially among large growers. The introductory value proposition usually revolves around monitoring– allowing growers to verify that their irrigation plan is being carried out by their employees. Technology vendors often focus on this initial, and less complex, value proposition because of a persistent lack of confidence amongst growers in the remote control aspects of the systems. While full automation of irrigation promises labor savings, the reality is that growers still desire significant oversight of their systems to manage the risk of possible losses, and so the touted benefits are not realized. In other words, though completely automated scheduling and execution may be possible, there are significant - albeit justified - psychological barriers (i.e., loss aversion) to adoption.

[1] Extensive discussion in Wiseconn interview transcript. Also see Wiseconn case studies with tree growers who have seen significant success with pulse irrigation here and here.

Barriers to Adoption of Irrigation Tech in Washington Orchards

Overall Opportunity for Growers: The key opportunities of adopting irrigation technologies are:

1) cost savings, particularly in terms of water, energy, labor, and nutrients;

2) increased confidence in irrigation decision-making; and

3) the ability to explore new irrigation strategies that could have direct benefits to yield and quality.

Further, there's also emerging evidence that adoption of irrigation technologies could also unlock additional revenue streams, for example via ecosystem service payments.

However, for most growers to seize these opportunities, several barriers will have to be overcome.

Support: The question of who will provide hardware maintenance and help trouble-shoot software, especially during particularly sensitive times of the year, remains relatively unanswered in the irrigated orchard space. In general, irrigation supply and installation companies do not install emerging irrigation tech tools (i.e., sensors, software, automatic valves, etc.), and thus do not service them. Growers must therefore rely on irrigation technology companies themselves for maintenance and support, but these companies often lack the resources to employ sufficient field service support. Larger growers may have on-staff tech support that can calibrate sensors and debug software, but medium and small growers are more dependent on limited regional support staff to deal with issues as they arise.

Cost: Especially for small/mid-sized growers, cost of technology remains a concern. Though there is a consensus amongst irrigation experts that per-acre returns to investments in irrigation tech tend to be consistent across scale (i.e., such that bigger growers do not benefit more than smaller ones), larger growers are better able to amortize costs across a larger footprint.

Learning curve to effective use: Though irrigation software systems are becoming increasingly intuitive to navigate, translating the data from various sensors into decisions and then actions requires both education and habit-building. This work is unique to each operation and requires both training and incentives that prompt growers and irrigation managers to change practices (e.g., regular interaction with the tools). Summiting this learning curve is inevitably more difficult for more resource-constrained, or less technology-savvy, growers.

There are multiple layers to this barrier throughout the orchard and across roles. Irrigators who use the tools daily to control irrigation have to learn how to use apps to follow a predetermined schedule. Farmers/managers who create the schedule have to learn to read and analyze the data from multiple sensors and monitoring tools to determine an effective strategy. And at some level, owners/executives have to learn to create reports and read out data that's valuable to investors/regulators/etc.

Confidence in the system: Growers have varying degrees of confidence in different aspects of advanced irrigation technologies. While confidence in soil sensor data outputs is relatively high (perhaps too high given that many may be un-calibrated), grower confidence in monitoring systems is more spotty, and levels of confidence in control systems can be significantly lower still. Given the large amounts of capital involved, growers often do not perceive the benefits to outweigh the costs of a possible system failure.

Value proposition: Though there are cost-savings to be had from optimizing irrigation, it is not always clear to growers whether those savings justify the cost of implementing advanced irrigation systems. Lack of available, third-party verified data to that effect is a significant part of the problem.

Supplementary value propositions also tend to appeal to some kinds of growers more than others. For example, many software and monitoring providers point to the value of having access to data and reports around water-usage and climate impact. Though this is valuable for large, vertically integrated growers that engage outside investors especially, for many smaller, private growers who don't feel pressure to provide this information, this value proposition does not land.

Crowded landscape: Especially for the most commonly available tools like soil sensors, it is increasingly time-consuming and confusing to evaluate and select options. This is especially true for growers with fewer resources and/or capabilities. This is less of a problem when it comes to the control and monitoring technologies, of which there are fewer.

Irrigation Technology Strategies

A rapid increase in experimentation with, and adoption of, irrigation technology is possible in the next two years, though expectations should be tempered by the fact that a dramatic increase in the number of orchard acres utilizing these systems may not be possible in such a short window. Existing vendors recommend a multi-year adoption plan for growers, one which begins with step-wise exploration into sensors. These sensors can provide data for basic analyses, and then be combined with control and monitoring systems over time as growers gain confidence and competence with systems.

The following strategies have been identified to catalyze an increase in adoption:

Create and improve incentives for new and existing irrigation service providers to support advanced irrigation technologies. A major barrier to adopting more irrigation tech is uncertainty related to the cost and availability of maintenance resources. WTFRC can participate in encouraging organizations with existing service presence in the region to explore providing these services, as well as create incentives for new providers to fill the gaps.

End Goal: Eliminate real and perceived service gaps that can limit growers from investing in advanced irrigation technologies.

Priority: 2

Example Activities:

- Host or support events bringing together existing irrigation providers and other retailers/trusted advisors with irrigation tech companies to facilitate partnerships
- Encourage research into the benefits of supporting irrigation tech companies, irrigation companies, and/or growers to actually provide this support in such a way that enables them to move towards financially sustainable and adequate services
- Support total cost of ownership studies which directly quantify service costs/service opportunity for would-be providers

Increase the availability of third-party data showing the effectiveness of irrigation technologies. Most data about the efficacy of irrigation technologies in Washington orchards comes exclusively from the companies who deliver the tools. WTFRC can participate in funding activities that verify claims in real world operating conditions in the region, providing growers with additional resources to help them navigate the landscape of technologies.

End Goal: Increase confidence in the effectiveness of existing and emerging irrigation technologies.

Priority: 2

Example Activities:

- Support independent validation of irrigation company claims (for example, a trial around converting tree sensor data to real-time water demand)
- Fund commercial trials specifically tailored to the operating conditions of Washington orchards (e.g., comparison of tools to enable deficit irrigation)
- Publish findings of existing third-party data on effective use of irrigation technologies in accessible forms (e.g., videos, blog articles, etc.) & disseminate to industry
- Fund ROI analyses for existing technologies

Develop a local evidence base for how irrigation technologies can enable the use of non-traditional irrigation techniques that improve fruit yield and/or quality. In other geographies, and outside of apples, strides have been made related to unconventional irrigation techniques (e.g., pulse irrigation) facilitated by advanced monitoring and control tools. Washington's general lack of water constraints has resulted in more limited local experimentation, meaning significant yield/quality improvements may still be possible.

End Goal: Improve apple yield and quality through innovative irrigation techniques.

Priority: 1

Example Activities:

- Fund research trials applying the latest irrigation techniques (e.g., pulse irrigation, deficit irrigation, soil-type specific irrigation, etc.) in Washington orchards with a specific focus on results related to quality
- Support applied research projects with highly specific objectives, for example, studies around reducing the frequency of bitter pit in HoneyCrisp apples with deficit irrigation strategies (with a particular focus on how growers can pursue these practices)
- Curate and amplify existing research and case studies on trial and experimentation results from other regions
- Coordinate and encourage collaborations that integrate expertise from local irrigation districts

Document and share irrigation technology strategies that growers are using to reduce costs. Though irrigation tech can create both labor and input savings, the general lack of concrete information about these benefits means there's little confidence in these additional value propositions. Finding ways to circulate both qualitative and quantitative information about experiences in cost-savings will help WTFRC build grower member's trust in irrigation advances.

End Goal: Motivate adoption of irrigation tech by appealing to cost-saving opportunities, and leveraging social proof.

Priority: 3

Example Activities:

- Highlight available state and federal grants, tax credits, etc. that are available for growers that can prove reduced water usage; include case studies of successful applicants and the outcomes they achieved.

- Provide a clear informational link between the long-term impacts of over-irrigation and nitrogen leaching accessible (e.g., amplifying real-world data and case studies related to the long-term impacts via podcasts, videos, etc.)
- Support trials/pilots around the provision of ecosystem service payments
- Develop a publicly accessible 'logic map' to enable varied types of growers to understand their options for irrigation tech given their specific needs (e.g., acreage, budget, trellising type, existing irrigation systems, water rights, etc) and goals.

Build capacity and capabilities for the effective use of irrigation technologies. WTFRC can find creative ways to help growers summit the learning curve to both unlock investment in irrigation tech, as well as improve utilization of existing investments.

End Goal: Improve the confidence and skills of operators across all levels of orchard operations related to effective use and optimal utilization of irrigation technologies.

Priority: 2

Example Activities:

- Ensure existing field days/demonstration days include specific content aimed at training/education for irrigators (facilitated in Spanish)
- Create an online, at-your-own-pace "Irrigator University" course for growers and managers that is customized for WA conditions and provides support and instruction in data analysis and decision-making
- Partner with WSTFA to create training material
- Incentivize establishing farm-level and industry-level baseline for water usage levels, and potentially also power usage related to irrigation

Short-list Priority: Crop Load Management

Current Crop Load Management Technology Landscape

Crop load management is a broad category of activities that encapsulates some of the most important tasks in the orchard. From winter pruning to seasonal thinning, all the way through harvest, the many tools and tasks that monitor apple trees and get them from dormancy to harvest are all inclusive of the broad term. Further, every Washington apple grower has a unique perspective on how these tasks are best carried out, when, and by whom to result in the best yield, quality, and least cost. Though growers might have this general end goal in common, crop load management is very much an art amongst apple growers, and there is much variation on the “standard practices” that are common in the industry from orchard to orchard.

Managing the precise amount of fruit each tree bears is essential to achieving consistent high yields of target quality fruit. Crop load management is accomplished in a stepwise manner through dormant pruning, blossom thinning, and fruitlet thinning. First, dormant pruning activities aim to remove all but the specific number of flower buds needed for full production. Next, blossoms are thinned or treated to ensure each desired flower sets a fruit. Lastly, any excess young fruit is removed through the green fruit thinning process, and the fruit loaded is monitored until harvest. If crop load is managed correctly, crop uniformity improves, which leads to better yields and more consistent cropping for the entirety of the life of the orchard.

Voices of the Industry
“We need to maximize our production per acre with our growing costs being so high. But also, there's a fine line in how much fruit we can pick per acre without affecting the next year's crop.” –Washington Apple Grower “Look at what the market pays the most for, and that's what you want to grow. So it might be a small range of apple sizes with a high degree of color and you can afford to grow less of those, and have less fruit in total, but more of those. So if you just fill the trees up, you can have lots of bins of fruit, lots and lots of pounds per acre, but low quality. And then also if you have one perfect apple per acre, it's not gonna pay very many bills either. So it's a balance of yield with quality. You have to have both at the highest level possible to maximize your profit.” –Washington Apple Grower “Sophisticated mapping of the orchards at various times at high speed, is gonna do the biggest thing in terms of being able to more efficiently use and more productively use your labor.” - Washington Apple Grower

Crop Load Management Technology Categories

Pruning tools: When it comes to pruning, the primary goal of technology is to improve the quality of the completed task rather than reducing the time or resources required to accomplish it (due largely to the fact that labor is less constrained during pruning season). How effectively pruning is completed can have a significant impact on both yield and quality at harvest, and on the labor demands required during thinning and harvesting. Therefore there are significant gains to investing in pruning technology, however, it is also the crop load management task that is currently least concentrated on by both growers seeking tech and technologists themselves.

There are currently no commercially available tools specifically marketed for improvement of pruning beyond some mechanical pruners. Therefore adoption of pruning tech is essentially nil.

The possibilities for future pruning tools are significant. Growers and experts cited multiple possible ways that pruning tech could offer value in the orchard; the two biggest categories being tools that improve the effectiveness of hand labor and tools that replace hand-pruning altogether. The first category could include anything from new pruning strategies that remove some of the "art" from the pruning process, to orchard systems that make pruning more straightforward, to computer vision tools that show day laborers exactly where to cut with the precision of a trained horticulturist. In the second category, robotic pruners that can determine the optimal bud count and make precise cuts without damaging trees or infrastructure would be a desirable long term goal. Most solutions like these are still in an experimentation phase.

Chemical thinning tools: Chemical thinning, through the application of plant growth regulators (PGRs) as well as some other chemical and mechanical means, is a powerful labor-reduction tool during the labor-intense thinning process. Chemical thinning can significantly reduce the need to hand-remove blossoms and fruitlets below a certain size. The apple industry has pressed chemical companies to increase their focus on making chemical thinning tools more numerous and more effective, since most available products were originally formulated for other purposes. Though there is a sense among growers that there are too few chemical thinning tools available, there are more chemical thinners/PGRs available to Washington apple growers than to most other apple growers in the world.

Example offerings include:

- Valent Bioscience: Plant growth regulator products include PoMaxa and Accede.
- Fine America: Plant growth regulator products include Excilis 9.5 SC
- NovaSource: Makers of products including lime-sulfur solutions for chemical thinning

Plant growth regulators also extend beyond thinning, and some other tools are currently being explored which might offer valuable alternatives in the future. WSU researchers, for example, are exploring the possibilities of precision pollination, a process which could be (in application) similar to chemical thinning, though with the potential for improved results.

The vast majority of Washington apple growers utilize chemical thinning tools annually, with exceptions during years with unusually light fruit loads. The biggest challenge growers currently have with chemical thinning tools, apart from the lack of selection, is a lack of consistent effects in the orchard, which is to some significant extent impacted by plant physiology. These inconsistencies can prove extreme, where in some years growers might not see any appreciable effect of their thinning programs, while in others, the same application schedule might result in detrimental over-thinning. Though there is some level of understanding about the weather and plant health conditions that factor into chemical effectiveness, lack of application tools that can respond to variable conditions (like commercially-available precision sprayers) and other tools make the optimization of chemical sprayer very difficult.

Hand-thinning (blossom, fruitlet, green fruit) tools: Depending on the effectiveness of pruning and chemical thinning regiments, sometimes additional thinning must be carried out by hand, in a labor intensive and costly way. Optimizing when and how this work is done is critical not only to minimizing costs, but also to ensuring that growers can achieve their yield and quality goals. Currently, few tools are widely available to improve outcomes or reduce costs during this period.

Two general strategies are being pursued to address these challenges; 1) create computer vision and data analysis tools that can fine-tune hand-thinning activities to improve the effectiveness of labor while reducing costs; and 2) create a robotic/autonomous machine to take over mid- to late-season thinning tasks. These two strategies can also be understood as two steps towards an autonomous harvesting future, as effective computer vision and data analysis is a vital early step in preparing for a robot-ready orchard.

Example offerings in the realm of computer vision and crop load data analysis include:

- Fruitscout - Smartphone app for precision crop load management
- Pometa (Previously Farmvision) - Precision crop load management using computer vision
- Green Atlas - Machine-mounted precision crop load management vision system
- Vivid Machines - Machine-mounted precision crop load management vision system
- Outfield - Drone-based visual orchard management system

Adoption rates for these tools remain low, especially given that most of these options are in a relatively early or even pre-market phase. However, multiple Washington apple growers are experimenting with these tools and are interested in participating in pilot activities.

The near-term value proposition for these tools is two-fold. First, a data-driven accounting of current crop load can be invaluable for informing decisions about where thinning is most critical and how thinning activities should best be managed. Second, a more detailed understanding of fruit load, including some information around harvest time, quality, size, and yield, is valuable for growers to know as early as possible, both for planning marketing activities and labor requirements.

Crop Load Modeling tools: Determining and controlling a precise number of apples per tree is critical throughout the season right up until harvest, not only because of the yield and quality impacts in the current year, but also due to the impacts that current fruit loads have on future yields and quality. This work is done throughout the season, from pruning through to harvest, and can be done through manual bud, flower, and fruit counts and through computer vision and modeling tools. Three current models include the carbon balance model, fruit growth rate model (see the Malsium app), and the pollen tube growth model, which each aim to help growers predict and optimize the number of fruits per tree, though using these models can be expensive and time consuming.

The current commercial tech options are primarily focused much later in the season than the academic models, which emphasize prediction as early in the season as possible. Existing solutions aim to predict harvest factors like fruit size, maturity, firmness, dry matter, and color primarily in the weeks immediately prior to harvest.

Example offerings include:

- FruitSpec - ATV-mounted in-season fruit monitor
- Orchard Robotics - ATV-mounted in-season monitor, possible scouting solution in future
- Aerobotics - Drone scanning coupled with smartphone imagery
- Rubens Technologies - Hand-held harvest timing and fruit quality monitoring tools
- PixoFarm - Hand-held fruit count monitoring and harvest prediction tool

Though these tools are generally more simple to adopt than those that require significant investments in capital (e.g., new equipment, retrofitting machinery, etc.), the commercially available tools are still not very widely adopted in Washington orchards. The academic models are more likely to be utilized. As both commercial and academic models become more reliable and actionable earlier in the season, and results become less costly to access, growers are likely to be increasingly interested in utilizing these tools.

The value proposition of crop load modeling tools is evident– the earlier and more reliably crop load can be predicted and understood, the better decisions farmers can make around deploying resources, from pruners to chemical thinners to hand thinners to harvesters. This is true at every stage in the process, though the effect becomes more pronounced earlier in the season.

Barriers to Adoption of Crop Load Management Tech in Washington Orchards

Overall Opportunity for Growers: The key opportunities of adopting crop load management technologies are

1) yield and quality improvements related to optimized plant and fruit health

2) overall better seasonal labor demand planning due to more effective pruning and thinning activities

3) reduced input costs related to chemical thinning.

However, for most growers to realize these benefits, several barriers will have to be overcome.

Lack of commercially available options: All four categories of crop load management technologies suffer from a lack of available options– though some more than others. Of the four, pruning tools are the most unavailable, and will likely be so for the near-term. Hand thinning and fruit load monitoring tools are more available, though there are few options that are widely commercialized and considered reliable. Chemical thinning options are the most available, but there is still significant room for new entrants, especially those with products specifically tailored to the needs of Washington apple growers.

Lack of complementary technologies: Especially when it comes to chemical thinning tools, one of the key limiters to their effectiveness is the fact that there are no tools available to apply chemistries with a high degree of precision. This both requires a more significant investment in inputs and leads to imperfect chemical thinning, which often leads to greater need for hand thinning. Were it possible to apply thinning tools with greater precision, that could dramatically improve the efficacy of existing chemical solutions.

Lack of skill and confidence with complex data and decision-making*:* Much of the data that is currently available through crop load management tools is complex, and does not necessarily translate in a linear way into action. Therefore it takes both a measure of comfort with data analysis and some commitment to wanting to make more data-driven decisions to see the value of many existing crop load management technologies.

An extension of this issue is a lack of digital nativity amongst agronomists. Even growers who are not necessarily crunching data themselves, and are instead relying fully or in part on an outside agronomist, often struggle to derive value from existing crop load management tools. This is in part because of the newness of the data types, but also to the limited digital training many agronomists receive today.

***Lack of proof points for ROI and risk analysis*:** Though it is widely accepted that successfully executing crop load management activities is *the* primary way to make or lose money in the orchard, it remains incredibly difficult to link specific decisions to specific outcomes. From pruning through to harvest, a near infinite amount of variables are at play, so to determine that a tool that improved pruning outcomes or finessed bloom count led directly to more yield, higher quality, or less labor is challenging. As this category develops, finding creative ways to calculate and prove ROI and risk avoidance will be vital.

Application constraints of existing technologies: Though some attention has been paid to the idea of monitoring and managing crop load at the individual tree level, the current technologies are not capable of doing that in cost- and time-efficient ways. Current tech can map blossoms (and in some cases, fruitlets) at the tree-level, but serving that information up in a timely and accurate - and ultimately actionable - way for chemical or hand-thinning is not currently possible.

Value proposition: Especially when it comes to data and vision systems in the realm of fruit load monitoring, there is still at times a lack of clarity around the value proposition to the grower, and whether available technologies actually deliver the promised value in a timely and affordable manner.

Crop Load Management Technology Strategies

An increase in engagement with, and adoption of, crop load management technologies is possible in the next two to five years.

To enhance the impactfulness of existing crop load management technologies and to further commercialization, WTFRC should consider pursuing the following strategies:

Incentivize research on the precision application of plant growth regulators. In terms of improving the efficacy of existing chemical thinning products and getting the most out of cutting edge tools (i.e. precision pollination), determining a more precise method of application, specifically at the blossom or cluster level, will be critically important.

End Goal: Improve the effectiveness of existing chemical thinning tools to reduce labor and input costs.

Priority: 2

Example Activities:

- Fund research to advance computer vision tools that can identify and address individual clusters and blossoms.
- Organize, and incentivize participation in, convenings of technologists and growers focused on collaboration, technology integration, and de-siloing.
- Provide funding/support to third-party researchers to quantify the value of precision application technologies as they emerge.
- Pursue research to understand how additional control / optimization of plant physiology can improve crop load management practices and technologies.

Advance the availability and effectiveness of crop load modeling tools, with special emphasis on early season prediction. Being able to understand and accurately predict the number of apples per tree as early in the season as possible is critical to maximizing returns and controlling costs during the crop load management process. Technologists have, to this point, largely focused on analyzing and modeling data from relatively late in the season, but there are significant gains to pressing innovators to address refined prediction as early in the season as possible.

End Goal: Farmers have access to high quality data around crop load management as early in the season as possible.

Priority: 1

Example Activities:

- Co-sponsor a competition encouraging crop load management technologists and researchers to offer predictions as early in the season as possible.
- Support technologists and researchers in making crop load management prediction models open source/publicly accessible.
- Support third-party research projects to verify the efficacy of existing crop load modeling tools.
- Fund research focused on connecting crop load management data interseasonally and refining pruning sampling methodologies to better identify fruiting versus vegetative nodes without extensive lab sampling.

Incentivize research and development work in pruning technology. If a grower can execute a finely-tuned pruning strategy well, significant impacts later in the season in terms of both improved yield and quality and reduced thinning costs occur. But pruning remains one of the least studied and technologically-advanced parts of the crop load management process. Creating a special research emphasis will highlight how critical this aspect of crop load management is to the industry.

End Goal: Increase the amount of technologists creating tools to advance pruning efficiency.

Priority: 1

Example Activities:

- Develop and disseminate content that highlights the need for further academic and commercial focus on pruning technologies; where possible, quantify the “prize” to be had for filling this gap.
- Execute targeted outreach, backed with a funding allocation, to encourage pruning tech work among key partners and collaborators.
- Fund research into faster differentiation between vegetative and fruiting buds for precision pruning applications.
- Promote exploratory research into the potential pruning-related benefits of specific tree training strategies.

Advance awareness of, and evidence for, the value of tech-enabled crop load management tools. Crop load management efforts and tasks are highly variable from orchard to orchard and even block to block, and growers often have conviction that common tools and models will not offer the right information or support to assist in decision-making in their particular circumstances. Engaging growers in a transparent conversation about what modern crop load management tools can do will be critical for advancing experimentation and adoption and creating momentum that fuels further innovation.

End Goal: Increase crop load management tool exploration and adoption among growers.

Priority: 3

Example Activities:

- Support third-party verification of claims made by existing crop load management technology providers, especially around return on investment and potential risks.
- Sponsor/support field days and workshops where farmers can interact and experiment with currently available crop load management tools.
- Pursue research that specifically quantifies the return-on-investment of existing and prospective crop load management tools in Washington orchards.
- Support the advancement of digital education in crop load management tools in state agronomic programs (WSU, etc.).

Short-list Priority: Harvesting Labor

Current Harvest Labor Technology Landscape

Harvesting labor is the single largest cost and single highest priority among the over 100 apple industry stakeholders in Washington State consulted for this project. At present, adoption of fully autonomous apple harvesting robots is minimal (trials and pilots only) and there are no commercially available apple harvesting robots. Instead, harvest is conducted manually. Yet, growers are facing annual labor shortages for some of the most labor-intensive seasonal tasks (picking/thinning/pruning), and the temporary foreign guest worker program (H-2A) is the only alternative.

For the purpose of this roadmap, harvest labor technology includes **Assistive Technologies**, **Labor Management Systems**, and **Harvesting Robots**.

Voices of the Industry
"I see that automated/mechanical harvesting is beyond years out... Yes, we need more focus on harvesting - but let's be realistic in what we need to focus on topics that have more potential for impact in the short term." - Industry vendor & service provider "I think everybody thought we'd be further along. I'm sure the people on that original committee who are, if they're still alive today, they're like, wow, we thought we would be leap years ahead of where we're at right now to try to replace people, and that's really what we have to do if we're gonna survive." – Washington Apple Grower "When the Washington State Tree Fruit Research Commission was formed, the primary rationale for the formation of it was to investigate the automation of harvesting because labor was short and people were not getting their crops harvested on a timely basis. And here we are 55 years later. And we're still trying to jump across that bridge." – Washington Apple Grower "Labor is the issue, and harvest is at the core of the labor issue." – Washington Apple Grower

Harvest Labor Technology Categories

Assistive Technologies include software enabled harvest-assist platforms and other worker-assistive technologies, such as crop transport systems or virtual reality (VR) assistive headsets. Harvest platforms have been around since the 1990s, and have been used to increase hand-harvest efficiency and to eliminate ladder usage for pickers. They have been exhibited to show at least a 30% savings in labor hours required for harvest, and, when coupled with electric shears, a similar savings in pruning (Verbiest et al. 2020.) There are a wide range of platforms available on the market today (examples provided below.)

Looking forward, there is an opportunity to leverage digital technologies to increase the already proven value of harvest platforms through simple upgrades like variable rate cruise control. There are also opportunities to bridge the gap between today's harvesting robotics technologies (vision in particular) and the harvesting robotics technology of the future via increased data capture.

There are also opportunities beyond platforms to leverage technologies that increase worker efficiency, whether that is through VR training programs to decrease onboarding times and costs, human-operated hardware systems, or bin transportation systems.

Example offerings include:

Harvest Platforms:

- Automated Ag Systems'Bandit harvesters (multiple products)
- Huron Fruit Systems' Work Platform (simple harvesting and pruning platform)
- Provide Agro's Chariot (simple harvesting and pruning platform)
- N. Blosi's Zip 30 (simple harvesting and pruning platform - basically a scissor lift)
- Orsi Groups' Lifitng Platforms (simple harvesting and pruning platforms)
- Blueline Manufacturing's Orchard Harvesting Platform (mid-complexity harvesting and pruning platform)
- Argiles AF-10 EVOLUTION (relatively complex harvesting and pruning platform)
- Munckof's Pluk-O-Trak (relatively complex harvesting and pruning platform)
- Oesco's Revo Piuma 4WD (relatively complex harvesting and pruning platform)

Harvest Assistant Technologies:

- Daxo Robotics
- Precise Manufacturing's Bin Haulers
- Huron Fruit System's Self-propelled Bin Shuttle

Relevant Research:

- *Bin-Dog* - Transports full apple bins autonomously, reducing need for forklift drivers.
- Stavros Vougioukas's work with "next-generation, robotic harvest-aid orchard platforms" (results are pre peer-review) - Opportunities to outfit platforms with low-tech technologies (eg/ variable rate cruise control) to increase worker efficiency incrementally.
- Manoj Karkee's work with harvesting robots and image libraries
- Ming Luo's work with soft-growing robots and "Design, Modeling, and Control of a Low-Cost and Rapid Response Soft-Growing Manipulator for Orchard Operation"

Labor management software systems will play a critical role in the short, mid, and long term in integrating all of the aforementioned technologies throughout this roadmap. Labor management software systems enable growers to get a handle on their costs on a per field/orchard basis, thus enabling individual growers to calculate the ROIs of various technology improvements and make the appropriate decisions for their operations. In the short term, labor management software provides a means to more efficiently deploy scarce labor resources and to assess the efficacy of readily available commercial technologies on individual operations. In the mid term, labor management software products will create a layer of data that is essential to better understand the true value that growers can capture from harvest labor assistive technologies. In the long term, these labor management technologies will provide a means to integrate humans and robotics in order to most efficiently deploy a blended workforce of the future.

Example offerings include:

Labor Management Systems - Timekeeping

- Pago - Ag labor platform designed to help Farms and Farm Labor Contractors with wages and labor law compliance; integrates with Ganaz
- FieldClock - Simple timekeeping software
- PickTrace -
- CropTracker -
- HeavyConnect - Food safety, worker timecard, and QA/QC-program compliance software

Labor Management Systems - HR/Compliance

- Ganaz - Workforce management platform to help ag and food processing employers recruit, retain, communicate, onboard, train and pay their workforce (H2A.) Integrates with multiple Timekeeping systems.
- Harvust - Farm worker onboarding and HR software
- Croft - Earlier stage H2A recruiter, incubated by Purdue & Dial Labs
- Seso* - H2A recruiter and compliance software

Labor Management Systems - Integrated Crop Management

- Dataphyll - RFID & software based orchard management and timekeeping platform
- Hectre - Orchard management and fruit sizing/quality assessment software

Harvesting Robots are the end goal. If it were possible to wave a magic wand and create a single technical solution to the harvest labor problem, most apple industry experts would build an affordable robot that can operate fully autonomously to harvest, thin, and prune apples with <4-5% fruit damage rates (current standard for hand harvest.) However, this has proven to be quite challenging, and it will likely take a long time to get there (see barriers, below) There are some quasi-commercial solutions that exist, but none are widely available or truly hardened. Most of the focus in the next 2-3 years for harvesting robots is therefore likely to be R&D focused.

Example offerings include:

- Advanced Farm* - Custom-built robotic harvesters for apples and strawberries
- Fresh Fruit Robotics* -
- Ripe Robotics
- Tevel
- Nanovel (not active in apples but claims that it translates easily)
- Aigritec (also does chem thinning)
- Milano Technical Group
- RIP: Abundant Robotics

Barriers to Adoption of Harvesting Technologies in Washington Orchards

Overall Opportunity for Growers: The key opportunities of adopting harvest labor technologies are:

1) Cutting back on demand for increasingly hard-to-come-by seasonable labor during peak times
2) Increasing the efficiency of the existing workforce via augmentations.
3) Inserting collaborative robots into the existing workforce to do manual labor in a cost-effective, safe manner, freeing human workers up for higher value tasks.

However, for most growers to seize these opportunities, several barriers will have to be overcome.

Technical Complexity. Apple harvesting is a complex task with many technically complex subtasks. Integration of components of the system (vision, end-effectors, fruit transport, bin transport) is non-trivial, and individual components of the system are co-dependent. Because startup companies in the space are facing strong incentives to deliver commercial solutions, solution providers are often starting from scratch, meaning that (a) there are many inefficiencies in use of resources and (b) it's easy to run out of money before delivering a market-ready solution. Splitting the problem into components can help to some extent with this, but if the system is broken up too much, stitching the puzzle back together will be impossible.

Expensive. The cost of purchasing and servicing apple harvesting technology is going to be a barrier for most growers.

Diversity within operations. Orchard architecture is highly variable in terms of controllable elements like trellising and genetics, and in terms of less controllable factors, like, climate, weather, slope, and soil type. Not all orchards are designed with the intent to be "robot ready." Furthermore, apple harvesting must integrate with Crop Load Management systems, which are constantly evolving/imperfect.

Assessing businesses as well as technologies requires expertise. It is presumed that the "solutions" to apple harvest automation will be commercial, yet there are countless reasons that commercial products fail. A technologist with a perfect technical solution may run his company into the ground because he's not a skillful businessperson, for example. Similarly, a well intended businessperson might convince funders to invest in his product, for which he knows there is a market opportunity, but he may never be able to actually build the product. Therefore, it's essential to vet commercial products from a variety of perspectives to understand the risks and opportunities of any one particular project.

Harvest Labor Technology Strategies

While limited access to, and high costs of, harvesting labor is a high priority for Washington growers, it is unlikely to be resolved overnight by a comprehensive robotic solution. Instead, a phased approach to automation and labor-assistance technologies can help fill the existing gap.

The following strategies have been identified to put Washington Tree Fruit Growers on a realistic pathway towards alleviating harvest labor pressures in the short term while enabling a more holistic robotic solution in the long term.

Lower the costs of developing commercially viable mechanical/autonomous apple harvesting solutions.

End Goal: Increase the amount of collaborations between technology developers, academic researchers, and commercial R&D providers to reduce duplication of efforts in the development of harvest labor solutions.

Priority: 1

Example Activities:

- Support the development of common technical infrastructure and/or trial infrastructure, including apple transfer systems and bin fillers.
- Catalyze collaboration and co-opetition (i.e., when competitors work together for mutual benefit) by requiring WTFRC grantees to attend in-person, facilitated meetings
- Develop and publish an index/library of 'what did/didn't work' in prior harvest labor efforts to enable future technology companies/vendors to accelerate their progress, and to optimize for shared learnings regardless of commercial outcome. Consider collaboration, for example, with efforts like the Agtech Toolkit.
- Ensure RFPs target specific gaps in the existing landscape and/or focus on integration challenges

Educate vendors and developers to ensure harvest labor solutions are designed to work within the operational and financial constraints of existing systems.

End Goal: Vendors come to market not just with technology that works, but that is also affordable and easily integrated into apple orchards

Priority: 2

Example Activities:

- Continue to publish and share data on apple orchard crop budgets and management systems (e.g., Agtech Toolkit, Apples.Extension.Org, etc.)
- Create and publish an industry "primer," or overview of the characteristics of the industry, to support developers to get up to speed (e.g., # acres, costs, pain points, etc.)
- Consider novel service models that enable the cost of harvesting equipment to be dispersed in a way that is profitable to farm operations of various types, and economically viable for technology providers.

Help WA apple growers get "robot ready"

End Goal: WA apple growers are able to take advantage of emerging harvest labor solutions with minimal negative commercial impacts/trade offs.

Priority: 3

Example Activities:

- Support research that investigates the genetics behind traits that are optimal for robot ready canopies (e.g., weeping, smaller leaves, easier chem thinning, control of fruit abscission, bruising sensitivity, maturation, etc.)
- Continue to support and publish standards for "robot ready canopies."
- Support cost-studies comparing robot ready canopies to other trellising systems for both manual, partially mechanical, and fully autonomous systems.

Update WTFRC's RFP processes to efficiently engage the appropriate experts in vetting new research and commercialization proposals.

End Goal: Ensure that limited resources for harvest labor solutions are appropriately and efficiently distributed, based on a range of required lenses for evaluating technologies (e.g., technical, industry, commercial, etc.) and development teams.

Priority: 2

Example Activities:

- Ensure proposals are evaluated by the list of expert consultants created for this project (or similar) and use their guidance to ensure validity of projects.
- Create streamlined application and feedback processes to enable multiple parties to easily view and comment on/rate RFP submissions.
- Outline specific criteria for applicants to meet, considering the broad range of required assessment factors, including technical need and readiness level, team capacity & capabilities, and relevance to the priorities outlined in this roadmap.

Case study: SmartOrchard

The Smart Orchard project in Grandview, WA is headed by Steve Mantel and the team at Innov8.ag, and aims to optimize resource utilization, reduce waste, and increase yields by "sensorizing" the orchard. The specific focus of the project is on irrigation, nutrients, soil health, and plant health, with the overall objective of creating a more sustainable and efficient orchard. The annual report for the project will be released in Q4 2023.

Project Goals and Technologies

2023 was the third year of the Smart Orchard project, and the first year the project has been carried out in its new location, where the orchard is more highly variable in terms of terrain, topography, and plant and soil health. A focus in the past three seasons was to bring in a variety of commercially available sensors, from simplistic to highly complex, to experiment with what is currently possible in terms of data collection, processing, relatability, and return on investment. Specific goals for the 2023 season were to isolate irrigation and chemical thinning task maps to inform variable rate applications. Engaging with both University and commercial researchers was also a target outcome.

Tools and technologies in use:

- LiDAR
- Green Atlas Cartographer
- Smart Apply Intelligent Spray Control System
- Swan Systems
- Burrow Tractors

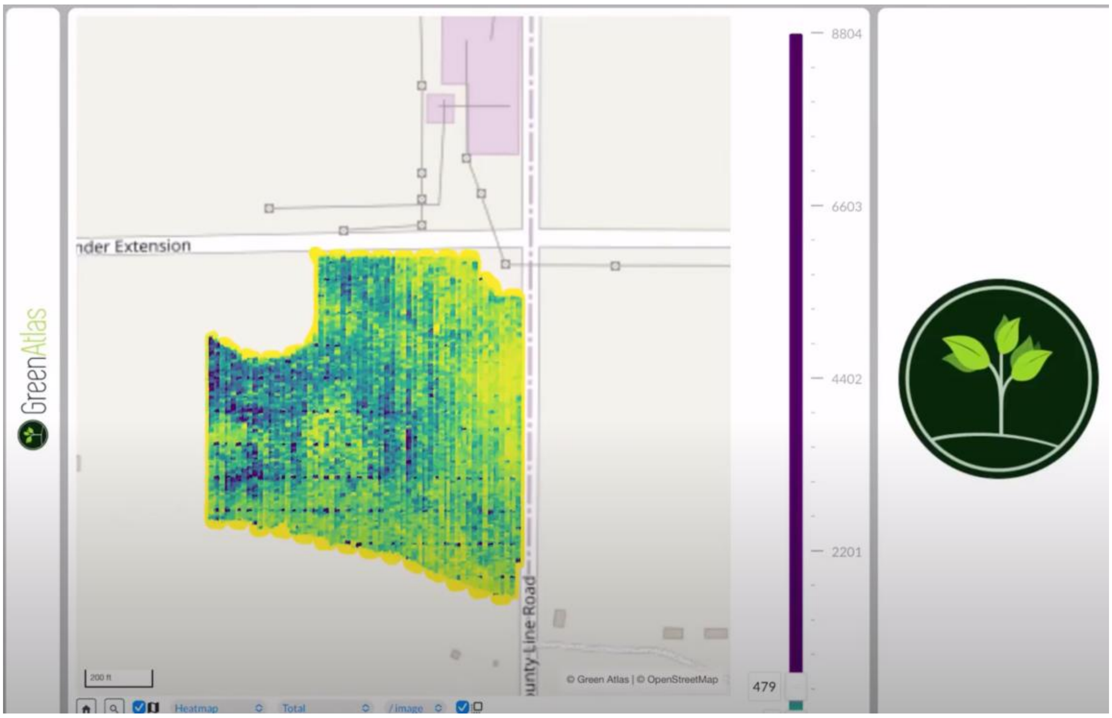
Shifting Orchard Locations

Correlating input data to yield was an early goal, but the project met with limitations when annual yield data was not widely accurate or readily available after the first season. This lack of information led to a heavier focus on crop load management tools in the second season, to allow researchers to be able to understand yield and quality impacts more immediately throughout the growing season. Green Atlas was the main partner that could provide crop load management data in-season in 2022. However, though crop load management data was collected in 2022, it was largely not actionable because of highly uniform conditions within the orchard which meant that the goal of separating the orchard into different management zones was not achieved. This uniformity prompted the move to the new location in 2023– an older, more variable Honey Crisp orchard– and led to the closure of the previous location.

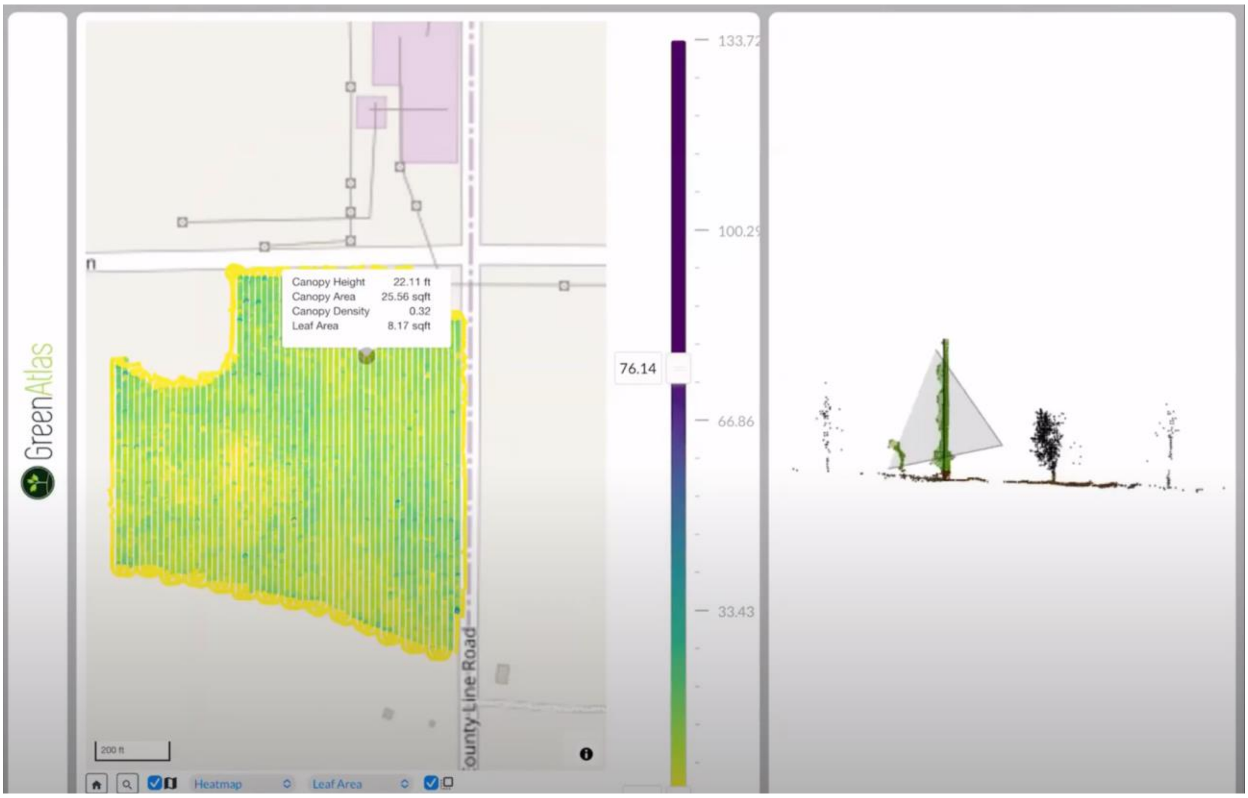
2023 Focus Areas and Early Results

Extensive crop load management data was available from the test orchard throughout the 2023 season, from cluster numbers to leaf area to fruit color index, and total apple counts per acre.

Blossom Density



Lidar imagery of actual tree on right, selected from map on left



Map to tree image

Computer vision zoom identifying blossoms

Additional focuses in 2023 were mapping, irrigation optimization, fertility optimization, and spray optimization, with a particular goal of creating zones to adopt more precise prescriptions. Five applications of a chemical thinner were done with greater precision, with the test area of the orchard isolated into three zones targeted with three different application levels ("high," "medium," and "low" application rates). To accomplish this, the grower did have to make three different passes through the field to apply at three different rates due to the immaturity of precision spray tools for orchards. The team did witness a noticeable increase in uniformity among cluster size across the three zones as compared to the control sections.

Laying the groundwork for automation

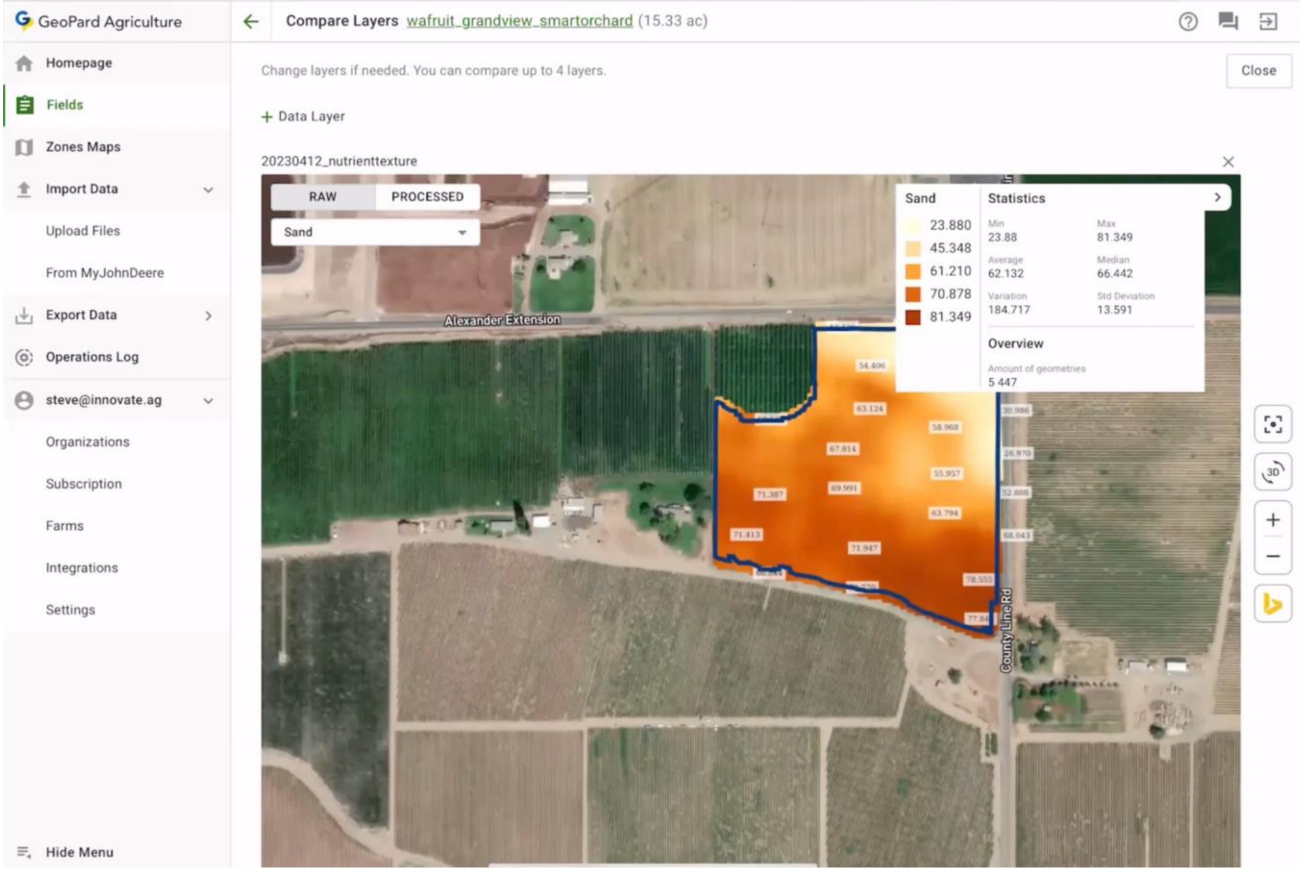
Bringing together different layers of data to make them all more relevant to growers is another key goal of this project. The team has been able to visualize inter-seasonal data around bi-annual bearing characteristics for Honey Crisps (see image below). This information can be translated into labor maps to advise with precision on intensity of pruning (which has led to consideration of other possible solutions, like marking the ground with green paint in front of “light prune” trees and with red paint for “heavy prune”). In a larger sense, however, this data makes a strong argument for developing and adopting tools and tech that can facilitate precision pruning. In other words, this kind of data is ready to be automated.

Top left shows yield density in 2023, top right yield density in 2022, and bottom shows yield density in 2021

Irrigation Experiments

On the irrigation side, the Innov8.ag team worked with SWAN Systems to pull in irrigation data, which was then overlaid with soil type data and the crop coefficient for the specific variety in the specific location, tied in with satellite imagery and weather forecasts to create additional advice for irrigation sets in a coming week.

Soil map data for the SmartOrchard site for integration with irrigation data



Takeaways and Areas for Improvement

The work of Innov8.ag provides a powerful, third-party perspective on the usability and usefulness of some of the commercially available tools, especially in the irrigation and crop load management spaces. It is valuable for the commission to have access to the findings of the SmartOrchard. Additionally, the project has served as a valuable convening tool, bringing together farmers and other stakeholders, and those in need of training, to share ideas and envision the future of technology in the industry. Growers too have gained some insight on soil type and prospective layout of future plantings, especially at the current Washington site, where the orchard will be replaced after the current season.

However, a few key improvements should be made to the project going forward.

1) **Representative site(s).** The SmartOrchard in 2023 operated in a very mature orchard. Going forward, finding a more representative orchard where the project can remain for a period of years or decades will be key to developing and verifying the results of inter-season data. Maintaining one or a few representative sites in the long term will increase the usability of the results for growers, and likely increase the intangible benefits of the orchard as a convening space.
2) **Focus.** Determining extremely clear and limited in-season goals with this project, and perhaps even curbing the number of questions under exploration at a given time, will likely result in more actionable results for growers. For example, though advanced irrigation tools and sensors have been in place in SmartOrchards at their various locations since the first season, many variables were being manipulated simultaneously, muddling the actionability of insights and replicability of results. Identifying a season in which the

only variable to be experimented with is water (as manipulated and tracked through various tools), for example, could yield more usable information than proceeding with a broad slate of variables and goals each season.

3) **Identifying areas for future work and collaboration.** The usability and applicability of SmartOrchard findings seem to be limited by two main factors: 1) the digital nativity of farm managers and agronomists; and 2) the availability of tools that facilitate precision activities.
    a) **Digital nativity.** In the first case, the Innov8.ag team has developed the ability to convert massive amounts of data into visualizations that could allow growers to isolate problem areas of the orchard, develop fine-tuned management plans, and understand in-orchard nuances at a granular level. To take full advantage of this, however, decisions-makers need to have advanced digital data processing and analysis skills.
    b) **Equipment to action recommendations.** In the second case, though Innov8.ag has made interesting advances in linking and overlaying data and being able to convert that data into shape files and tasks that could be carried out by precision equipment, there is an absence of precision equipment in the orchard space that can utilize those files to carry out those tasks. This is true in irrigation, nutrient and chemical application, and crop load management.

These limitations suggest that there must also be focus on closing gaps that exist beyond the scope of this project before the full benefits of SmartOrchard work can be realized by Washington growers.

Communications Plan

Key Messages for Key Audiences

- **Researchers & extension** - here's how you can best help the industry
- **Government** - here's what's top of mind and important to our industry
- **Growers** - we heard you! Here's our focus to solve these problems
- **Vendors and service providers** - Our industry is "open for business" and we want to work with you! We also need your help to make better solutions and improve existing offerings; here are our priorities, and some untapped opportunities

Key Artifacts

Format	Audiences	Notes
Trends & Barriers 3x Priorities 1x Case Study (PDFs)	All	• Each PDF to be published on WTFRC website, and downloadable • Some emphasis on aesthetics- visually engaging, easy to navigate, etc. - but more focus on content. • Future RFP applicants in particular will use this full version to shape their proposals and ensure they are aligned with identified WTFRC priorities
~2 page Executive summary (PDF)	Government	• Short, clear overview of the identified shortlisted areas and prioritized strategies within each • This document will **not** have an intro, all the details on methodology, etc. - just the shortlisted areas and prioritized activities within each
Executive summary and key findings/ messages (PPT)	All (growers - 1st priority)	• Present-able version of the roadmap (i.e., shortlisted areas and prioritized strategies within each) that WTFRC staff can use to "roll out" the roadmap • The presentation should take no more than 30 minutes • Notes and/or a voiceover will be provided to cover off key messages • This presentation will only have a very brief intro & methodology
Full Report (word doc)	WTFRC	• Editable version so WTFRC can make changes as needed • This version will **not** have any aesthetics but will have all the content

We also recommend that WTFRC create a landing page on the website for stakeholders to learn more about the roadmap, and download more materials. This page would contain a short description of the roadmap and the "why" behind it, as well as the key messages/findings. While we are happy to support the creation of such a page, WTFRC will be responsible for it.

Appendix - Non-prioritized strategies and activities

Baselining and ongoing data collection: Understanding how widespread the interest in, and adoption of, technologies is, is critical for ensuring the roadmap is not only on track, but also for measuring impacts

Techniques to control bruising during picking and thinning.

Quick and dirty commercial rootstock testing

Acquire IP from technology companies that have gone out of business, and make it available to others

Collaborate with irrigation districts, e.g., around development of holding ponds to save unused water

Support sociology/psychology research into the social aspects of technology adoption

In recognition of the fact that startup technology developers often require venture capital funding, the industry could play a role in helping companies attract money, e.g., education to ensure growers know the value of being champions and providing investor-facing support