Hort Innovation

Final Report

Innovative rootstocks for the Australian Macadamia industry

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Department of Agriculture and Fisheries, Queensland

Project code:

MC16000

Project:

Innovative rootstocks for the Australian Macadamia industry (MC16000)

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Public summary

Macadamia lags behind many other tree crops in terms of the development of rootstocks that improve commercial orchard performance. Indeed, there is limited evidence to convince growers that choice of rootstock will influence tree growth and/or yield, so it is not surprising that recent industry expansion has been based on the traditional choices of 'H2' and 'Beaumont'; rootstock varieties that were selected solely on their nursery performance and ease of propagation. This project sought to address this problem, motivated by the possibility that orchard productivity might be improved by using better rootstock genetics.

The strategy was to screen as much diverse genetic material as could be found, and to do so under commercial production conditions for a long period of time; recognising that results from young trees in short-term trials can produce misleading information. More than 200 rootstock treatments were included in the experiment, representing 141 named varieties collected from 8 different pollination environments. 'HAES741' was used as the standard scion across the whole trial. These trees were propagated by the project team and planted (3.5 m x 7 m spacing) within a new commercial planting at Bundaberg in December 2007. Evidence for the high standard of orchard management is reflected in the strong commercial production harvested from the trial site, with yields averaging more than 4 t/ha (nut-in-shell at 10% moisture) in the 5 year period funded by this project. This provides confidence that the rootstocks have been assessed under optimum production conditions. New and more efficient methods of yield assessment were developed so that this large field trial (~2,000 trees) could be measured prior to every commercial harvest in the first 10 years of production.

The project identified a handful of new rootstocks that should be tested in large scale commercial plantings. These include 'A268', 'Own Venture' and 'A4'. These newly discovered rootstocks may provide growers with an opportunity to improve productivity without any change to management activities or input costs. The current commercial rootstocks 'H2' and 'Beaumont' were mid-range in their performance amongst the 141 named varieties in the trial, and still represent a good choice until the superior performance of our new rootstock options is confirmed in large block plantings. Results also demonstrated poor performance of many treatments in the experiment, with the implication that growers must insist on known rootstock germplasm when establishing new plantings. Whilst there was good evidence that rootstocks influenced yield, obvious impacts on tree size and vigour were lacking beyond a few rootstocks that produced small and unhealthy trees. There were no clear opportunities to reduce tree size using rootstocks, despite the large amount of genetic material screened in the experiment.

Focusing on the big-picture of rootstock genetic diversity has opened up new opportunities for rootstock development using these few best-bets with greater replication and investigating the role of the pollen parent. At an operation level, this low-cost project has demonstrated how new industry opportunities can be identified that may improve productivity without increasing inputs.

Keywords

macadamia; rootstock; yield; yield efficiency; canopy size; nut quality; LiDAR; visual ratings.

Introduction

Rootstocks are an extremely cost-effective means of improving orchard productivity, and yet it is an arena that has been poorly explored with macadamia (Trochoulias 1992). Yield and yield efficiency are the key traits most consistently influenced by rootstock in trees crops (Rom & Carlson 1987; Castle & Warrington 1995). These same traits are among the main drivers of macadamia orchard profitability in an industry characterised by intrinsically low yields compared with most other horticultural crops. More recent efforts to demonstrate rootstock effects on macadamia yield (Neal et al., 2016) have not seen the industry progress beyond rootstocks like 'H2' and 'Beaumont', selections chosen by commercial nurserymen for their seedling vigour and ease of vegetative propagation characteristics. This project aimed to go beyond endorsing current industry practice and efficiently investigate a vast array of genetic material to pinpoint a small group of genotypes that offer best prospects of productivity improvement. The technology will be immediately applicable by industry, requiring no change in current practices (grafting onto seedlings), and offering ongoing annual benefits without additional cost. The key outcome has been the discovery of the best performers from within a large amount of genetic diversity.

Experienced horticulturists have long recognised that orchards pass through various life stages, transitioning from small, well-lit individual trees, to large, crowded trees competing for light and other resources (Bright et al. 2016). This transition has a major impact on orchard productivity, although it is common place for scientists to work with young trees for just a few seasons and then assume the results can be extrapolated to the entire orchard life cycle. By contrast, this project has the opportunity to assess yield effects in mature trees for five successive seasons from the time of inter-row

canopy closure (year 7) and will thus give an indication of rootstock performance in a competitive orchard environment.
Current research is tackling issues of macadamia productivity from a number of angles. Regional variety trials Series 3 Phase 2 (MC11001) are assessing the performance of up to 30 selections across replicated trials conducted at nine sites in Queensland and New South Wales. These mature selections are evaluated across the trial sites for yield and quality metrics however the application of novel rootstocks is not a major focus of these trials. Rootstock / scion combinations are being investigated in macadamia, avocado and mango as part of the Hort Innovation co-funded Transforming subtropical / tropical tree crop productivity project (AI13004). Commencing in 2013, the potential of a number of rootstocks sourced from *Macadamia* and related genera is in the early stages and is mostly focusing on dwarfing. It is conceivable that genotypes from this project will provide novel sources of rootstock material for incorporation into subsequent activities in AI13004 and AS18000.
Partitioning variance, and understanding the difference between accuracy and precision, are fundamental to making any real progress in finding better rootstocks for the macadamia industry. These concepts form a key plank in the efficient methodology that will test the contribution of rootstocks to macadamia yield and discover the most useful genotypes for increasing orchard productivity.
This project aimed to extend current industry practice by efficiently investigating a vast array of genetic material in order to pinpoint a selection of genotypes that offer the best prospects for rootstock mediated productivity improvement. The technology will be immediately applicable by industry, requiring no change in current practices (grafting onto seedlings), and, once established, will potentially offer ongoing annual benefits without additional cost. The key outcome will be finding those genotypes with the most promise from within a large amount of genetic diversity.
The project team are experienced in delivering new rootstock technology to Australian horticultural industries having delivered meaningful improvements by identifying better rootstock for both the Australian mango ('Sg Siput', 'MYP') and citrus ('Benton', 'Barkley') industries. In this project, we will apply this successful recipe to the macadamia industry. The team currently operate an extensive network of citrus rootstock experiments at nine commercial sites throughout Queensland, containing more than 3,500 trees and almost 500 unique rootstock genotypes. By applying the latest statistical design and analysis techniques, and development of highly efficient assessment methodologies we have been able to quickly identify superior rootstock germplasm ready for commercial deployment. Our rootstock research has been published in international peer reviewed journals including HortScience, Journal of the American Society for Horticultural Science, Scientia Horticulturae, and Trees.

Methodology

An extensive field experiment was planted by the project team on a commercial orchard near Bundaberg in 2007. This resource formed the cornerstone of the project and shaped the methodology employed. It consists of 2,044 trees on 204 different rootstocks. These rootstocks represent 141 distinct genotypes sourced as seed from eight different locations. Where possible, the same genotype was sourced from multiple locations so that the influence of pollination environment could be estimated. Use was made of the excellent molecular characterisation work which had been completed by Cameron Peace just prior to seed collection in 2005. The experiment contains 662 plots of 3 trees per plot. This system of 3-tree plots was based on citrus rootstock research experience and was designed to enable the centre of each plot to be assessed without interference from neighbouring treatments. The large plot size was also designed to enable electronic data collection and harvesting, although the promised robotic technology (MC03020) has yet to become available (Dunn et al., 2006). These 3-tree plots also provided an opportunity to 'eye-ball' rootstock effects by having multiples (3) of the same rootstock treatment growing immediately adjacent. As trees become larger and canopies close, these 3-tree plots provided a further advantage in that they more accurately represent what would happen in a solid commercial planting of each rootstock variety, competing with siblings rather than different rootstock treatments.
A balanced spatial design was employed to allocate the 662 plots, using statistical techniques that have been employed with great success to improve the efficiency of field crops research. Treatment replication varied from 1 to 6. A single scion, 'HAES741', was chosen because of its commercial importance and susceptibility to Abnormal Vertical Growth (O'Farrell et al., 2016); it was anticipated that rootstocks may provide some means of solving this serious industry issue. Tree spacing was 3.5 m x 7 m and canopy closure began to occur within-the-row in about May 2015. The trial site was treated as a normal commercial orchard and received a very high standard of management throughout the life of this project.
Project resources were used to determine rootstock effects on yield prior to every commercial harvest for the seasons 2017 to 2022. This provided the most accurate and meaningful measure of seasonal nut drop patterns, as well as yield. Nut quality was examined to ensure that any promising rootstocks, in terms of productivity, are not suffering quality downgrades. Various measures of tree size and growth rates were made including the pioneering use of the LiDAR system developed by Green Atlas. Scoring systems were developed and implemented for important commercial traits such as Abnormal Vertical Growth, canopy density, tree stability, and graft incompatibility.

At the time of the Stop/go review (November 2019) a decision was made on which treatments warrant more extensive testing (different locations, additional scions) and the necessary germplasm collected and propagated by the project team to protect and facilitate future assessments.

Results and discussion

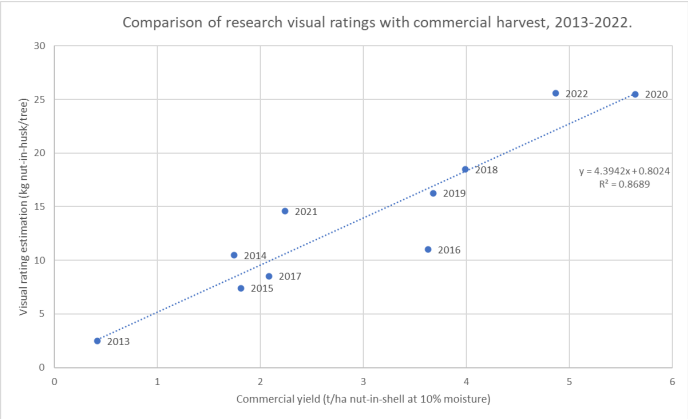
Detailed information has been provided within Milestone reports submitted during the project period. Likewise a very large amount of data has been collected from this extensive field trial (204 treatments; 2,000 trees) during multiple assessments within each of 5 consecutive harvest seasons. Consequently, for the purposes of this report it seems best to provide a brief summary of results related to the assessment methodology and the two extreme subsets in terms of rootstock performance. In this way industry can immediately receive all relevant information while the project team continue the task of preparing scientific publications.

Table 1 summarises the visual rating calibration data obtained on each of the 26 assessment sessions that occurred during the project period. The number of assessment occasions in each year was determined by the commercial collaborator and varied from 3 to 6. The number of Assessors available at each of these dates varied from 3 to 5, with 3 being considered the bare minimum requirement. Calibration of the rating scores was consistently good, averaging 0.869 and ranging from 0.733 to 0.970. This provides strong evidence that the efficient yield assessment methodology developed by the project allows an accurate measure of performance.

Table 1: Calibration summary for 26 assessment occasions that occurred during the 6 years of the project (2017-2022) for 664 individual 3-tree plots.

Year	Occasion	Number of Assessors	R2 value	Equation X	Constant
2017	A	4	0.9043	2.2574	3.65
2017	B	3	0.8019	2.3785	3.21
2017	C	3	0.9223	2.5296	1.68
2018	A	4	0.9321	1.4489	2.08
2018	B	4	0.8080	3.7551	4.15
2018	C	4	0.8273	4.6391	9.31
2018	D	3	0.7325	2.6412	2.64
2018	E	4	0.9697	0.6614	0.30
2019	A	3	0.8871	1.3213	2.06
2019	B	4	0.7588	2.6918	6.47
2019	C	3	0.8464	2.1176	4.65
2019	D	3	0.9385	2.7240	2.47
2019	E	3	0.9425	1.4327	0.62
2020	A	5	0.8790	0.7667	0.64
2020	B	4	0.8752	3.2749	4.63
2020	C	4	0.8370	2.7566	6.44
2020	D	3	0.7529	1.7550	4.62
2020	E	5	0.8999	1.0849	7.07
2020	F	5	0.9368	2.0992	2.14
2021	A	4	0.8833	1.1621	0.84
2021	B	4	0.8925	5.1272	8.98
2021	C	4	0.8981	4.8122	4.44
2021	D	4	0.8733	0.7194	0.33
2022	A	4	0.8267	4.1899	4.78
2022	B	3	0.8722	4.1274	10.6
2022	C	4	0.8836	8.1935	11.2

Further evidence for the effectiveness of the method is found at a whole-orchard level where farm records for the block containing the research trial (6.4 ha) is compared to our average tree yields calculated from just 30 calibration trees harvested at each occasion. There is an excellent relationship across the 10 seasons of assessment (5 from within this project period), particularly considering that the commercial assessment of yield is likely to be subject to as much error (if not more) that our research technique.



<u>Figure 1:</u> Relationship between research visual ratings and commercial farm records for 6.4 ha of 'HAES741' during the first 10 years of production.

The top 20 and bottom 20 of the 204 Treatments in terms of cumulative yield from 2012 to 2022 are listed in Table 2. It also gives the replicate numbers as well as individual season performance from 2017 to 2022.

<u>Table 2:</u> Top and bottom performers out of 204 rootstock Treatments assessed for yield from 2012 to 2022 (traditional rootstocks shown in yellow).

Treatment	Variety	Source	Reps	Sum 2012-22	Std	Y2017	Y2018	Y2019	Y2020	Y2021	Y2022	Ranking
63	A268	Winfield	2	194.9	1.1	13.7	23.2	22.2	28.7	26.7	37.0	1
224	816	MRS	1	182.5		12.1	23.7	22.7	28.5	25.5	35.1	2
127	794	MRS	1	174.8		13.9	23.1	20.1	29.4	23.0	26.8	3
15	804	MRS	1	173.1		6.6	30.1	16.5	25.0	22.2	36.7	4
123	1/40B	MRS	1	172.4		7.9	20.0	20.0	28.8	22.2	39.8	5
86	Own Venture	Wolvie	5	171.6	18.6	11.3	21.3	19.4	27.6	20.6	30.1	6
189	A4	Beerwah	5	170.6	28.9	9.5	22.3	19.3	26.7	18.5	35.8	7
49	2/48B	MRS	1	169.0		9.9	18.1	22.6	28.1	23.9	38.5	8
139	218	Wolvie	4	168.5	24.6	9.9	21.1	18.6	26.9	19.6	35.0	9
236	313	Wolvie	1	166.9		9.1	21.9	19.9	26.6	15.9	35.7	10
130	A16	Winfield	2	166.9	2.1	13.8	23.5	18.9	25.5	13.7	33.5	11
64	816	Winfield	3	166.5	10.7	7.5	24.3	17.7	27.8	19.9	34.0	12
166	1/40B	Winfield	2	165.0	8.4	8.7	23.8	21.2	26.8	13.1	32.2	13
85	781	Wolvie	1	164.7		10.8	20.0	17.0	28.5	15.7	29.4	14
36	791	Wolvie	5	164.4	15.6	12.0	19.3	16.5	28.5	19.9	32.3	15
195	Young1	MRS	4	164.2	15.3	10.1	19.9	16.6	29.9	16.6	34.2	16
164	A387	Winfield	3	164.1	3.7	10.7	18.3	20.3	27.9	17.1	34.7	17
2	1/2B	MRS	2	163.9	18.1	9.2	23.7	13.2	28.3	15.6	34.3	18
176	218	Wolvie	1	163.5		16.6	22.7	19.6	27.3	10.2	37.7	19
201	842	MRS	1	162.9		8.3	18.2	21.5	27.3	17.6	34.5	20
3	H2	MRS	5	159.6	23.4	7.8	20.5	17.7	26.9	16.9	32.8	29
32	Beaumont	Beerwah	6	153.3	22.4	7.5	17.1	18.4	26.9	11.8	35.2	54
148	H2	SeaHot	5	151.6	10.1	8.5	17.7	17.4	25.1	14.8	30.8	62
169	H2	SeaEle	5	150.7	18.5	9.4	15.4	19.3	26.0	15.4	29.1	70
143	H2	SeaGol	6	147.2	15.8	7.4	16.5	15.6	26.1	12.6	32.5	86
34	H2	Beerwah	2	137.0	3.5	5.7	16.9	18.8	24.6	17.0	28.6	155
9	Beaumont	MRS	3	133.7	17.9	7.0	21.4	15.9	20.4	10.5	23.7	173
156	3/74B	MRS	1	128.4		6.1	20.0	12.0	24.7	18.4	22.3	185
93	836	Wolvie	5	127.5	28.4	8.2	12.6	11.9	23.7	11.6	26.3	186
113	NG8	Winfield	4	126.8	31.8	9.7	16.2	13.3	23.4	11.4	29.7	187
30	815	Wolvie	4	126.4	25.1	6.2	18.7	14.4	23.1	10.4	25.2	188
175	51	Wolvie	1	126.2		7.9	15.3	9.7	24.8	9.0	19.4	189
140	108	Wolvie	5	124.1	24.6	7.7	17.8	14.8	21.0	11.8	27.4	190
196	Release	MRS	3	123.7	11.8	6.9	16.0	14.2	24.5	13.5	27.0	191
84	447	Wolvie	1	123.5		9.7	16.5	15.3	27.8	16.2	10.9	192
66	2/18Mc	Winfield	2	121.6	35.5	8.5	14.9	13.6	24.8	14.6	25.0	193
69	148	Wolvie	4	121.6	39.7	5.6	16.7	12.2	24.9	12.3	26.4	194
31	207	Wolvie	2	121.3	7.5	8.1	13.6	16.6	21.1	6.3	29.2	195
6	NG18	MRS	2	119.7	6.6	6.5	16.1	11.7	19.4	7.0	25.0	196
144	A422	Winfield	2	119.5	58.4	4.9	16.8	13.2	22.4	13.1	25.0	197
141	660	Wolvie	2	119.0	24.6	4.0	11.9	16.6	24.9	14.2	19.6	198
207	783	MRS	1	115.8		9.1	19.6	15.1	17.5	3.4	27.5	199
47	791	MRS	1	113.6		6.3	21.9	9.7	19.4	1.8	25.1	200
214	4/7Mc	Winfield	2	113.3	1.2	4.0	16.8	15.4	22.2	12.9	15.8	201
125	814	MRS	1	111.4		3.8	15.3	5.9	25.5	5.7	24.4	202
44	344	MRS	2	101.6	31.2	8.4	10.8	11.8	18.3	11.7	21.0	203
170	H2	SeaDun	1	63.9		0.5	11.8	7.8	19.3	11.4	12.3	204

Thus the project was successful in:

1. Identifying a small group of novel rootstocks worthy of industry adoption and testing.
2. Establishing a subset of rootstocks that warrant further evaluation with greater replication.
3. Developing highly efficient research techniques that allow rootstock research to be conduct at low-cost.

Outputs

Project outputs, as contracted in the Research Agreement (23rd February 2017) and Variation Agreement Research (14th December 2021, CON-000995-3) are detailed in the table below:

Table 3. Output summary

Output	Description	Detail
A program logic and monitoring and evaluation plan with linkage to Hort Innovation and industry/fund objectives.	Prepared for Hort Innovation as part of the project application and included in Research Agreement.	The Program Logic and Monitoring and Evaluation Plan were included in the Research Agreement.
Annual milestone status reports (December).	Submit milestone reports to Hort Innovation and respond to feedback.	All Milestone Reports were submitted to Hort Innovation and discussions held with their Program Manager.
A Stop/go review with Hort Innovation at the end of 3 year of the project (November 2019).	A review was held in conjunction with Hort Innovation and industry and confirmed that the project should proceed.	Details of the Stop/go review were given in Milestone Report 104, Achievement (a): *In conjunction with Horticulture Innovation Australia Ltd. review data and results from three seasons of experiments (2017-2019) to determine whether the project is on track to meet objectives. Determine if the project should proceed or be terminated. If results of commercial relevance are being obtained then provide advice on the nature and extent of new nursery work to validate any promising rootstocks across a greater range of scions and sites.* Data and results of the project were presented to the Macadamia Industry Variety Improvement Committee (MIVIC) on the 26th February 2019 at Nambour, where it was determined that the project was on track and should proceed. Information on some of the more promising rootstocks (from a horticultural perspective, prior to statistical data analysis) was also presented and taken onboard by the industry consultants and leaders who were present (with the intent of incorporating this germplasm into their current seasons sowings). With a modest budget, MC16000 was originally envisaged as requiring a funding boost if results supported the need for additional field trials. The results to date suggest that an additional field trial is required to properly test a much smaller subset of treatments (but with great replication). Fortuitously, and thanks to the efficient operation of the project team and close cooperation with industry, this additional work has commenced within the existing budget.
Presentation of results to Hort Innovation and the macadamia Strategic Investment Advisory Pane, as results may have a negative outcome on current varieties. Due to this	Cautious distribution of project results to ensure no negative impacts on industry.	During project development and sign-off, Hort Innovation were particularly concerned about the potential for project results to have a negative outcome on current varieties. Consequently, this was included as an Output to ensure the project team remained cognizant of their concerns. At the completion of the project these initial concerns now seem overly cautious. None-the-less, the project has been conducted in an open and transparent manner, with clear emphasis on data limitations and the practical realities of

sensitivity, the final outcomes should not be released to Industry until they have been presented. A general project update will be communicated to Industry using the appropriate channel at least annually and detail information that is not sensitive that will otherwise compromise the outcome of the Investment.		differentiating rootstock differences in tree crop research. Furthermore, the industry leadership group for this subject area, MIVIC, was kept up-to-date with project results at each of their meetings and the article describing final rootstock outcomes was published at their urging. The project has delivered useful industry outcomes (namely new rootstocks) without causing any negative impacts or disruption within industry or industry bodies.
A final report.	Final report prepared.	This current document addresses this Outcome requirement.
Guided access to the main trial site for interested industry stake holders to assist in understanding the scientific rigour and commercial applicability of data generated from the project.	The trial site was made available for anyone who wanted to inspect the work.	During the course of the project, individuals and small groups were taken to the trial site so that they could appreciate the material being used to generate the data, and the scale of the experiment. There are few rootstock trials in any tree crop that contain more than 200 treatments and almost 2,000 trees. These visitors included commercial and research horticulturists, growers, consultants, managers and investors. Such 'seeing-is-believing' visits provided an opportunity for industry stake holders to appreciate the challenges of identify superior rootstocks in a non-apomictic tree species. It requires large scale field trials, managed at a high level, and assessed for a long period of time. The visits enabled a greater appreciation of the scientific rigour underlying project data, and its commercial applicability given the way the experiment was designed and executed.
Recommendation of new rootstock varieties worthy of broader-scale testing/assessment.	Recommend new rootstocks that warrant commercial use.	A small number of rootstocks have been identified that offer opportunities to improve macadamia productivity. An article on this was prepared for the AMS New Bulletin (Winter 2021). This article encourages growers/nurserypeople to test 'A268', 'Own Venture' and 'A4', and to plant them in commercial size block for comparison with the traditional rootstocks 'H2' and 'Beaumont'. The article also recommends that industry stick with these traditional rootstocks (because they performed mid-range in the experiment and have served industry well) but include the new rootstocks on perhaps 10-20% of new plantings; a conservative strategy that encourages adoption and potential improvement in industry productivity while not increasing risk.
Extension/communication activities	While not formally listed in the Research Agreement some of the main activities are mentioned here. The extension component of this project was very small because the work focused on finding the best SUBSET	Throughout the project period, participation (in person where possible) at all MIVIC meetings when on duty. Updates provided, questions responded to, and feedback taken onboard. Throughout the project period, regular interactions with the macadamia scion breeding team to compare observations and new techniques. Hosted visit by 22 industry representatives to the main field

	of rootstock germplasm at a time when evidence for the commercial relevance of rootstock was lacking.	trial site, 1st August 2017. Feedback provided by regional representatives. Participated in SIAP future physiology workshop 1-2 August 2017. Concerns expressed in Milestone Report 102. Pat O'Farrell (industry expert on AVG) engaged to search for emerging symptoms and report to stakeholders, 29th August 2017. Only limited evidence was found and this did not progress to any extent during the subsequent project period. Visiting horticulturists (5) inspected trial site September 2018. Industry consultants (3), nurserymen (1) and investors (2) visited the trial site and spent significant time inspecting each of the replicate plots for the treatments that were showing most promise in the data summary, 29th September 2020. Data summary subsequently made available in Milestone Report 105. Clear and concise summary report prepared for the AMS News Bulletin, Winter 2021. Recommended that growers trial some of the new rootstocks like 'A268', 'Own Venture' and 'A4' on 10-20% of new plantings.

Outcomes

Project outcomes, as contracted in the Research Agreement (23rd February 2017) and Variation Agreement Research (14th December 2021, CON-000995-3) are detailed in the table below:

Table 4. Outcome summary

Outcome	Alignment to fund outcome, strategy and KPI	Description	Evidence
Improved understanding of the role rootstocks (half-sib families) may exhibit on yield, yield efficiency, canopy growth, growth rate, nut drop pattern, and nut quality on the macadamia scion variety 'HAES741'.	Sustainably increasing the productivity of Australian macadamia farms.	Detail data concerning yield, yield efficiency, canopy growth, growth rate, nut drop pattern, and nut quality were conducted consistently throughout the project period.	Extensive electronic data files containing all of the information, including calibration equations and validation where appropriate. Summary table of top and bottom 20 ranked Treatments (out of 204) made available to industry. Sufficient broad-scale assessment of horticultural traits to ensure no negative impacts from novel new rootstocks identified in the project.
Industry awareness of novel rootstocks and their performance characteristics relative to industry standards.	Identifying and advocating opportunities for orchard development and expansion.	Make industry aware of novel rootstocks and what advantages they may offer over existing industry standards.	Primary evidence is the article published in the AMS News Bulletin (Winter 2021) which provides industry with simple information gleamed from the project. It provides 3 novel rootstocks worth testing alongside industry standards. Just as importantly, it warns industry of the productivity dangers of using untested germplasm as rootstocks, noting that some of the 204 treatments tested in the project

			have performed badly and would be disastrous in a commercial situation.
Estimate productivity gains/losses likely to occur with different rootstocks and make this available to predict their likely impact on enterprise profitability (relatively simple because all options are cost-neutral).	Sustainably increasing the productivity of Australian macadamia farms.	Use scientifically rigorous methodologies to collect and compare data so that productivity gains/losses can be extrapolated to enterprise profitability.	The strong field-work ethos of the project team ensured that every piece of productivity data was validly collected and collated during the project period. This required extensive nut yield assessment, often at short notice, prior to each commercial harvest from the trial site. Collation of this data first occurred in 2020 and was made available to interested industry parties using a ranking system. Details of the top 20 and bottom 20 ranked treatments (out of 204 treatments) was also presented in Milestone Report 105 (Achievements (h)). The top 20 treatments yielded 43% higher than the bottom 20 treatments, suggesting possibilities for improvements in enterprise profitability, and certainly demonstrating the dangers of using untested germplasm as rootstocks.
Increased willingness of orchardists and nurserymen to evaluate new rootstocks, and for extension agents and consultants to recommend rootstocks as a means of improving economic performance.	Identifying and advocating opportunities for orchard development and expansion.	Has there been an increase in interest in rootstocks amongst industry? Are nursery people willing to evaluate new rootstocks? Are growers prepared to host new rootstock trials? Are extension agents and consultants more convinced about the economic importance of rootstocks?	At the start of this project, the CEO of the lead industry body was quoted as saying "industry are not interested in rootstocks." Likewise, a macadamia physiology workshop in 2017, attended by 22 industry and research representatives rated rootstock research as their lowest priority. Certainly this has changed, and the extensive data collected as part of this project is largely responsible for this outcome. MIVIC have invited update reports at each of their meetings, there has been industry pressure to prepare articles for the AMS News Bulletin, and major players have wanted access to trial data and to inspect the trial site. Extension agents and consultants are looking for information on new rootstocks worth testing. Rootstocks offer a means of incrementally increasing productivity without increasing input costs and data from this project has built a case for this in

			macadamia.
Consider social and environmental outcomes of identifying rootstock genotypes that are better able to withstand periods of high winds, a common threat in many Australian production areas.		Windstorms can be a major limitation to macadamia production, and is the main reason why 'Beaumont' cutting rootstocks are used successfully in South Africa but are unsuitable in Australia (our production areas experience far more wind). Rootstocks that provide strong anchorage are important, because although severe wind conditions are rare (they may not occur for many years in a row) they cause major damage.	The project period has been relatively benign in terms of extreme weather events in the Bundaberg region where the trial is located. This is indeed fortuitous give the enormous expansion in plantings that has occurred during this period; because young orchards are most prone to wind damage. None-the-less, early data from the field trial showed a strong influence of rootstock on wind-blows. This will be incorporated in future publications and possible relationships with long-term tree health.

Monitoring and evaluation

Project Key Evaluation criteria, as contracted in the Research Agreement (23rd February 2017) and Variation Agreement Research (14th December 2021, CON-000995-3) are detailed in the table below. Because these were formulated under a different M&E Plan format to that now required in this table, some modifications have been necessary. The M&E Plan identified 4 main assumptions and external factors (access to trial site; working relationship with trial host; project team remaining intact and close to the trail site; severe weather events) that might disrupt the project work and it is pleasing that none of these eventuated to any extent.

The Program Logic (see Research Agreement) also provided a flow chart based on possible events and it is most pleasing that the Outputs and Outcomes are consistent with the most positive Impact scenarios.

Table 5. Key Evaluation Questions

Key Evaluation Question	**Project performance**	**Continuous improvement opportunities**
Conclusively demonstrate whether or not rootstock influences macadamia performance in a mature orchard situation (post canopy closure).	*Excellent field site collaboration ensuring all information gathered.* A high level of communication was maintained with the manager of the trial site throughout the project, ensuring that all required data were collected. *All data carefully collated and available electronically for analysis.* Data has been collated in a timely manner (with 24hrs of collection) to ensure integrity. It is stored electronically with Notes to aid future interpretation and use. *A clear and concise statement concerning Objective 1.* The article prepared for AMN News Bulletin (Winter 2021) provides a clear and	The purpose of this project was to screen as much germplasm as possible and identify a SUBSET of top performers that could then be tested with greater replication and statistical validity (ability to detect smaller, but commercially meaningful, differences). We needed to conduct this large-scale testing of a broad range of germplasm with MATURE TREES (canopy closure and annual pruning to manage canopy size). The dangers of making premature selection using data collected from young trees is well known. This project now completes this burdensome task so that the opportunity now exists to validate the superior performance of

	concise statement that rootstocks are an important component of tree genetics and orchard performance, with effects detectable in mature orchards that have achieved canopy closure and are subject to annual pruning to maintain canopy size.	the SUBSET of best performing rootstocks. By testing this SUBSET alongside the traditional rootstocks 'H2' and 'Beaumont', and with far higher replication, it will be possible to refine industry recommendations and start the important task of quantifying pollen parent impacts. The methodologies developed in this current project enable continuing rootstock research to be conducted at low cost to industry.
Define production and productivity effects of more than 200 different rootstocks on 'HAES741' and benchmark against current commercial standards.	*Excellent field site collaboration ensuring all information gathered.* As above, a concerted effort has been made to ensure good communication with the trial host and to collect required data without causing any disruption to commercial activities. *All data carefully collated and available electronically for analysis.* As above. With nearly 2,000 trees in the experiment, and data collected from 664 individuals over a 10 year period, the need for careful data organisation is obvious. Just as important as the data itself has been routine file-notes detailing trial activities and observations which will be critical to accurate data interpretation. Notes were made at the end of each data collection activity describing what was done, by whom, as well as general observations. *Solid and consistent (every season, every harvest of every season) data obtained from committed field trial management and assessment.* Throughout the project period (as well as the 5 harvest seasons prior) the project team collected the necessary data without incident. This was a significant achievement given that the trial was located on a commercial property within an existing orchard of 'HAES741', and sometimes there was little warning of an upcoming commercial harvest.	Future developments must build on the work completed in this project, having demonstrated the useful role of rootstocks and identify a SUBSET of germplasm worthy of thorough testing. The onerous task of assessing more than 200 treatments over 10 consecutive seasons of production has been successfully completed. Having demonstrated limited rootstock impacts on nut quality traits and canopy size, any future work can be improved by focusing on productivity (using the efficient yield assessment techniques pioneered in the current project). With such a focus on productivity (plus the need for large numbers of replicates managed under commercial conditions) an important opportunity for improvement is to ensure that future developments occur in close proximity to the project team (so that accurate yield assessments can be made at short notice during the harvest season).
Discover any additional commercial benefits of rootstock genetics such as tree stability, resistance to Abnormal Vertical Growth, and	New information on how different rootstocks affect tree performance (e.g. growth, health, disease). The project team inspected every tree on at least 5 occasions each season,	It was disappointing that greater effects on canopy development were not demonstrated with the extensive range of germplasm testing in this project. However this finding creates

delayed incompatibility.	looking for any signs of tree health problems, AVG, or delayed incompatibility. Compatibility was further estimated by annual trunk circumference measurements, which while primarily intended to describe vigour are also an opportunity to look for graft union abnormalities. Given the large amount of genetic material present within the experiment it is perhaps surprising that more differences in other traits were not observed. Indeed, even though different species are present as rootstocks (including *Macadamia jansenii*) they are largely indistinguishable in terms of their impact on 'HAES741'. This has important implications for future rootstock research, suggesting that efforts should continue to predominantly focus on productivity gains. *Data available for all 204 rootstocks.* See above. The data have been collated for all 204 rootstocks. *Interested stakeholders able to visit and inspect the field site.* The site has been available for visitation by any interested parties, and the project leader had been happy to show such people through the site. It is important that stakeholders understand the extent of the experiment used to generate the data and the high standard of management under which the 204 treatments have been compared. *Strong attendance and high satisfaction of industry stakeholders attending such events (grower field day).* There were very few grower field days during the later stages of the project (partly as a result of COVID restrictions at this time) and so visits were restricted to individuals and smaller groups. They expressed high satisfaction with the quality of the work and a desire to obtain the superior material identified in the project. Increased industry interest in rootstocks also reflects high satisfaction with the project work, as new opportunities for improving productivity are	an important opportunity for improvement because it suggest that industry need to focus on other ways of managing canopy size. We may be able to increase productivity using better rootstocks but it seems unlikely that tree growth can be contained. Instead, future developments may concentrate on mechanical/chemical canopy management as well as scion genetics (for which there are large differences in canopy size between varieties). Promising claims of vigour controlling macadamia rootstocks need to be properly tested, but canopy size control should not be the primary concern of future developments, simply because our evidence suggests it is unlikely to succeed (at least with the extensive range of germplasm we have tested). Important opportunities for improving industry adoption and validation remain. An active process of supplying seed from our best performing source-trees directly to commercial nurseries is envisaged. This will get large quantities of known-pedigree material into commercial plantings. These can be monitored at limited cost and in a way that best suits the nursery/grower. 'Availability' is a significant impediment to rootstock adoption and this opportunity will help to validate information generated from the project and ensure long-term industry adoption of new rootstocks. Supplying seed to nurseries will be critical to getting uptake of this new technology and the project team will undertake this task post-project.

	recognised.	

Recommendations

1. That growers and investors be encouraged to test new rootstocks (identified in this project) on about 10-20% of their plantings.
2. That macadamia nurseries source material of 'A268', 'Own Venture' and 'A4' and include these seed lots at the same time they are propagating 'H2' and 'Beaumont'.
3. That the project team collect seed from 2-5 of the best performing Treatments in the experiment, by returning to the original source tree, and then distribute this seed in bulk to interested commercial nurseries.
4. That commercial scale blocks of various scion varieties are planted on 'A268', 'Own Venture' and 'A4' in a way that gives growers confidence in their relative merit compared with 'H2' and 'Beaumont'.
5. That new rootstock trials are established using the SUBSET of germplasm identified in this project, with far greater replication.
6. That the role of the pollen parent in rootstock performance is investigated using a trial design with a small number of seed parents, large replication, and molecular testing of seedlings to determine likely pedigree. This will help in the challenging task of developing better commercial rootstocks for non-apomictic tree crops that do not develop proper root systems via vegetative propagation.
7. That rootstock research remains a small but consistent component of the industry research portfolio.

References

Bright J, Alt S, Commens R (2016) *Macadamia integrated orchard management practice guide 2016*. NSW Dept of Primary Industries, 24p.

Castle WS, Warrington IJ (1995) Rootstock as a fruit quality factor in citrus and deciduous tree crops. *New Zealand Journal of Crop and Horticultural Science* 23: 383-394.

Dunn M, Billingsley J, Bell D, (2006) Vision based macadamia yield assessment. *Sensor Review* 26:312 – 317.

Neal JM, Kelly A, Hardner CM, McConchie C, Topp BL (2016) Preliminary evaluation of macadamia rootstocks for yield and tree height. *Acta Horticulturae* 1109: 181-188.

O'Farrell PO, LeLagadecD, Searle C (2016) 'Abnormal vertical growth': a disorder threatening the viability of the Australian macadamia industry. *Acta Horticulturae* 1109: 143-150.

Rom RC, Carlson RF (1987) *Rootstocks for fruit crops*. Wiley & Sons, New York, 494p.

Trochoulias T (1992) Rootstock type affects macadamia performance. *Acta Horticulturae* 296:147-152.

Intellectual property

No project IP or commercialisation to report. The research has been conducted in way that avoids developing IP complications. Field site contracts further ensured that industry access to information was not restricted.

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