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Vegetative Precision Propagation: Sensor Platform Year 2 Final Report



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EXECUTIVE SUMMARY

The opportunity

Greenhouse propagation of *Pinus radiata* seedlings is affected by spatial and temporal variation in temperature, humidity, light, airflow and root-zone conditions. Although greenhouses are often managed as uniform production spaces, this work shows that localised microclimates can develop within the same greenhouse and may contribute to uneven germination, seedling growth and root development. This study provides an opportunity to use sensor-based monitoring to identify and quantify these micro-environmental differences, both known and unknown, and provide a practical foundation for more precise, data-driven nursery management.

Key results

This project successfully established and expanded an integrated environmental monitoring platform comprising the greenhouse mobile sensor array (**GREENs**), the soil monitoring network (**RHIZONET**), the plant canopy sensors (**CANOPY**) and the environmental database (**ENVIROBase**) that brings all the datasets together. GREENs demonstrated that the greenhouse environment was not uniform, with repeatable temperature, humidity and photosynthetically active radiation patterns occurring across the greenhouse throughout the day. Localised hotspots reached approximately 30˚C, while cooler and more humid zones were associated with the wet wall and shaded greenhouse areas. Light measurements also varied over short distances, indicating structural shading and solar angle, creating fine-scale differences in light exposure.

RHIZONET and CANOPY extended monitoring to the plant scale by measuring root-zone and plant canopy conditions around seedlings. The pilot trial provided preliminary biological evidence that these microsite differences may influence early *P. radiata* development. Germination rate differences were relatively small and non-significant, but seedling height, crown diameter and root traits varied among microsites. Root diameter decreased with an increase in root-zone temperature, with significantly greater root diameter in the northeast location near the wet wall, where it is cooler, than in the southeast and centre locations, while warmer root-zone conditions were associated with finer roots. These findings indicate that greenhouse microsites can influence different aspects of seedling growth performance.

The Nursery Survey identified rooting, mother plant management and environmental variability as the principal industry challenges and revealed substantial variation in technological maturity among the nurseries.

Implications for the industry

- The GREENS platform demonstrated that greenhouse microclimate variability can be objectively quantified. This supports the next stage of development and validation of a lightweight commercial monitoring system that translates the research platform into a practical tool for commercial forest nurseries.
- RHIZONET and CANOPY demonstrated that root-zone and plant canopy microclimates can be objectively monitored and related to early seedling performance. These platforms provide the foundation for developing practical monitoring tools and modular production systems for Fast Rooting and Mother Plant management in commercial nurseries.
- ENVIROBase established the data infrastructure required to integrate greenhouse, canopy and root-zone information into a unified platform. This will support environmental modelling and practical decision-support tools for commercial forest nurseries.
- The nursery survey confirmed that the project's research direction addresses key industry challenges while helping to prioritise future developments. These findings highlight the need for modular technologies that can be progressively adopted across nurseries with different production systems, while reinforcing the importance of a comprehensive Techno-Economic Analysis (TEA) to objectively evaluate technology adoption pathways.

Future work

- Consolidate and streamline the sensor platform through a robust, replicated greenhouse experiment integrating GREENS, RHIZONET, CANOPY, ENVIROBase and PINE-EYE (from the Imaging Technologies task).
- Develop and validate plant-environment models linking greenhouse microclimates with germination, seedling growth, rooting and plant quality.
- Evaluate the suitability of forest greenhouses for vertical farming and quantify their productive potential and infrastructure requirements.
- Translate the research platform into a lightweight prototype monitoring system that can be evaluated in partnership with greenhouse technology providers and commercial nurseries.
- Continue developing modular production systems, including Fast Rooting and Mother Plant modules, as part of the long-term Greenhouses of the Future strategy.

INTRODUCTION

Increasing high-quality *Pinus radiata* (D. Don) seedling production requires more uniform growing conditions across the greenhouse systems. Although greenhouses provide greater environmental control than outdoor production systems, conditions within them remain spatially and temporally heterogeneous, with temperature, relative humidity, light, airflow, and substrate moisture varying across the production space. This variation can create distinct microenvironments that influence germination, rooting, survival and early growth, resulting in uneven seedling development. Homogenising these greenhouse conditions therefore requires spatially explicit environmental monitoring that can identify where and when microenvironmental heterogeneity occurs and provide the information needed to support more consistent and productive propagation outcomes. However, to date, this has rarely been explored for integration into semi-automatic forest tree nursery shade/greenhouse systems.

The Precision Propagation's **Micro-climate modelling and control via a mobile Sensor platform** milestone was developed to address this knowledge gap by establishing an environmental monitoring platform in a greenhouse environment. The platform is designed to capture fine-scale temperature and humidity patterns via a moving platform structure, sensors, data pipelines and data storage infrastructure. By collecting environmental data at multiple positions, the platform provides a basis for identifying when and where microenvironments evolve and for linking these patterns to greenhouse management decisions and future propagation protocols. This will allow for an optimally designed prototype for industry testing, creating opportunities to complement the Imaging Technology work stream that was developed to monitor germination and seedling growth.

The sensor platform contributes to the wider programme goal of improving *P. radiata* propagation by moving greenhouse management from broad, assumed conditions toward measured, spatially explicit and temporally resolved environmental information. Preliminary mapping of internal greenhouse conditions can reveal persistent hot, cool, dry or humid zones, as well as daily and seasonal shifts associated with greenhouse controls such as fans, wet walls, sprinklers and ventilation. This information is important for interpreting germination and seedling growth responses, improving experimental design, and identifying practical opportunities to reduce unwanted variability across greenhouse crops. This new knowledge will enable fit-for-purpose sensing systems that will optimise indoor propagation for forestry crops.

This milestone focused on the establishment of an environmental platform prototype in a greenhouse to closely monitor microenvironments (such as temperature, light and humidity) as well as plant environments in soil and surrounding air. The contracted deliverables were:

(1) Expand the mobile sensor platform to provide three modules to cover the greenhouse more fully (hereafter called GREENs);

(2) Expand and further develop the environmental sensor platform to include plant microenvironments in soil/potting media (Rhizosphere Observation Network, RHIZONET) and plant microclimates around the plant itself (CANOPY);

(3) Develop an environmental database to collect, store and integrate data from the above sensor platforms;

(4) Conduct a nursery survey to gather information on key issues in containerised nursery production to identify key production challenges, environmental management practices, and technology adoption (reported in the Sensor Platform Interim report (Corbett-Lad, Salekin, Siqueira, & Salvatierra, 2026) and Imaging Technologies final report (Siqueira, Grant, Dunn, & Salvatierra, 2026)).

These deliverables will provide the preliminary mapping of where and when greenhouse microenvironments evolve over time and space. Together with seedling trials, they provide the technical and biological foundation for a data-driven approach to greenhouse environmental characterisation.

METHODS AND MATERIALS

An integrated environmental monitoring platform was custom-developed in a research greenhouse to characterise the microclimate variation within the greenhouse at multiple scales. The platform comprises three complementary components. Firstly, the greenhouse environmental sensing system (GREENs) which measures the environment of the greenhouse. The second component is the rhizosphere observation network (RHIZONET), which is positioned within the container of germinating seeds and the root zone of seedlings. The third component is the canopy observation network (hereafter CANOPY), which measures the immediate surroundings of seedlings. The real-time data collected from GREENs, CANOPY and RHIZONET is consolidated into an environmental database, which we refer to as ENVIROBase.

Together, these systems were designed to capture the internal greenhouse, above-container, and within-container environments experienced by greenhouse plants. Measurements of air temperature, relative humidity, photosynthetically active radiation, light intensity, carbon dioxide, leaf wetness, substrate temperature, volumetric water content and electrical conductivity were used to identify where and when microclimatic conditions varied within the greenhouse. The resulting data provide a basis for assessing the effects of greenhouse controls, understanding plant-scale environmental variation, and supporting future development of environmental management strategies that improve seedling growth, quality and uniformity.

(1) Sensor platform expansion

Experimental greenhouse

The study site is in the Bioeconomy Science Institute – Scion Group's K3 greenhouse. The greenhouse is 9.1m wide, 20.9m long, and 5.5m at its highest point. The greenhouse is aligned from northwest to southeast. The east wall faces an open field, while the other three walls adjoin other greenhouses. A meteorological station is located ~95 m northeast of the study nursery.

Temperature, humidity and photosynthetically active radiation (PAR, µmol/m²/s) data were collected from the nursery's local meteorological station. The sensors are connected to a

Campbell Scientific data logger (Campbell Scientific Inc., Utah, USA) which sends data to a web-based platform hosted by Scott Tech (Hamilton, New Zealand) called *Envirodata*, where it can be downloaded remotely (Figure 1).



Figure 1 *Study greenhouse and meteorological station*

Sensor platform installation in the greenhouse

The greenhouse environmental sensing system (referred to as GREENs hereon in) consists of three moving platforms developed and adapted by *Jupiter II Light Movers* with a total of 116 SenseCAP *S2101* combined temperature and humidity sensors and 6 SenseCAP *Industrial photosynthetically active radiation* sensors (PAR). Sensors were attached at 1m intervals both vertically and horizontally, allowing GREENs to provide coverage across the entire greenhouse (Figure 2). More information about the Jupiter II light mover and the additional build alterations required to build the three platforms in Appendix A.



Figure 2 *Three moving sensor platforms that make up GREENs in the experimental greenhouse.*

GREENs used air temperature, relative humidity and photosynthetically active radiation (PAR) sensors (refer to Appendix B for more information). These battery-powered wireless LoRaWAN sensors include Bluetooth connectivity for direct configuration through the Sense craft application. Each sensor was configured to connect to Scion's LoRaWAN network to enable remote device management and automated data transfer from the greenhouse (Figure 6).

PAR was used instead of light because this measure represents the exact wavelengths needed to fuel photosynthesis, create sugars, and drive growth, whereas light is a measure of brightness as perceived by the human eye. The human eye is most sensitive to green and yellow light, which are highly visible but inefficiently used by plants. The PAR sensor was selected because it can operate across the full humidity range experienced in the experimental greenhouse, from 0 to 100% relative humidity (Figure 6).

The sensor is designed for environmental monitoring applications, including smart farming and cold-chain systems, and is suitable for use in greenhouse environments. Sensor readings were transmitted via LoRaWAN and managed through the ChirpStack application server, and stored in Influx DB with automated downloads scheduled to a local server for storage and analysis (refer to Appendix C for more information about data flow).



Figure 3 *GREENs sensors*

Greenhouse Environmental Controls

The control systems in the greenhouse comprised two fans mounted on the southeast wall and a wet wall mounted on the northwest wall. Under normal operation, both controls are activated by a single sensor when the greenhouse air temperature reaches 22°C. There is no irrigation system (so plants are watered by hand using a garden hose or watering cans), and the roof is not capable of passive ventilation (i.e. a sealed roof design) (Figure 7).

To assess the contribution of each control to reducing spatial and temporal variation in indoor conditions, the wet wall and fans were tested independently. Each treatment was initiated at 3:00 pm and maintained continuously for one week. The trial consisted of four phases: no manual controls, fans operating only, wet wall operating only and all controls operating (Table 1).

Temperature and humidity data at 00:00 am, 06:00 am, 12:00 pm, and 18:00 pm were chosen to realise the shape of the diurnal temperature and humidity cycle. Values were averaged across the study period for each greenhouse platform. The data was interpolated using ordinary kriging to visualise the horizontal and vertical diurnal fluctuations of the internal greenhouse environment.

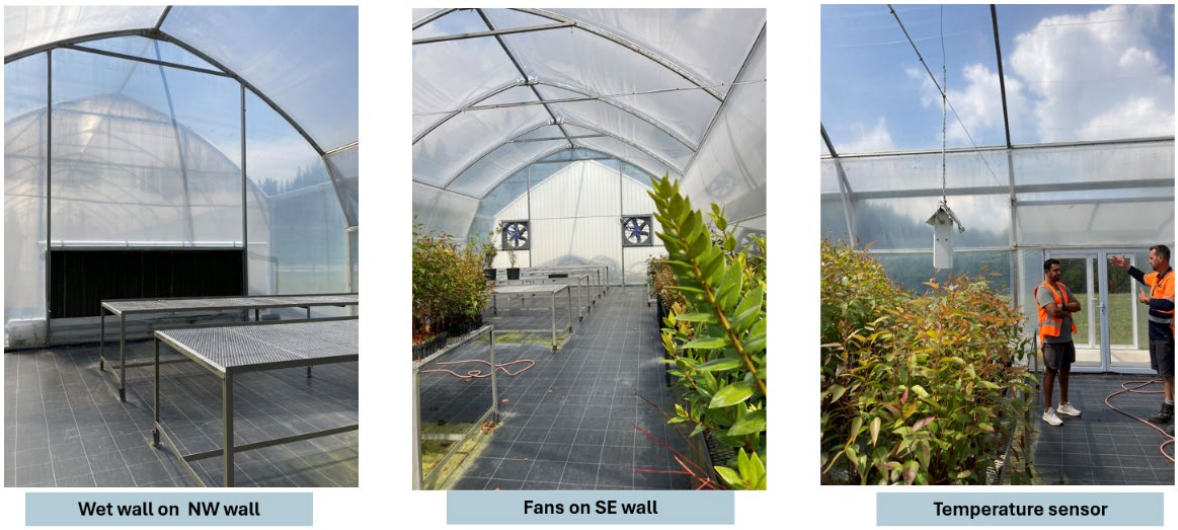


Figure 4 *Controls in the greenhouse*

(2) Expansion of the greenhouse environmental sensor platform

The GREENs platform was expanded to include the *Rhizosphere Observation Network* (RHIZONET) and *Canopy Observation Network* (CANOPY), which together characterise the in-soil and immediate surrounding microclimates experienced by seedlings. RHIZONET comprises combined soil temperature, volumetric water content and electrical conductivity sensors installed within the seedling root zone, while CANOPY comprises light-intensity, photosynthetically active radiation, leaf-wetness, and combined air temperature, humidity and CO_2 sensors. Ten paired RHIZONET and CANOPY clusters are active, five of which are located at representative greenhouse microclimates in each corner and the centre of the greenhouse (Figures 8 and 11). These measurements quantify environmental conditions influencing root-zone water availability, plant stress, photosynthesis, seedling growth and production. Both networks use the LoRaWAN, ChirpStack and local-server data-management workflow, which can be found in Appendix C. Sensor specifications are provided in Appendix B.

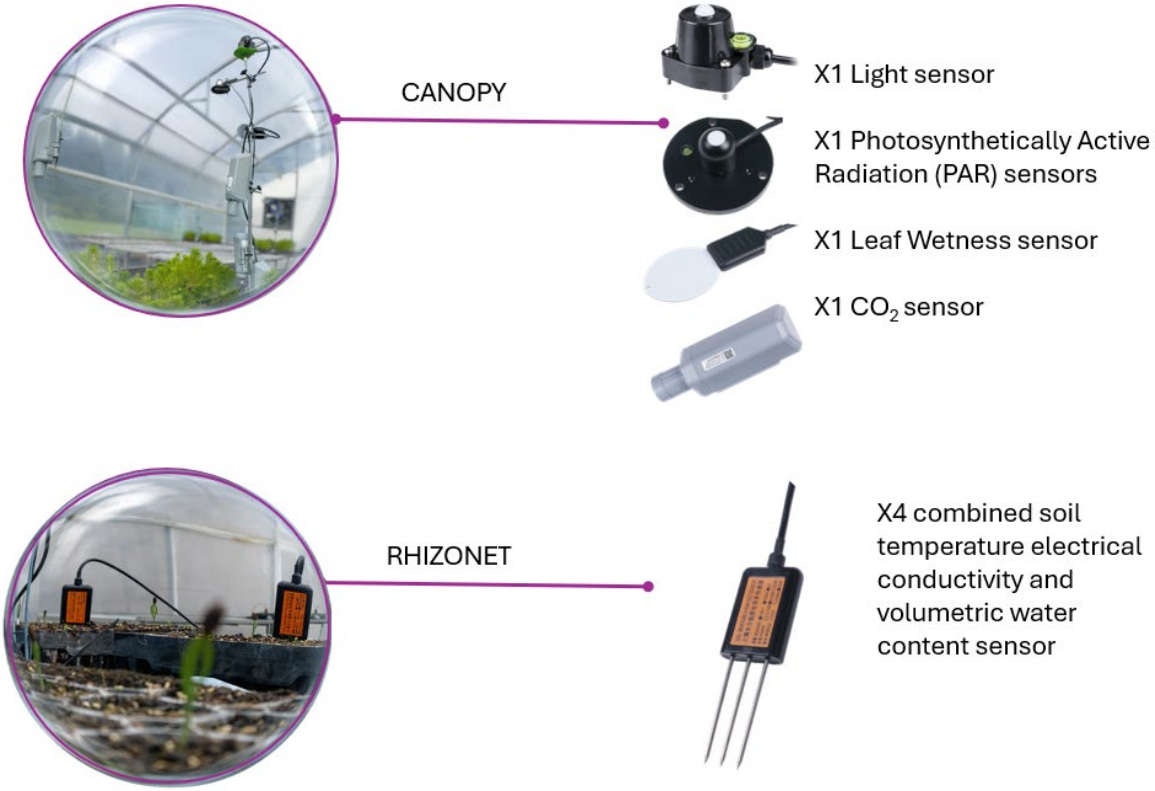


Figure 5 *Sensors making up each RHIZONET and CANOPY cluster*

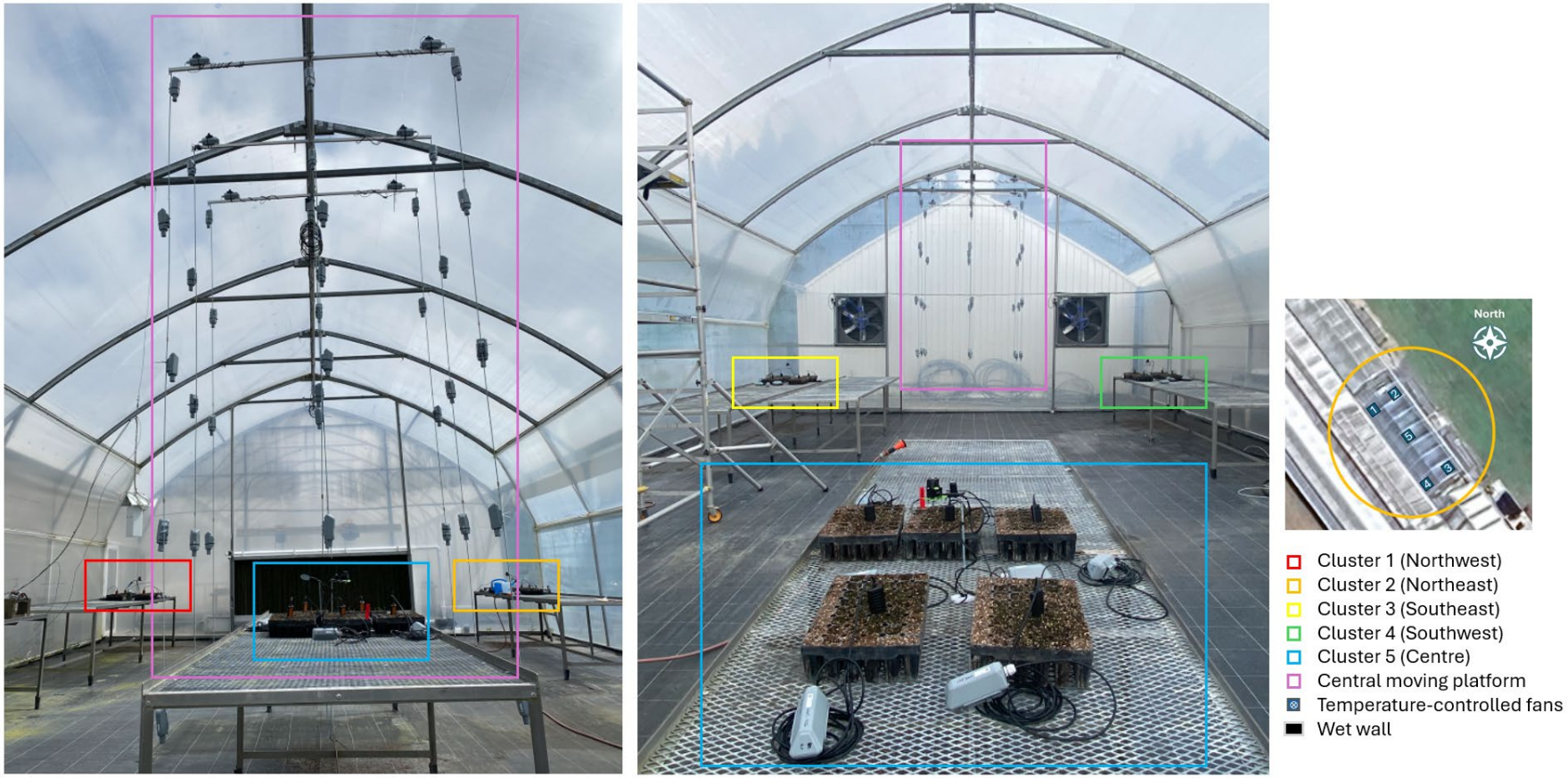


Figure 6 Experimental greenhouse location and CANOPY and RHIZONET microenvironment placements.

(3) Environmental database

ENVIROBase is the project's central environmental-data repository, designed to bring together greenhouse, canopy and root-zone measurements collected by GREENs, RHIZONET and CANOPY. Sensor data are transmitted through Scion's LoRaWAN network to ChirpStack, an application server designed to manage LoRaWAN sensor networks, decode incoming measurements and route them to downstream systems. ChirpStack does not provide long-term storage (Refer to APPENDIX C for data flow). Instead, it transfers the processed sensor data to InfluxDB, a time-series database designed to store, organise and retrieve large volumes of continuously collected environmental data.

InfluxDB forms the current technical foundation of ENVIROBase. It enables data from multiple sensor types and locations to be stored in a common structure and queried across time and space. This provides the project with a research-ready platform for detecting environmental trends, identifying recurring microsites and gradients, checking data quality, and exploring relationships among greenhouse conditions, root-zone conditions and seedling performance.

Pilot experiments on the impact of microclimates on germination and growth

To date, we have anecdotal evidence that greenhouse microsite variability affects seedling growth and germination of *P. radiata*. This pilot trial was set up to quantify at a high level if greenhouse microclimatic conditions influence seed germination and growth during early developmental stages.

Seed source and preparation

Pine cones from *P. radiata* were collected and air-dried to facilitate seed extraction. The open pollinated seeds were cleaned and subjected to cool, moist stratification at 4°C for three weeks, then sown in propagation trays (125cm^3 with 48 cells) filled with standard potting mix composed of pine bark, coco fibre and pumice 3mm (45: 30: 25 v/v) and amended with a slow-release fertiliser.

Watering regime

Watering frequency was initially set to twice weekly (Monday and Friday) prior to germination and increased to three times weekly (Monday, Wednesday and Friday) as plant demand increased post-germination. To maintain consistency during watering, the control tray in microclimate 5 (centre of the greenhouse) was weighed at field capacity at the beginning of the experiment (day 0) and then again on subsequent watering days. The difference between the initial field-capacity weight and weight loss on watering days was used to measure the amount of water each tray would receive, assuming 1kg mass loss = 1 L of water.

Capturing seed germination

Germination was recorded on days 0, 29 and 51 by counting the total number of sprouted seeds in each tray. After 51 days, seedling height (cm) and crown diameter (mm) were measured until the end of the study period.



Figure 7 *Growth in the central micro-environment (5) on 25th September*

Capturing root biomass (root growth)

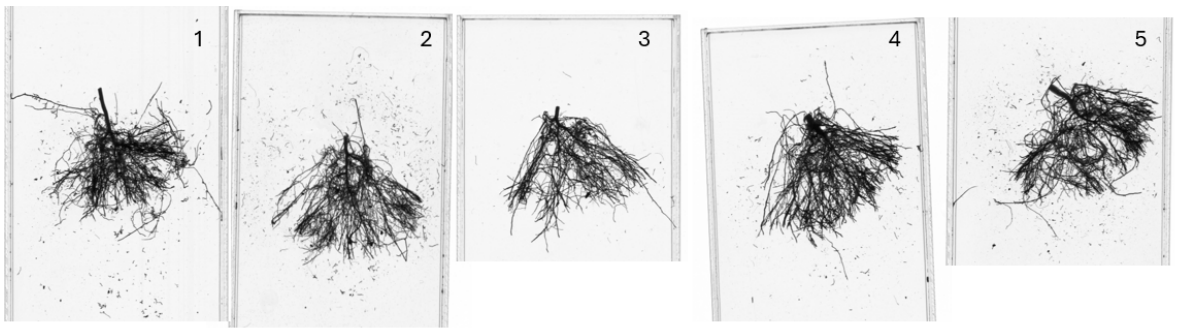


Figure 8 *Examples of root scans from each of the five microenvironments*

On 4th March 2026, 3 seedlings from the pilot trial were destructively sampled from each of four trays within five representative greenhouse clusters. Root systems were carefully washed to remove all substrate before scanning with the WinRHIZO image analysis system to quantify root length, surface area, average diameter, root volume and the number of root tips. Following the scan, roots were weighed for fresh biomass, dried to determine root dry weight, and seedling height and stem diameter were also recorded.

(4) The nursery survey

To ensure that the development of *Micro-climate modelling and control via Sensor Platform* milestone aligns with current industry needs, a nursery survey was undertaken to identify key production challenges, environmental practices, and technology adoptions in New Zealand forest nurseries. The survey methodology and comprehensive results were presented in the *Imaging Technologies Interim and Final Reports* (Siquiera *et al.* 2026a, b) and are therefore not repeated here. Only the findings directly relevant to the development of the micro-climate modelling and control via a sensor platform are summarised in this report.

RESULTS

(1) Mapping internal greenhouse variability using GREENs

As previous analysis has shown, there is significant internal variability in the greenhouse environment. This analysis provides a simple but useful first step towards identifying where environmental variability occurs within the greenhouse. Rather than considering the greenhouse as a uniform growing space, the maps in Figure 11 and Figure 12 reveal recurring, localised patterns which change throughout the day, helping to identify when and where environmental conditions are most variable.

Across the GREENs, temperature generally increased from early morning, peaking around midday, before declining during the evening. Relative humidity showed an inverse pattern, with high early morning values, lower humidity around midday and increasing humidity later in the day and in the evening. Figure 5 and Figure 6 highlight how sun, shade and environmental controls have hourly effects on microsite conditions.

Early morning (6:00 am to 9:00 am)

From 6:00 am to 8:00 am, there is a stream of cooler, humid air running through the centre of the greenhouse from north-west to south-east. The likely cause of this is the wet wall, as this runs continuously regardless of temperature.

Mid-morning to early afternoon (10:00 am to 13:00)

From 10:00 to 13:00, the temperature decreases in front of the wet wall and increases in the south-east, east and northern sides of the greenhouse in line with the direction of the sun. At its peak, temperatures reach 30°C in these hotspots. The cooler spots sit on the southwest, west and northwest side of the greenhouse where adjoining greenhouses create a permanent shade. Humidity varies very little, if at all, during this period

Afternoon to early evening (14:00 to 18:00)

In the late afternoon and early evening, the whole greenhouse decreases in temperature and increases in humidity; however, the southwest side stays warmer for longer while the rest of the greenhouse decreases in temperature relatively homogeneously.

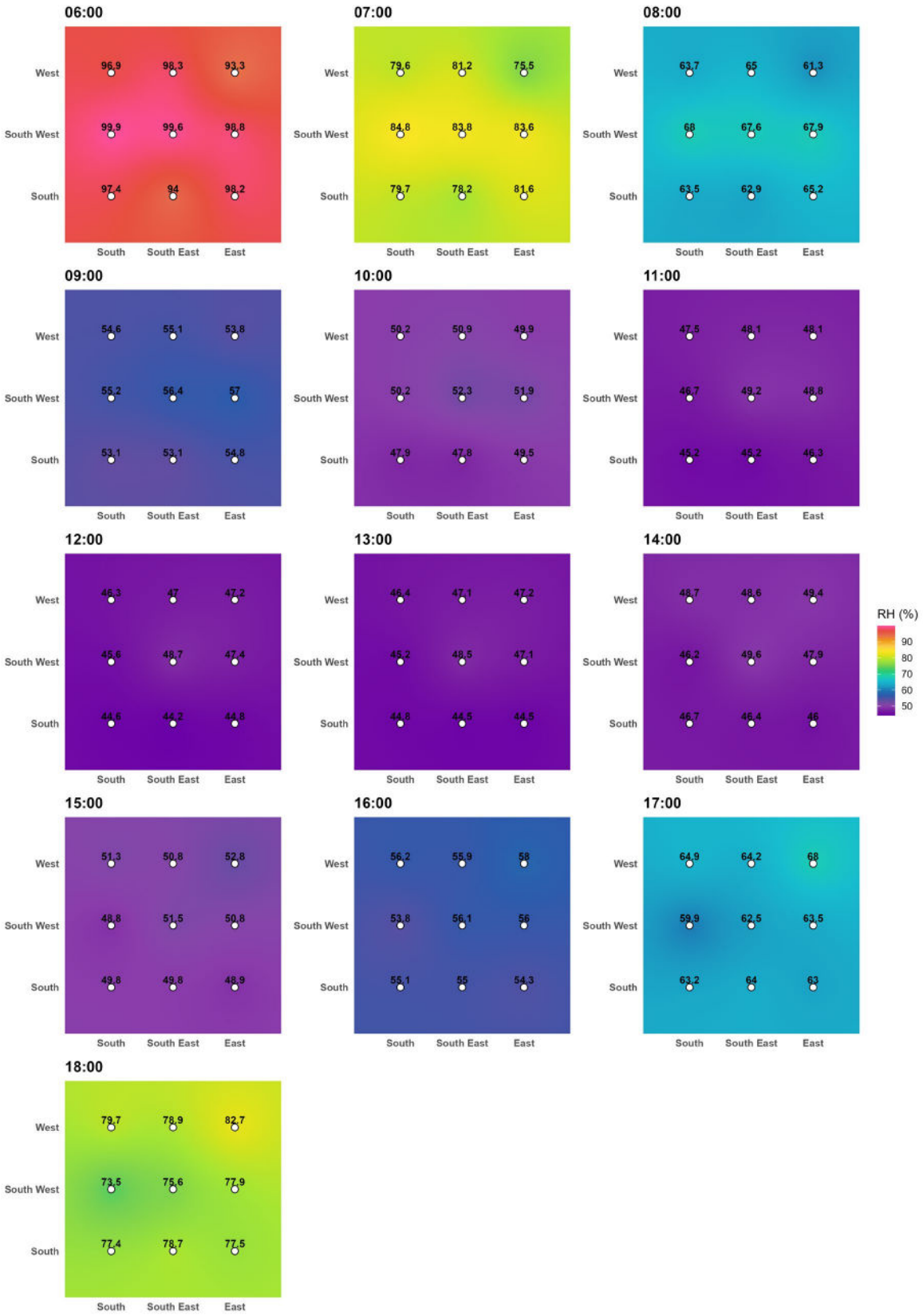


Figure 9 *Mean hourly humidity from 6:00am to 18:00pm of each cardinal direction of the sensor platform (numbers = humidity (%) above white dots (sensor location) during the study period using ordinary kriging to visualise variability.*

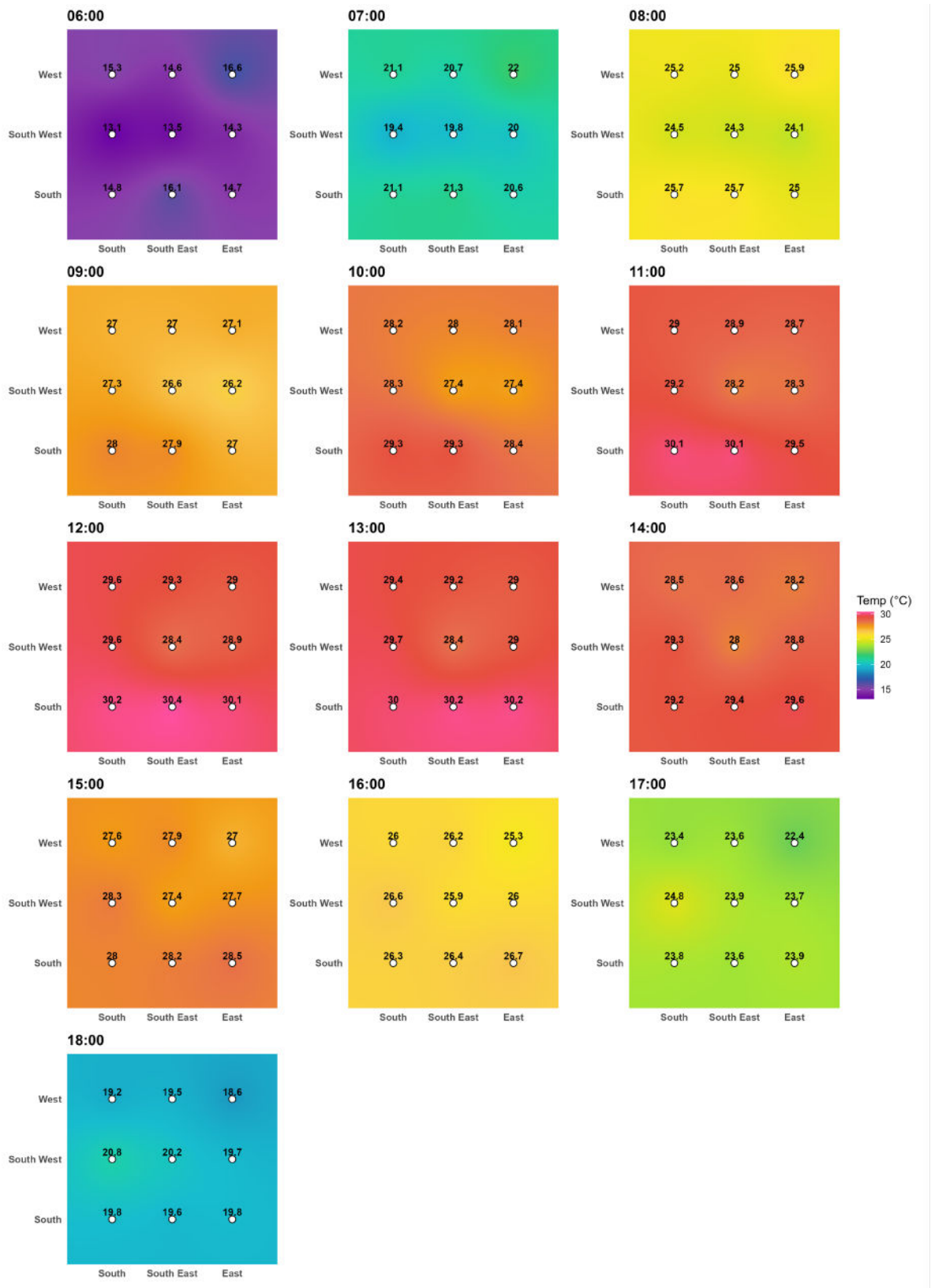


Figure 10 *Mean hourly temperature from 6:00am to 18:00pm of each cardinal direction of the sensor platform (numbers = temperature (oC) above white dots (sensor location) during the study period using ordinary kriging to visualise variability.*

Greenhouse internal vs external Photosynthetically Active Radiation

Preliminary findings show significant differences in photosynthetically active radiation (PAR) between the six sensors spaced only one meter apart within the greenhouse. These differences are likely caused by structural shading (e.g. roof supports) as the sun moves across the sky. Because PAR directly drives photosynthesis, this level of variability can lead to uneven seedling growth and survival. For commercial greenhouses, this highlights a key opportunity to identify and manage light variability to improve uniform seedling growth.

A caveat to these preliminary findings is that the PAR sensors were mounted on top of the platform (5 meters above the ground) to avoid self-shading. Consequently, they may not fully represent the light conditions experienced by seedlings sitting on typical greenhouse tables. Data from the local met station shows PAR varies with height and suggests light conditions closer to the seedlings may be less variable (Figure 7).

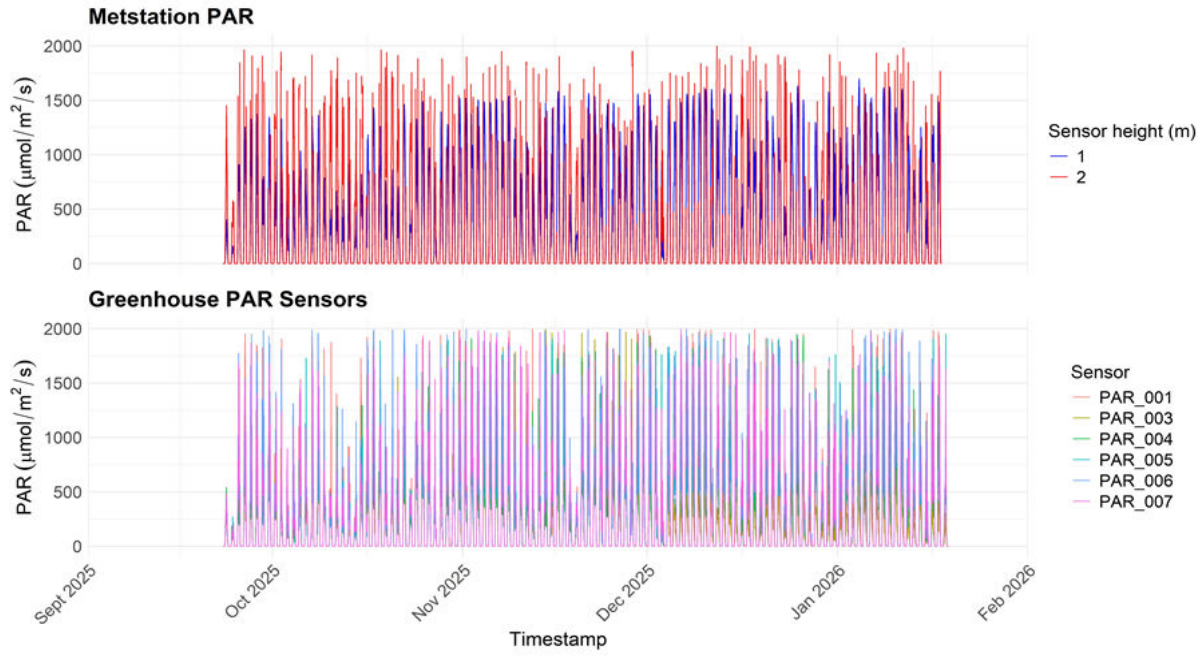


Figure 11 *Snapshot of photosynthetically active radiation (PAR) data from the external metstation (top) and the internal GREENs.*

(2-3) Integration of data from GREENs, RHIZONET and CANOPY

To date, data has been collected, stored, and analysed from one mobile GREENS sensor platform, RHIZONET, and CANOPY. However, full integration will require data from all three GREENS mobile platforms, together with germination and seedling growth data from the pilot experiments described below. Development of the preliminary ENVIROBase database has begun, and collection and storage of the different environmental and plant datasets are now underway.

Microsite variability in germination

Final germination counts were used to calculate germination percentage and germination speed for each microenvironment. These measures, together with seedling height and growth, were explored alongside the micro-environmental data to identify possible relationships between microclimates and plant responses.

Germination increased over time, then levelled off once most seeds that were going to germinate had done so. Total germination was highest around day 29 and declined slightly afterwards. This suggests that the different microenvironments may have influenced germination, although the differences between treatments were small (Figure 15).

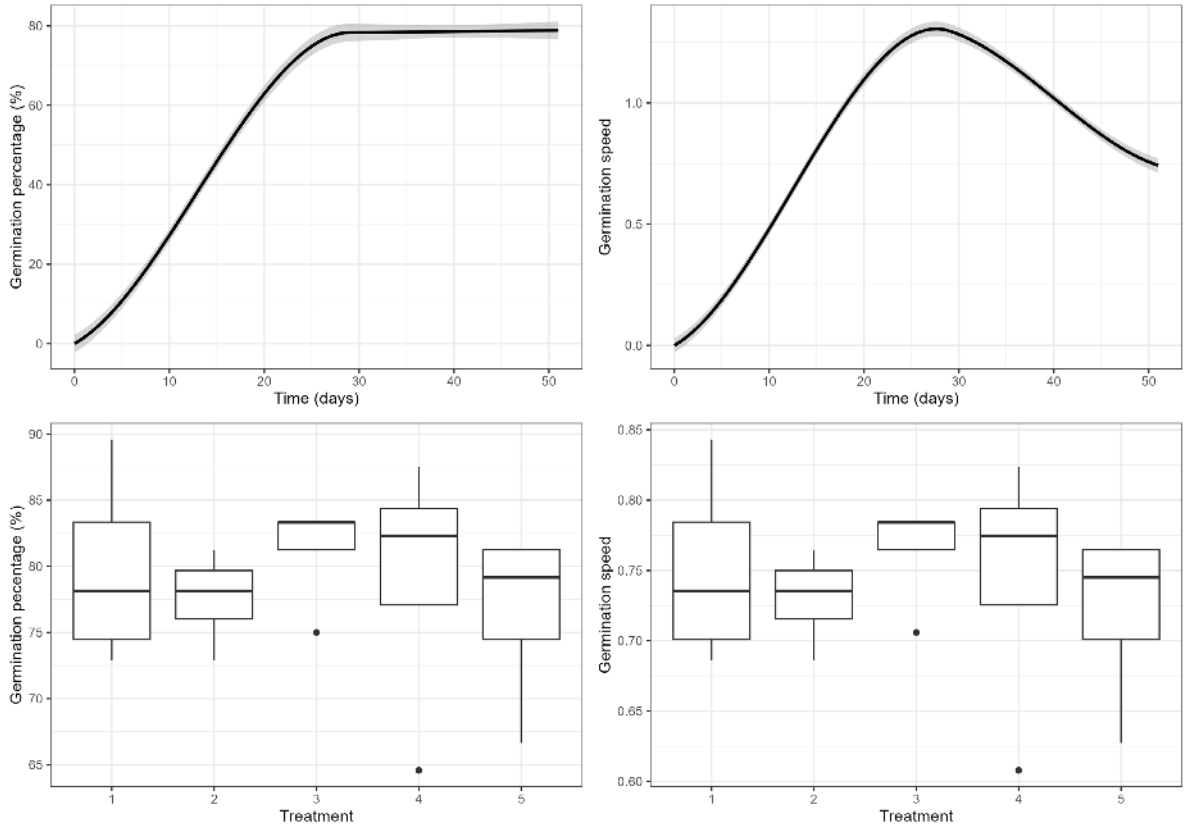


Figure 12 *Germination trends at greenhouse microenvironment*

Microsite variability in seedling growth

Seedling growth differed among the microsites in ways that were consistent with the observed germination patterns. Seedlings in the central microsite location showed the greatest increase in height, followed by those in microclimate 3 in the south-east corner of the greenhouse. Seedling height in microclimates 1, 2 and 4 was broadly similar.

Crown diameter followed a different trajectory. Microclimates 5 and 3 initially showed the greatest increase in crown diameter, but from approximately day 100, microclimate 1 showed the strongest growth. As microclimate 1 was located to the west of the wet wall and is in a shaded position due to an adjoining greenhouse. Therefore, this pattern may reflect increasingly favourable conditions for larger seedlings, such as greater humidity or improved water availability.

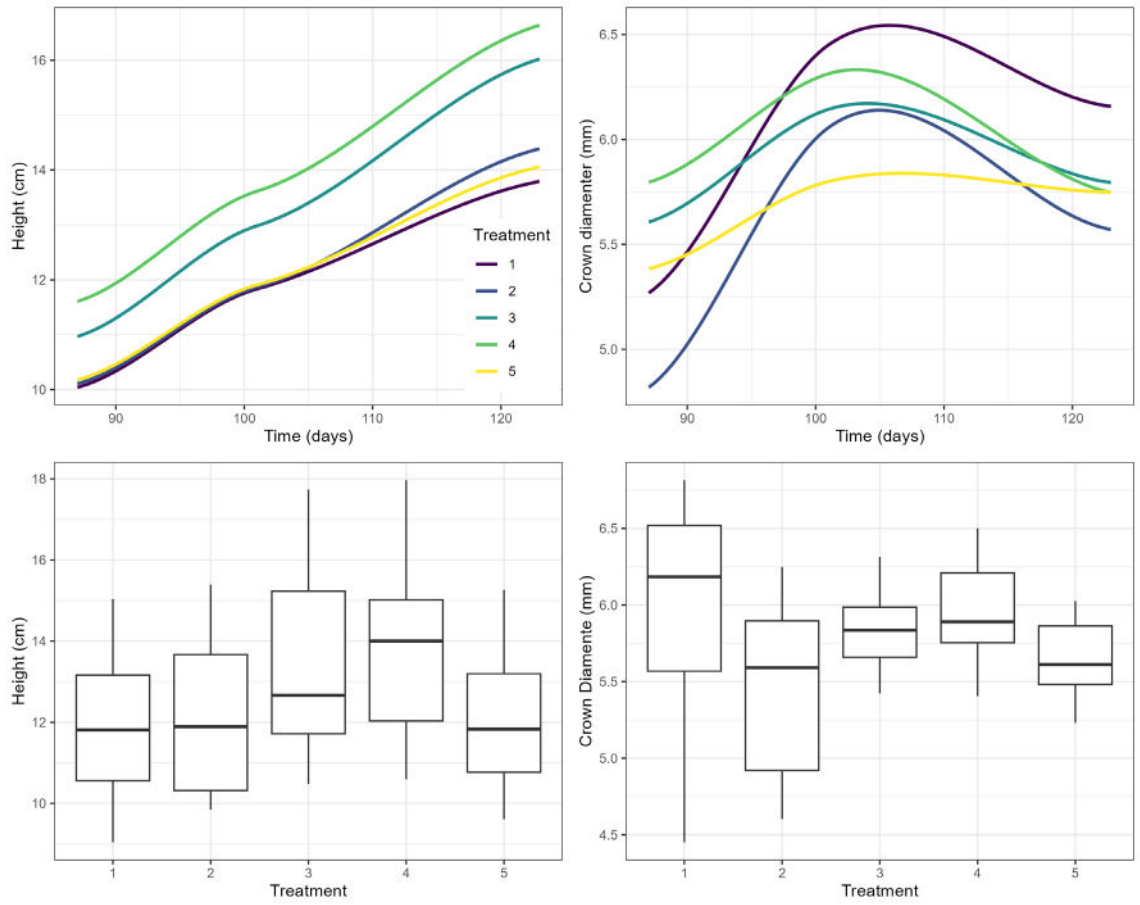


Figure 13 *Seedling growth trends at greenhouse microenvironment*

Root growth

Root length differed among greenhouse microenvironments, with microenvironment 2 (in the northern corner, near the wet wall) producing significantly longer roots than microenvironment 3 (southeast corner) and 5 (centre). Other measured root traits, including root surface area, average diameter, root volume, root-tip number and dry weight, did not differ significantly between microenvironments (Figure 21).

Exploratory analysis of the five microenvironment averages found no clear relationship between root traits and average, minimum or maximum volumetric water content. However, average root diameter had a negative relationship with both average and maximum soil temperature, indicating that warmer micro-environments were associated with finer roots. This result should be interpreted cautiously because the relationship was based on only five microsite-level observations.

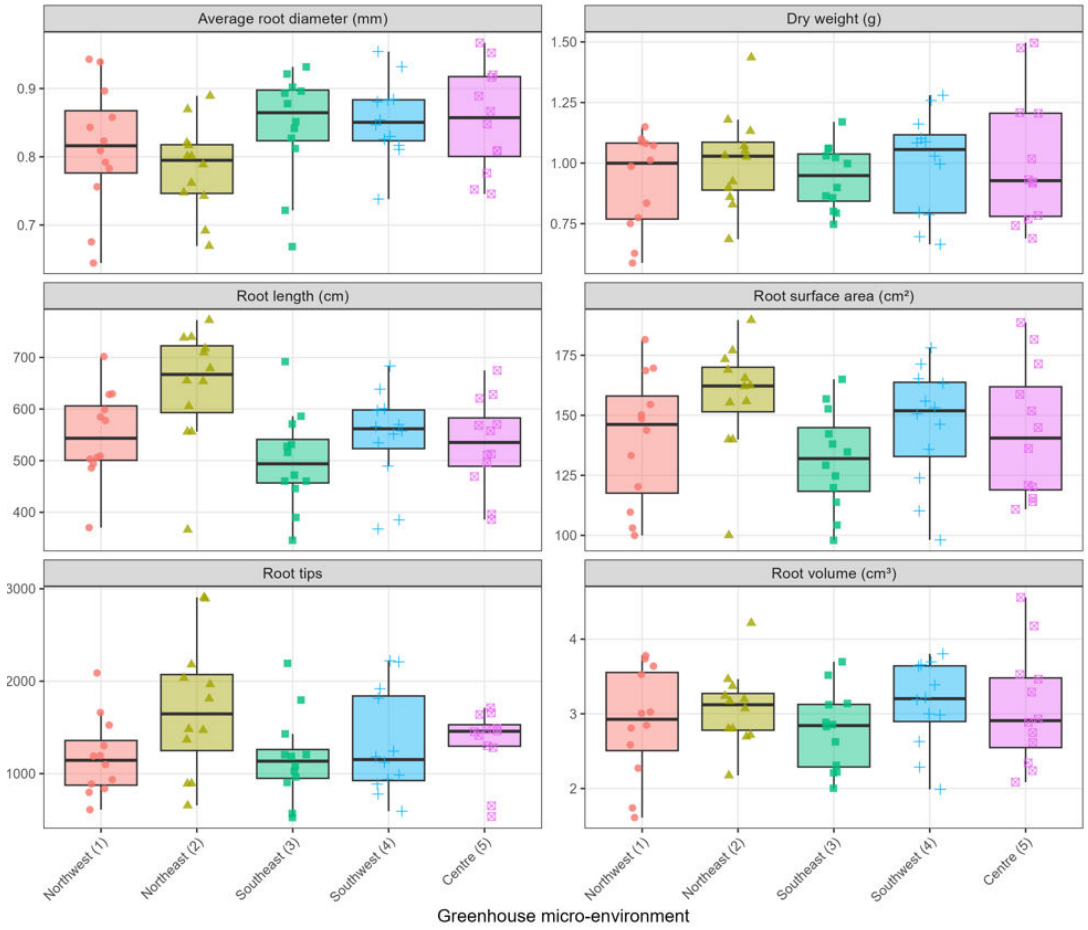


Figure 15 *Box plots of root analysis in each micro-environment*

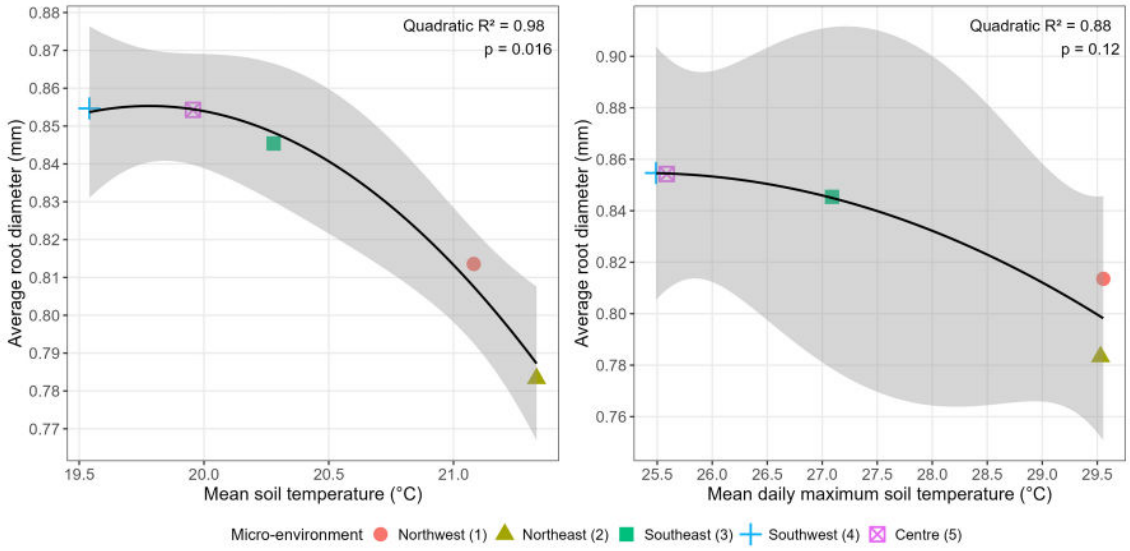


Figure 14 *Relationship between average root diameter (left) and mean daily soil maximum (right) soil temperature*

(4) The nursery survey

The survey identified rooting performance, mother plant management, and production costs as the main challenges associated with clonal propagation. Responses also highlighted considerable differences in technological maturity among the nurseries, limited environmental monitoring, and the absence of comprehensive standardised propagation protocols. These findings support and reinforce the need for modular and optimised environmental monitoring systems and practical data-driven decision tools that can be progressively adopted in different nursery production systems.

DISCUSSION

Understanding and keeping greenhouse environmental variables consistent is important for greenhouse production. Germinating *P. radiata* seeds have a narrow (17.5˚C to 25˚C) optimal germination environmental range (Bloomberg, 2009), while ideal growth temperatures range between 20 and 23ºC during the day and 5ºC to 11ºC at night (Burdon, 1994). If temperatures remain consistently between 32 and 39ºC, then this can cause stem deformation and seedling mortality due to thermal stress. Photosynthetically active radiation (PAR) which represents the wavelengths of light available for photosynthesis and therefore the energy available to support seedling growth. Although PAR is not expected to be a primary driver of *P. radiata* germination, spatial differences in PAR may contribute to subsequent variation in seedling growth by affecting the amount of light available for plants to produce sugars and build new tissues; however, its effects are moderated by interacting constraints such as temperature, humidity and root-zone water availability (José Álvarez, 2013). Root-zone water availability is also critical. Water fills pore spaces in the growing medium, and overwatering restricts oxygen supply to roots and increases the risk of poor root function or disease, whereas insufficient water reduces root water uptake and can lead to plant water stress, wilting and reduced growth (Bloomberg, 2009). These variables interact to influence seedling water demand, photosynthesis, root function and growth. It is therefore important to map multiple environmental variables across space and time, rather than assuming that a single factor is responsible for increased or reduced plant production.

The combined GREENs, CANOPY and RHIZONET results demonstrate that the greenhouse should not be considered a spatially uniform growing environment. GREENs mapping identified recurring temperature and humidity patterns that varied across the greenhouse and through the day. In particular, a cooler and more humid airflow pathway occurred through the central greenhouse during the early morning, likely associated with wet-wall operation, while temperatures increased from mid-morning to early afternoon in the southeast, east and northern areas. During this period, localised hotspots reached approximately 30°C, whereas the northwest and southwest areas remained cooler because of persistent shading from adjoining structures. Relative humidity generally showed the inverse pattern to temperature, declining during the warmest part of the day before increasing again in the afternoon and evening. Together, these results show that greenhouse controls, solar exposure and structural shading created repeatable microsites rather than a single, homogeneous environment.

The internal PAR measurements supported this interpretation by showing substantial variation among sensors located only one metre apart. Although the PAR sensors were positioned above crop height and therefore may not fully represent the light environment at seedling level, the pattern indicates that roof structure and moving solar angle can create fine-scale differences in radiation exposure. This is important because temperature, humidity and light act together to influence evaporative demand, photosynthesis and plant water use. Therefore, the temperature hotspots identified by **GREENs** are unlikely to represent temperature alone; they are likely to be part of broader microsite conditions involving differing radiation, humidity and airflow.

RHIZONET and **CANOPY** extended this greenhouse-scale mapping to the plant scale by measuring the conditions experienced directly within and around seedling containers. This enabled the five representative locations to be treated as distinct microsites characterised by combinations of root-zone temperature, substrate moisture, electrical conductivity, air temperature, humidity, leaf wetness and light. The value of this approach is that a location identified as warm, shaded, humid or exposed by GREENs can be interpreted in relation to the root-zone and canopy conditions likely to influence seedling development. Rather than relying on a single central greenhouse sensor, the combined platform provides a means of identifying locations where seedlings are repeatedly exposed to different environmental conditions.

The **pilot trial** provided preliminary biological evidence that these microsite differences were associated with variation in early *P. radiata* development. Germination followed the expected pattern of increasing rapidly before reaching a plateau, and differences among microsites were relatively small. This suggests that the environmental variation present during the trial conducted during the spring/summer was not sufficient to produce strong differences in final germination, but it may still have influenced germination timing and early establishment. In contrast, post-germination responses differed more clearly among microsites. Seedlings located in the central microsite showed the greatest increase in height, followed by those in the southeast location, whereas height growth in the other locations was broadly similar. Crown diameter followed a different pattern: the central and southeast microsites initially showed stronger growth, while the northwest microsite showed the greatest increase later in the trial. These contrasting responses suggest that conditions favouring height growth were not necessarily the same as those favouring stem thickening, and that seedling growth was likely responding to combinations of temperature, humidity, light, water availability and airflow rather than to a single environmental driver.

Root responses provided further support for the presence of biologically meaningful microsites. Root length was significantly greater in the northeast location, near the wet wall, than in the southeast and central locations. Root traits were not clearly related to average, minimum or maximum volumetric water content, which may reflect the consistent manual watering regime and the fact that volumetric water content does not fully capture water availability to roots. However, average root diameter declined as mean and maximum soil temperatures increased, indicating that warmer root-zone conditions were associated with finer roots. This relationship is biologically plausible, as warmer root zones can alter root morphology and increase plant water demand; however, it remains exploratory because it was based on only five microsite-level observations and cannot demonstrate causation.

Taken together, the results indicate that greenhouse hotspots and cooler or more shaded areas were associated with different patterns of above- and below-ground seedling development. The central and southeast microsites were associated with stronger height growth, the northwest microsite with later crown-diameter growth, and the northeast microsite with longer roots. These responses were not uniformly positive or negative, demonstrating that a microsite may favour one aspect of seedling development while constraining another. This is particularly relevant for nursery production, where crop quality depends not only on rapid growth but also on balanced shoot and root development, uniformity and resilience after planting.

The practical implication is that GREENs, CANOPY and RHIZONET provide a complementary system for identifying persistent environmental hotspots before differences in seedling quality become visually apparent. GREENs can locate recurring warm, cool, humid or high-radiation zones across the greenhouse; CANOPY and RHIZONET can determine the canopy and root-zone conditions experienced by seedlings within those zones; and plant measurements can test whether these conditions are associated with differences in germination, growth and root development. This information could support more targeted use of existing greenhouse controls,

including altered fan or wet-wall operation, revised irrigation timing, relocating sensitive crops away from persistent hotspots, or positioning the control sensor in a location that better represents the warmest part of the greenhouse.

The pilot trial was not designed to isolate individual environmental drivers, so the results should be interpreted as evidence of association rather than direct cause and effect. Manual irrigation, limited control over temperature and humidity, relatively infrequent germination measurements, and the small number of monitored microsites also limited the ability to separate the effects of individual variables. A further limitation was the loss of CANOPY and RHIZONET data collected between the start of the trial in September and November. A failure in the cloud-to-database transfer process meant these data were not retained in ENVIROBase. This prevented a complete analysis of environmental conditions and plant responses across the full trial period. Despite these limitations, the trial demonstrated the value of combining greenhouse-scale and plant-scale monitoring with seedling performance measurements. The data-transfer issue was traced to a data-management workflow error, and revised procedures have been implemented to prevent recurrence.

The next experiment should use replicated experimental units, verified sensor data capture before sowing, more frequent germination and growth assessments, and controlled irrigation and environmental treatments. This would allow the platform to move from identifying microsites associated with growth variation to testing which environmental factors can be managed to improve seedling uniformity and quality. A further extension will be to use ENVIROBase data from GREENS, CANOPY and RHIZONET to refine future sensor design and deployment. This will help identify the minimum sensor configuration needed to capture the environmental conditions most relevant to seedling performance. The aim is to develop a simpler, lower-cost monitoring system that still provides useful biological information for greenhouse management.

ENVIROBase currently allows the research team to store, interrogate and explore environmental trends within the experimental greenhouse. The current system describes one experimental greenhouse and is not itself ready for commercial deployment. However, it demonstrates how similar sensor networks could be used in commercial nurseries to monitor growing conditions and support more responsive environmental control. Further work is needed to determine the most practical commercial format and how the system would be adapted to different nursery environments and production requirements.

Finally, **survey** findings support the strategic direction of the Sensor Platform by identifying opportunities where environmental monitoring can deliver the greatest operational value. In particular, RHIZONET and CANOPY have strong potential to improve rooting performance and Mother Plant management, while GREENS and ENVIROBase can enhance environmental understanding, detect stress zones, and support data-based management. The diversity of nursery infrastructure supports the development of modular implementations that can accommodate different levels of technological adoption.

CONCLUSION

This research shows that greenhouse growing conditions are not uniform, even within a relatively small production space. Temperature, humidity and photosynthetically active radiation varied across the greenhouse and throughout the day, creating local micro-environments that seedlings may experience differently. The **GREENs** platform demonstrated that these patterns can be measured spatially and used to identify persistent hot, cool, shaded or humid areas that may not be apparent from a single fixed sensor.

The expansion of the platform through **RHIZONET** and **CANOPY** provided a more complete picture of the environment experienced by seedlings. By monitoring both canopy and root-zone conditions, the system can link greenhouse conditions with those that influence water availability, root development, photosynthesis and plant growth.

The **pilot trial** provided quantified evidence that micro-environmental variation may influence early *P. radiata* development. Germination differences were relatively small, but seedling height, crown diameter and root length varied among greenhouse locations. Root length was greater in the northeast location than in the southeast and centre locations, while warmer root-zone conditions were associated with finer roots. Although these findings are exploratory, they show that differences in greenhouse conditions can be reflected in plant growth and root development.

For nursery and greenhouse managers, the practical value of this work is the ability to identify where crop conditions differ before uneven growth becomes visually obvious. This information can support more informed use of existing environmental controls, including fans, wet walls, irrigation timing and crop placement. Rather than managing the greenhouse as one uniform space, managers can use sensor data to identify locations that may require different management or where particular crops are likely to perform more consistently.

Overall, **GREENs**, **CANOPY**, **RHIZONET** and **ENVIROBase** provide a foundation for improving crop uniformity by replacing assumed greenhouse conditions with real-time information. Combining greenhouse, plant canopy, and root-zone monitoring creates a practical pathway for understanding why seedlings perform differently across a nursery and for testing whether changes in greenhouse management lead to more consistent plant quality and production. By continuing this research, we can create a model which is transferable to other greenhouse and nursery managers to help identify microclimates and manage them to optimise production.

The **survey** confirmed that improved environmental monitoring and understanding represent significant opportunities for enhancing propagation efficiency in New Zealand forest nurseries. The findings provide a clear rationale for prioritising modular sensor technologies, environmental modelling, and the development of modular production systems (e.g., Fast Rooting and Mother Plant Modules) that facilitate the progressive adoption of technology through hybrid nursery systems or configurations.

NEXT STEPS

The project has established a prototype greenhouse environmental sensing system (GREENs) comprising three functional mobile modules capable of monitoring conditions throughout the volume of the greenhouse. Initial trials have also been completed to assess greenhouse environmental variation under different manual-control settings, including operation of the wet wall and fans.

Next, we will complete the consolidated GREENs analysis using all three mobile modules, rather than the first module alone. This will assess spatial and temporal variability across the full greenhouse and evaluate the effects of wet walls, fans and other manual controls. Photosynthetically active radiation sensors will also be reconfigured to reduce reflection from surrounding surfaces. The combined GREENs, CANOPY and RHIZONET data will then be used to recommend improved greenhouse management, including more targeted irrigation, to reduce persistent microsite variability.

During the current year, the platform was also expanded to **include RHIZONET and CANOPY**, enabling measurement of root-zone and plant-canopy-scale conditions alongside broader greenhouse conditions. This pilot work demonstrated the feasibility of combining greenhouse, canopy and root-zone measurements to identify microsites and examine their association with early seedling development.

Over the next 12 months, we will build on the findings and operational lessons from the **pilot trial** and undertake a more robust, replicated greenhouse experiment which will test the relationships between microsite conditions and seedling development. The pilot trial demonstrated the value of combining greenhouse-scale, canopy and root-zone measurements, while also identifying the need for improved data capture, greater replication, more frequent plant assessments and additional measurements of energy balance and water availability. Together, these additions will help confirm that irrigation and root-zone water availability are adequate for optimum plant performance, allowing differences in germination and growth to be interpreted more confidently in relation to the wider greenhouse microenvironment.

Seed germination will be assessed twice daily to capture differences in timing and rate. Once true leaves have developed, seedling growth will be monitored every second day. Pine-eye imaging will also be evaluated as a complementary tool to provide higher-resolution tracking of germination and growth, reduce reliance on manual assessments, and link plant-performance data with the environmental monitoring platform.

The trial will use a single known genetic seed source and replicated trays across representative greenhouse microsites. This will help distinguish environmental effects from genetic or tray-level variation. The integrated environmental and biological dataset will support robust predictive models of greenhouse conditions and plant performance. Over time, these models may help identify conditions associated with plant stress, uneven development, and favourable growth.

A key next step is to expand the current pilot into a robust greenhouse experiment. The raw sensor data will support the development of automated functions within ENVIROBase to calculate meaningful environmental variables, such as vapour pressure deficit (VPD), cumulative light, and available water. These derived variables will provide a more useful environmental dataset for future greenhouse experiments and operational monitoring. Once linked with germination, growth and quality data, the platform could support the development and validation of environmental models and practical decision-support tools for greenhouse and nursery managers.

Modelling

Following the pilot trial, the next phase will focus on developing physiology-based models of germination and seedling growth. These models will optimise sensor-based data collection and improve understanding how greenhouse environmental conditions influence *P. radiata* germination, seedling growth, and quality. Ultimately, they will provide a practical framework for integrating plan physiology with nursery management. Furthermore, it will equip end users with a practical decision-support tool to evaluate what-if scenarios under controlled nursery conditions.

Seed germination timing will be modelled using time-to-event analysis integrated with biologically meaningful plant physiological relationships. Germination thresholds and percentiles will be parameterised under varying environmental conditions, forming the basis for a seedling growth model that links greenhouse conditions with plant development, field establishment potential, and future plantation productivity.

Together, these models will provide a mechanistic understanding of how greenhouse microclimates influence seed germination, seedling growth, and plant quality. They will support optimisation of nursery management, improve seedling performance, and strengthen evidence-based decision-making throughout the nursery-to-field value chain.

Beyond their research value, these models will provide the scientific basis for developing lightweight commercial versions of the sensor platform. By combining simplified environmental monitoring with validated plant–environment models, the platform will interpret greenhouse conditions in terms of their effects on germination, growth, rooting, and plant quality. Complex environmental measurements will be synthesised into practical information that explains production variability and supports evaluation of greenhouse management strategies.

The models will also integrate with complementary crop-monitoring technologies, including imaging systems and mobile sensing devices. While imaging technologies identify where differences in germination, growth, canopy development, or plant stress occur, the GAIA-NET platform (GREENS, CANOPY and RHIZONET) will explain why those differences occur. Together, these technologies represent an important step from observation to diagnosis, supporting future environmental models, visualisation tools, and precision nursery management.

A subsequent experiment could evaluate the suitability of greenhouses for **vertical farming** of *P. radiata* by comparing conventional greenhouse production with seedlings grown at different vertical levels. The study will assess the strengths, limitations, productive potential, and potential infrastructure requirements (e.g. supplemental lighting and irrigation) of vertical production systems. The sensor platform will play a central role by quantifying changes in PAR, temperature, humidity, and substrate water content across production levels, providing the environmental information required to objectively evaluate the feasibility of vertical farming in forest nurseries.

A crucial next step will be to **engage with commercial nursery providers and greenhouse technology suppliers** to align the platform with existing commercial infrastructure and environmental control systems. This engagement will help identify opportunities to integrate environmental monitoring with available actuators and management solutions, while defining the minimum sensor configuration required for a practical, cost-effective monitoring platform. The goal is to translate the research platform into an industry-ready system that supports environmental management based on evidence in commercial forest greenhouses.

RECOMENDATIONS

Experimental recommendations

The pilot trial demonstrated that seed germination and early seedling growth can differ among greenhouse micro-environments. This provides quantified evidence that local variation in environmental conditions may affect crop development, rather than relying only on anecdotal observations. However, the pilot trial was designed to identify broad patterns of the sensor platform and experimental approach. A more comprehensive and controlled experiment is now required to identify the environmental conditions that promote reliable and uniform *P. radiata* germination and seedling growth. The next study should use a single, high-quality seed source with a known genetic background to minimise variation caused by seed

quality or genetics. Germination conditions should be tested in a controlled greenhouse experiment, with particular attention to substrate moisture and temperature. This would allow the project to identify optimal ranges of water availability and temperature that support rapid, uniform germination while avoiding conditions that delay germination, reduce germination percentage or create uneven seedling development.

Biological measurements should be collected at a frequency that better matches the environmental data. Germination should be assessed daily, or more frequently during peak emergence, while seedling growth should be measured at regular intervals throughout establishment and include a record for emergence of true leaves. This will produce a higher-resolution biological dataset that can be aligned with the high-frequency data collected through GREENs, CANOPY and RHIZONET. Before the experiment begins, the full data pipeline should be tested from sensor to LoRaWAN, ChirpStack, InfluxDB and local backup to ensure that no data is lost during the trial.

The environmental monitoring system should also be expanded to strengthen the interpretation of plant responses. Photosynthetically active radiation (PAR) measurements should be retained because they quantify the light available for photosynthesis. To enhance these measurements, a net-radiation sensor should be added to measure the balance of incoming and outgoing energy available to the seedlings. This would help distinguish whether differences in growth among greenhouse positions or vertical levels are associated with PAR alone or with broader differences in thermal energy available for plant growth. This sensor, along with its measurements, would make this experiment scientifically robust and would elevate the ENVIROBase dataset, which will be used for modelling.

RHIZONET sensors should continue to measure root-zone temperature, volumetric water content and electrical conductivity within selected containers. Where feasible, additional root-zone measurements such as substrate pH should also be included. Linking these data with CANOPY measurements, GREENs maps, external meteorological data and repeated plant measurements will create a multi-scale dataset describing the conditions actually experienced by each group of seedlings.

Strategic recommendations

The nursery survey revealed substantial variation in production systems and technological maturity across New Zealand forest nurseries. These findings support the development of a **Techno-economic Analysis (TEA)** framework to evaluate the progressive adoption of modular technologies across bare-root, containerised, and hybrid nursery systems, extending through field establishment to quantify long-term costs, benefits, and return on investment.

The successful demonstration of the research platform supports the development of lightweight commercial versions of the sensor platform. Progressive translation of the research platform into practical monitoring systems would facilitate industry adoption while maintaining the scientific capability required for continued model development.

Advanced Visualisation

As environmental monitoring expands, effective data visualisation will become increasingly important for translating large environmental datasets into practical management decisions. Beyond the continued development of ENVIROBase and user-friendly dashboards, future work could explore **augmented** or **mixed reality interfaces** as innovative tools for visualising environmental models and greenhouse conditions or measurements in real time. Such technologies have the potential to improve data interpretation, support rapid decision making, and accelerate the adoption of precision nursery management.

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APPENDIX A: Jupiter II light mover

The *Jupiter II Light Mover* is a commercial-grade automated track system designed for hydroponic grow rooms to move HPS, metal halide, and LED grow lights in a fixed pattern. Given this, the mover was originally designed to move across a small grow room (usually up to 5 meters) and created to move the load of a grow light. The supplier upgraded built additional rails to enable the mover to span the 20 meters of our study greenhouse and also upgraded the motor to carry the weight of the sensors and the threaded rods without the risk of damaging the teeth of the motor (Figure A1). Our facilities team extended the power cable and designed a support system to reduce drag of the cable as the system travels and adjusted the supports holding the movers to the truss of the greenhouse to account for a 20cm gradient change from one side of the greenhouse to the other (Figure A2)

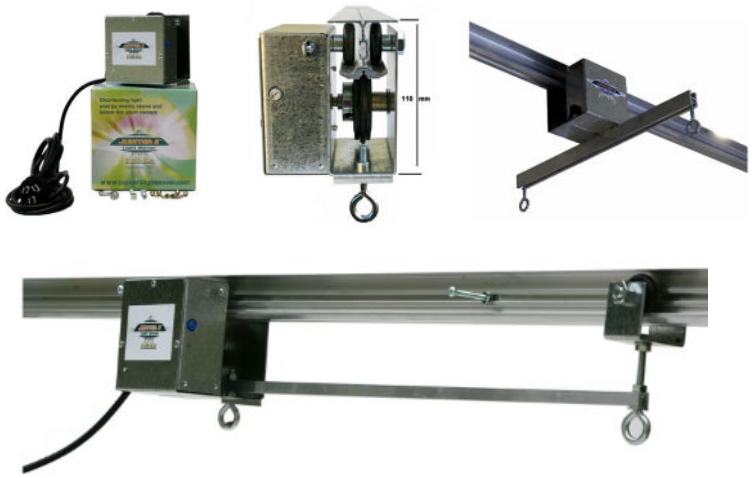


Figure 16 *Jupiter II light mover kit*

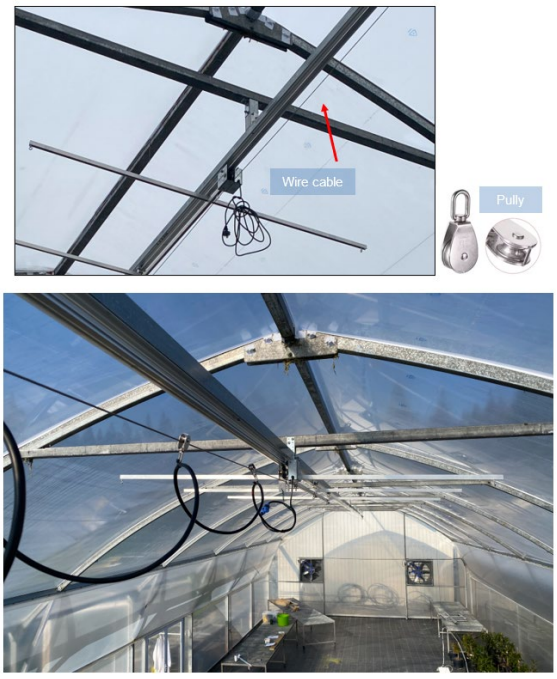


Figure 17 *Additional supports custom built to power and support the moving platform.*

Table A2 Sensors specifications for CANOPY AND RHIZONET

Measurement type	Range	Accuracy	Resolution
Air temperature	-40 to +85 °C	±0.2 °C	0.01 °C
Air humidity	0 to 100% RH	±1.8% RH	0.01% RH
Light intensity	0 to 160,000 lux	±5%	1 lux
Photosynthetically active radiation	0 to 2500 µmol m^{-2} s^{-1}	Maximum deviation 1%	1 µmol m^{-2} s^{-1}
Leaf wetness	0 to 100%	±5%	0.1%
Leaf temperature	-40 to +80 °C	±0.5 °C	0.1 °C
Carbon dioxide	400 to 10,000 ppm	±(30 ppm + 3% of measured value) at 400–5000 ppm; ±10% of measured value at 5000–10,000 ppm	1 ppm
Soil temperature	-40 to +80 °C	±0.5 °C	0.1 °C
Soil volumetric water content	0 to 100% saturation	±2% at 0–50%; ±3% at 50–100%	0.03% at 0–50%; 1% at 50–100%

APPENDIX B: GREENs, CANOPY and RHIZONET specifications

Table B1 *GREENs sensor specifications*

Measurement type	Range	Accuracy	Resolution	Long-term drift per year
Air temperature	-40 to +85 °C	±0.2 °C	0.01 °C	<0.03 °C
Air humidity	0 to 100% RH	±1.8% RH	0.01% RH	<0.25% RH
Photo-synthetically active radiation	0 to 2500 µmol m^{-2} s^{-1}	Maximum deviation 1%	1 µmol/m^2·s	Year offset <2%

APPENDIX C: Data flow

