Decadal trends in plantation *Pinus radiata* (D. Don) forest growth

Serajis SALEKIN[1,2 *], Donald A. WHITE[1], Steven DOVEY[1], Yvette DICKINSON[1], Peter CLINTON[2] and Alec D. MACKAY[3]

[1]*Bioeconomy Science Institute, Rotorua, New Zealand*
[2]*Bioeconomy Science Institute, Tuhiraki, Lincoln, New Zealand*
[3]*Bioeconomy Science Institute, Grasslands Research Centre, Palmerston North, New Zealand*
*Corresponding author: serajis.salekin@bioeconomy.nz

Abstract

Plantation *Pinus radiata* (D. Don) forests are long-term crops uniquely exposed to climate change; trees planted today and harvested after 2050 will experience multiple cycles of variable rainfall, along with an anticipated increase of another approximately 100 ppm in atmospheric CO_2 (eCO_2) and associated warming. While process-based modelling has suggested substantial increases in tree growth in higher-rainfall regions, empirical model outputs indicate the rate of increases in productivity has slowed. We analysed three decades (1992–2022) of growth data across permanent *P. radiata* plots in New Zealand to quantify recent trends in plantation productivity and to assess the implications of any decline for the sector, farm forestry and the wider economy. *P. radiata* growth increased by 25% from the 1990s to the 2000s but plateaued to a <5% gain in the 2010s, despite predicted benefits from rising eCO_2, and continued adoption of improved germplasm, silvicultural practices and the practice of planting on landscapes with a pastoral history. The age-class distribution became increasingly skewed towards recently established and younger plantations in later decades, which may partially mask underlying changes in productivity. These findings indicate that gains in forest productivity have slowed, highlighting the need for more targeted management interventions to maximise the benefits of eCO_2 through efficient water and nutrient supply and utilisation.

Keywords: climate change, growth trend, *Pinus radiata*, plantation forest

Introduction

Plantation forestry, dominated by *Pinus radiata* (D. Don), is economically pivotal to New Zealand (New Zealand Forest Owners Association 2023). Owing to its adaptability across a wide range of environmental conditions, *P. radiata* has become the species of choice, producing a diverse array of forest products (Mead 2013) and delivering multiple values beyond timber production, including carbon sequestration (Paul and Wakelin 2024; Salekin et al. 2024), soil and water protection (Yao et al. 2021) and recreation (Bayne et al. 2022).

In recent decades, forests globally have exhibited climate-induced increases in mortality (Lu et al. 2026) and disturbances (Grünig et al. 2026), alongside declines in growth rates (Bose et al. 2025; Hacket-Pain et al. 2025) and fecundity (Clark et al. 2026). These trends are largely attributed to the increasing frequency and severity of climate extremes, including droughts, heatwaves and floods (Cook et al. 2014; Spinoni et al. 2018). Developing a robust understanding of these processes is hindered by the reliance of many large-scale studies on model-based analyses that integrate detailed process representations (Dalmonech et al. 2026). Moreover, such studies often lack sufficient temporal resolution (Evans et al. 2021) and/or are depend on indirect proxies of growth, such as remotely sensed metrics of greenness (Arend et al. 2023). Although observational studies based on multi-species tree-ring data at annual resolution are valuable, they remain relatively scarce (Klesse et al. 2018; Martinez del Castillo et al. 2024). These limitations highlight the need for analyses based on directly observed, spatiotemporal datasets, such as permanent sample plots or, ideally, national forest inventories.

Climate change impacts in New Zealand broadly reflect global patterns (Salinger and Griffiths 2001; Withers et al. 2007; Hopkins et al. 2015). However, due to their geographic location and topography, plantation forests in New Zealand are uniquely exposed to spatially contrasting climatic conditions, for example, drought in some regions and excess moisture in others. This is further complicated by the highly localised nature of such events in both space and time. As elsewhere, assessments of plantation forest growth under recent and future climate scenarios in New Zealand have predominantly relied on either process-based models (Watt et al. 2018) or empirical growth models (Mackay et al. 2023; Salekin et al. 2026). Notably, these approaches have produced contrasting results; process-based studies generally project increased productivity under elevated atmospheric carbon dioxide (eCO_2) and warming, whereas empirical analyses indicate declining

ISSN 2463-2872 (Print) ISSN 2463-2880 (Online) https://doi.org/10.33584/jnzg.2026.88.3889

productivity. Resolving this discrepancy is critical for operational forestry and carbon accounting, as overly optimistic projection may encourage investment in low-productivity sites, while diminished confidence in empirical models may constrain sectoral development.

These contrasting findings, combined with the urgency of the issue, raise a key question: what do observe data reveal about on-the-ground trends in *P. radiata* productivity? This study addresses this question using data spanning the past three decades. Specifically, we utilised three decades (1992–2022) of nationwide measurements, the longest continuous ground-truth dataset available for *P. radiata* to i) analyse temporal growth trends and ii) quantify the magnitude of these changes using statistical approaches. In doing so, we aim to provide a robust, observation-based assessment of growth dynamics in New Zealand's *P. radiata* planation forests.

Materials and Methods

Data

This study used data from New Zealand permanent sample plots (PSPs) (Pilaar and Dunlop 1990). All *P. radiata* PSPs measured between 1992 to 2022 and aged up to 25 years were included, resulting in a total of 9652 plots across the country (Figure 1). The dataset was partitioned into three decades: i) 1992–2001, ii) 2002–2011 and iii) 2012–2022. The dataset encompassed a wide range of stand ages (Figure 2), stand size classes, basal area (m^2/ha) and stockings (Table 1). From the dataset, mean annual basal area increment (m^2/ha/year) was calculated by dividing total stand-level basal area (m^2/ha) by measurement age in years. This was used as the response variable because of its capability to better capture stand-level growth, and it is often used as the central component in many growth and yield simulators (Monserud and Sterba 1996).

Table 1 Descriptive statistics of the datasets (n=9652).

Attribute	Minimum	Maximum	Mean
Age (years)	0.05	25	13.25
Stocking (trees/ha)	7	2713.3	659
Basal area (m^2/ha)	14.46	257.47	29.85

Analyses

All analyses were conducted in the R statistical environment (version 4.4.1;R core team 2022). To examine the general temporal trend in cumulative mean annual basal area increment, a non-parametric local regression using locally weighted least squares regression (LOESS) was applied with default span of 0.65 (i.e., 65% of the data) (Jacoby 2000; Gijbels and Prosdocimi 2010). LOESS combines the simplicity of classical regression with the flexibility of non-linear regression (Gijbels and Prosdocimi 2010).

As the PSPs measurements were collected periodically, a repeated-measure analysis of variance (ANOVA) using Satterthwaite's approximation for degrees of freedom was used to test site-specific changes in basal area increment (m^2/ha/year). Given the site characteristics, including age effects, were likely to vary, the final model included 'Decade' as fixed effect and 'Site' and 'Age' as random effects. Tukey's post-hoc comparisons were conducted using the Kenward-Roger approximation for all statistically significant situations.

Results

Stand-level growth, expressed as cumulative mean annual basal area (m^2/ha/year), increased from the first decade (1992–2001) to the most recent decade (2012–2022) (Figure 3A). However, the rate of increase has clearly slowed over time. Figure 3B shows that basal area increment increased significantly between 1992–2001 and 2002–2011, amounting to approximately 25%. This upward trend continued into 2012–2022 but has slowed to less than 5% and was no longer statistically significant from 2002–2011. In addition, a pronounced decline in productivity gain was observed around age 10 years, likely reflecting changes in the timing and/or intensity of silvicultural practices, a pattern not evident in the 1992–2001 period.

Discussion

The results of this empirical, ground-based observational study are consistent with other long-term analyses from Central Europe (Pretzsch et al. 2014) and global temperate forest (McMahon et al. 2010). Although, growth increased over time, it plateaued towards the end of the rotation, and the rate of increase slowed from the mid to recent decades. This deceleration is likely driven by multiple interacting factors, and their cumulative effects.

Pinus radiata has undergone several decades of intensive genetic improvement (Jayawickrama and Carson 2000), and its silvicultural regimes have been progressively optimised to maximise growth potential and enhance tolerance across a wide range of sites and climatic conditions (Mason 2023). For example, Kimberley et al. (2015) demonstrated a ~25% difference in standing volume between highly improved and unimproved genetic material. Despite the advances in genetic merit, productivity gains have slowed in the most recent decade, suggesting that the adoption of improved germplasm and management practices may be masking underlying declines in site productivity. The increases in the frequency and intensity of climatic anomalies, which affect regional

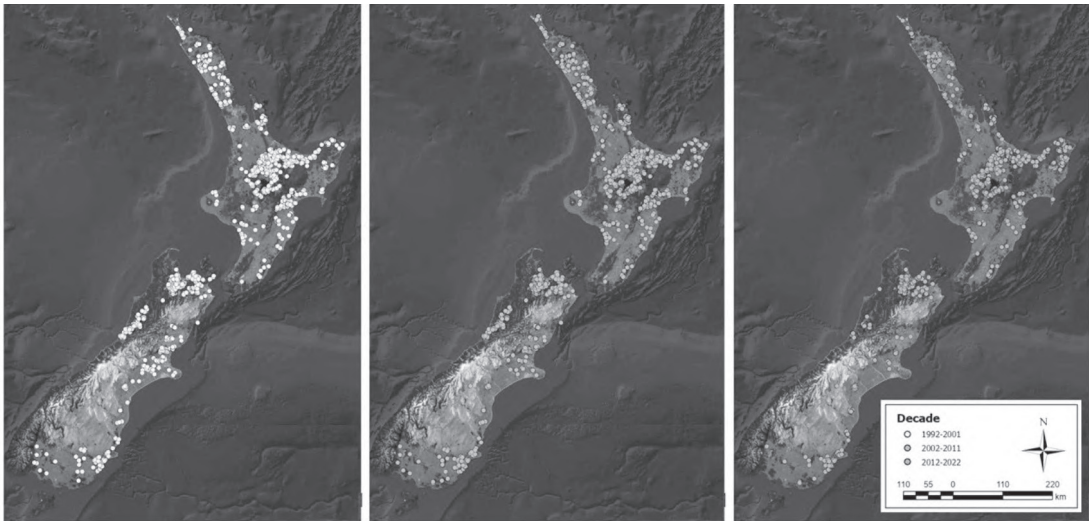


Figure 1 Distribution of permanent sample plots at different decades.

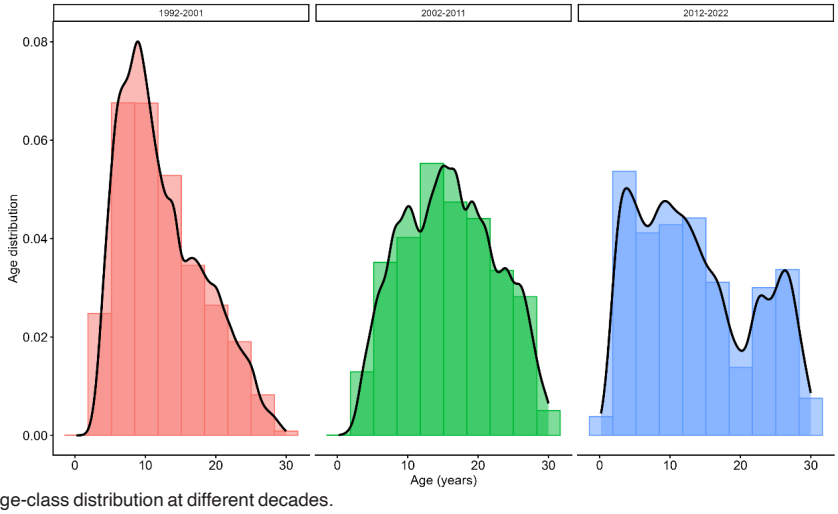


Figure 2 Age-class distribution at different decades.

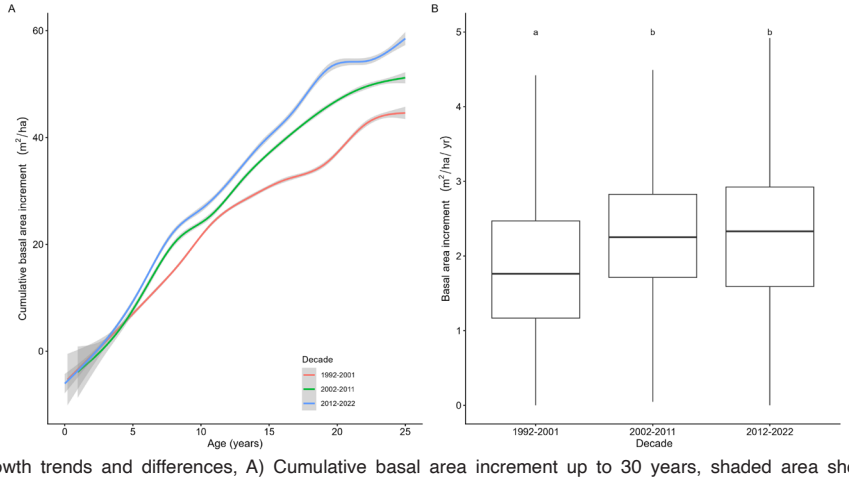


Figure 3 Growth trends and differences, A) Cumulative basal area increment up to 30 years, shaded area showed the 95% confidence interval and B) differences in decadal basal area increment for 25 years.

growth conditions differently, cannot be ruled out as another key factor contributing to the changes being seen (Withers et al. 2007; Caloiero 2014; Hopkins et al. 2015). For example, the National Institute of Water and Atmospheric Research (2024) recently recorded the warmest year on record, alongside increasing rainfall extremes (Sigid et al. 2026). Such climatic variability may also exacerbate pest and disease pressures (Wakelin et al. 2018), contributing cumulatively to reduced growth in *P. radiata*. In addition, recent changes in land use, including the continued expansion of exotic plantations onto land previously under pastoral use (e.g., Land Use Capability Class 6 and above) in more recent years, may also influence observed productivity trends, particularly as many of these stands occur in the final decade of the current study (Paul and Wakelin 2024).

Tree growth is fundamentally an ecophysiological process governed by interactions among climatic, edaphic and physiological factors (Johnson et al. 2011; Hu et al. 2023), as well as stand- and tree-level demographic processes (Pretzsch et al. 2022). Understanding these responses under global climate change is critical for informing mitigation strategies. However, studies focusing on individual drivers, such as warming or elevated CO_2 (eCO_2), although well explored (McMahon et al. 2010; Pretzsch et al. 2014; Watt et al. 2018), do not capture the full complexity of forest responses. For instance, the effect of eCO_2 are strongly mediated by nutrient availability, particularly nitrogen deposition and supply (Fang et al. 2014; Terrer et al. 2019), as well as by extreme climatic events (Reichstein et al. 2013), soil conditions (Körner 2006; Beets et al. 2019), stand structure and scaling to the landscape level (Bugmann and Bigler 2011). Integrating these interacting factors remains a major challenge and a key knowledge gap in this and related research.

Conclusion

This study provides an empirical analysis of *P. radiata* plantations growth dynamics over past three decades in New Zealand. Overall, growth exhibited an upward trajectory until 2011, after which it slowed and plateaued during the most recent decade. Moreover, the rate of increase in basal area increment has clearly declined, indicating a stagnation in productivity gains despite the continued adoption of improved management practices by the sector.

From a management perspective, these findings underscore the importance of adaptive strategies to sustain future productivity under changing environmental conditions. Optimising water and nutrient use efficiency, refining silvicultural practices, and enhancing resilience to climatic extremes will be essential to maintain and improve growth performance. Continued long-term monitoring through PSPs networks remains critical for detecting emerging trends, reducing uncertainty, and supporting evidence-based decision-making for the forestry sector and the wider bioeconomy in New Zealand.

ACKNOWLEDGEMENTS

The authors would like to thank PSP database manager Christine Dodunski, all the PSPs owners for permitting and arranging these data; Priscilla Corbett-Lad for the help with Figure 1; and two internal reviewers for their valuable comments, which helped to improve the manuscript.

FUNDING

This research was funded by Scion's Strategic Science Investment Fund (SSIF) and the Forest Growers Levy Trust (FGLT) through the Resilient Forests Programme (Task No. A89220).

REFERENCES

Arend M, Hoch G, Kahmen A. 2023. Stem growth phenology, not canopy greening, constrains deciduous tree growth. *Tree Physiology 44*: https://doi.org/10.1093/treephys/tpad160

Bayne K, Scott MB, Yao RT. 2022. Getting flow: The place of production forests in the rise of mountain biking. *Forests 13*: 1326. https://doi.org/10.3390/f13081326

Beets PN, Kimberley MO, Garrett LG, Paul TSH, Matson AL. 2019. Soil productivity drivers in New Zealand planted forests. *Forest Ecology and Management 449*: 117480. https://doi.org/10.1016/j.foreco.2019.117480

Bose AK, Etzold S, Meusburger K, Gessler A, Baltensweiler A, Braun S, Buchmann N, Camarero JJ, Haeni M, Kahmen A, Peters RL, Sterck FJ, Tresch S, Walthert L, Zweifel R. 2025. Decreasing stem growth in common european tree species despite earlier growth onset. *Global Change Biology 31*: e70318. https://doi.org/10.1111/gcb.70318

Bugmann H, Bigler C. 2011. Will the CO_2 fertilization effect in forests be offset by reduced tree longevity? *Oecologia 165*: 533-544. https://doi.org/10.1007/s00442-010-1837-4

Caloiero T. 2014. Analysis of rainfall trend in New Zealand. *Environmental Earth Sciences 73*: 6297-6310. https://doi.org/10.1007/s12665-014-3852-y

Clark JS, Andrus R, Arianoutsou M, Ascoli D, Bergeron Y, Bogdziewicz M, Boivin T, … Żywiec M. 2026. Continental contrasts in climate extremes that control tree fecundity. *Global Change Biology 32*: e70738. https://doi.org/10.1111/gcb.70738

Cook BI, Smerdon JE, Seager R, Coats S. 2014. Global warming and 21st century drying. *Climate Dynamics*

43: 2607-2627. https://doi.org/10.1007/s00382-014-2075-y

Dalmonech D, Vangi E, Quesada Chacón D, Collalti A. 2026. Decadal climate-driven decoupling between gross primary productivity and tree growth in Mediterranean forests. *Forest Ecology and Management 615*: 123843. https://doi.org/10.1016/j.foreco.2026.123843

Evans MEK, DeRose RJ, Klesse S, Girardin MP, Heilman KA, Alexander MR, Arsenault A, Babst F, Bouchard M, Cahoon SMP, Campbell EM, Dietze M, … GaytÁn SAV. 2021. Adding tree rings to North America's national forest inventories: An essential tool to guide drawdown of atmospheric CO_2. *BioScience 72*: 233-246. https://doi.org/10.1093/biosci/biab119

Fang J, Kato T, Guo Z, Yang Y, Hu H, Shen H, Zhao X, Kishimoto-Mo AW, Tang Y, Houghton RA. 2014. Evidence for environmentally enhanced forest growth. *Proceedings of the National Academy of Sciences 111*: 9527-9532. https://doi.org/10.1073/pnas.1402333111

Gijbels I, Prosdocimi I. 2010. Loess. *WIREs Computational Statistics 2*: 590-599. https://doi.org/10.1002/wics.104

Grünig M, Rammer W, Senf C, Albrich K, André F, Augustynczik ALD, Baumann M, Bohn FJ, Bouwman M, Bugmann H, Collalti A, Cristal I, Dalmonech D, … Seidl R. 2026. Climate change will increase forest disturbances in Europe throughout the 21st century. *Science 391*: eadx6329. https://doi.org/10.1126/science.adx6329

Hacket-Pain A, Szymkowiak J, Journé V, Barczyk MK, Thomas PA, Lageard JGA, Kelly D, Bogdziewicz M. 2025. Growth decline in European beech associated with temperature-driven increase in reproductive allocation. *Proceedings of the National Academy of Sciences 122*: e2423181122. https://doi.org/10.1073/pnas.2423181122

Hopkins D, Campbell-Hunt C, Carter L, Higham JES, Rosin C. 2015. Climate change and Aotearoa New Zealand. *WIREs Climate Change 6*: 559-583. https://doi.org/10.1002/wcc.355

Hu Y, Sperotto RA, Koubouris G, Stojnić S, Bellaloui N. 2023. Tree ecophysiology in the context of climate change. *Journal of Forestry Research 34*: 1-5. https://doi.org/10.1007/s11676-023-01596-4

Jacoby WG. 2000. Loess: a nonparametric, graphical tool for depicting relationships between variables. *Electoral Studies 19*: 577-613. https://doi.org/10.1016/S0261-3794(99)00028-1

Jayawickrama KJS, Carson MJ. 2000. A breeding strategy for the New Zealand radiata pine breeding cooperative. *Silvae Genetica 49*: 82-90.

Johnson DM, McCulloh KA, Reinhardt K. 2011. The earliest stages of tree growth: development, physiology and impacts of microclimate. In: Meinzer FC, Lachenbruch B, Dawson TE Ed. *Size- and Age-Related Changes in Tree Structure and Function*, pp. 65–87. Dordrecht: Springer Netherlands. https://doi.org/10.1007/978-94-007-1242-3_3

Kimberley MO, Moore JR, Dungey HS. 2015. Quantification of realised genetic gain in radiata pine and its incorporation into growth and yield modelling systems. *Canadian Journal of Forest Research 45*: 1676-1687. https://doi.org/10.1139/cjfr-2015-0191

Klesse S, Babst F, Lienert S, Spahni R, Joos F, Bouriaud O, Carrer M, Di Filippo A, Poulter B, Trotsiuk V, Wilson R, Frank DC. 2018. A combined tree ring and vegetation model assessment of European forest growth sensitivity to interannual climate variability. *Global Biogeochemical Cycles 32*: 1226-1240. https://doi.org/10.1029/2017GB005856

Körner C. 2006. Plant CO_2 responses: an issue of definition, time and resource supply. *New Phytologist 172*: 393-411. https://doi.org/10.1111/j.1469-8137.2006.01886.x

Lu R, Williams LJ, Trouvé R, Murphy BP, Baker PJ, Carle H, Forrester DI, Green PT, Liddell MJ, Marunda C, Mannes D, Mazanec R, Ngugi MR, Neldner VJ, Prior L, Ruthrof KX, Suitor S, Xia J, Medlyn BE. 2026. Pervasive increase in tree mortality across the Australian continent. *Nature Plants 12*: 62-73. https://doi.org/10.1038/s41477-025-02188-2

Mackay A, Hutchinson K, Moore J, Dodd M, Lin Y, Muir P, Smith C, Vibart R, Bilotto F. 2023. Are observed rates of productivity compared to model predictions indicating negative climate impacts in perennial plants? *Journal of New Zealnd Grasslands 85*: 51-60. https://doi.org/10.33584/jnzg.2023.85.3669

Martinez del Castillo E, Torbenson MCA, Reinig F, Tejedor E, de Luis M, Esper J. 2024. Contrasting future Growth of norway spruce and scots pine forests under warming climate. *Global Change Biology 30*: e17580. https://doi.org/10.1111/gcb.17580

Mason EG. 2023. Impacts of tending on attributes of radiata pine trees and stands in New Zealand – a review. *New Zealand Journal of Forestry Science 53*. https://doi.org/10.33494/nzjfs532023x178x

McMahon SM, Parker GG, Miller DR. 2010. Evidence for a recent increase in forest growth. *Proceedings of the National Academy of Sciences 107*: 3611-3615. https://doi.org/10.1073/pnas.0912376107

Mead D. 2013. *Sustainable management of Pinus radiata plantaions.* Rome.

Monserud RA, Sterba H. 1996. A basal area increment model for individual trees growing in even- and uneven-aged forest stands in Austria. *Forest Ecology and Management 80*: 57-80. https://doi.org/10.1016/0378-1127(95)03638-5

National Institute of Water and Atmospheric Research. 2024. *2023: New Zealand's second warmest year on record*. Auckland, New Zealand.

New Zealand Forest Owners Association. 2023. *Facts & figures 2022/23*. Wellington, New Zealand, 64 p.

Paul TSH, Wakelin SJ. 2024. New Zealand's planted forests–Carbon stocks and yield in fast growing exotic tree plantations of the Southern Hemisphere. *Trees, Forests and People 16*: 100590. https://doi.org/10.1016/j.tfp.2024.100590

Pilaar CH, Dunlop JD. 1990. The permanent sample plot system of the New Zealand Ministry of Forestry. *Bulletin des Recherches Agronomiques de Gembloux 25*: 5-17.

Pretzsch H, Biber P, Schütze G, Uhl E, Rötzer T. 2014. Forest stand growth dynamics in Central Europe have accelerated since 1870. *Nature Communications 5*: 4967. https://doi.org/10.1038/ncomms5967

Pretzsch H, del Río M, Giammarchi F, Uhl E, Tognetti R. 2022. Changes of tree and stand growth: Review and implications. In: Tognetti R, Smith M, Panzacchi P Ed. *Climate-Smart Forestry in Mountain Regions*, pp. 189-222. Cham: Springer International Publishing. https://doi.org/10.1007/978-3-030-80767-2_6

R core team. 2022. *R: A language and environment for statistical computing*. Vienna, Austria.: R Foundation for Statistical Computing.

Reichstein M, Bahn M, Ciais P, Frank D, Mahecha MD, Seneviratne SI, Zscheischler J, Beer C, Buchmann N, Frank DC, Papale D, Rammig A, Smith P, Thonicke K, van der Velde M, Vicca S, Walz A, Wattenbach M. 2013. Climate extremes and the carbon cycle. *Nature 500*: 287-295. https://doi.org/10.1038/nature12350

Salekin S, Dickinson YL, Bloomberg M, Meason DF. 2024. Carbon sequestration potential of plantation forests in New Zealand - no single tree species is universally best. *Carbon Balance and Management 19*: 11. https://doi.org/10.1186/s13021-024-00257-1

Salekin S, Dickinson Y, Liddell J, Dodunski C, Lad P, Dovey S, White DA, Pont D. 2026. Discrepancies between predictions of mainstream empirical growth models and observed forest growth of *Pinus radiata* (D. Don) plantations in New Zealand. *Forest Ecosystems 15*: 100404. https://doi.org/10.1016/j.fecs.2025.100404

Salinger MJ, Griffiths GM. 2001. Trends in New Zealand daily temperature and rainfall extremes. *International Journal of Climatology 21*: 1437-1452. https://doi.org/10.1002/joc.694

Sigid MF, Harrington LJ, Lewis H. 2026. On the future of extreme rainfall in New Zealand. *Earth's Future 14*: e2025EF007427. https://doi.org/10.1029/2025EF007427

Spinoni J, Vogt JV, Naumann G, Barbosa P, Dosio A. 2018. Will drought events become more frequent and severe in Europe? *International Journal of Climatology 38*: 1718-1736. https://doi.org/10.1002/joc.5291

Terrer C, Jackson RB, Prentice IC, Keenan TF, Kaiser C, Vicca S, Fisher JB, Reich PB, Stocker BD, Hungate BA, Peñuelas J,… Franklin O. 2019. Nitrogen and phosphorus constrain the CO_2 fertilization of global plant biomass. *Nature Climate Change 9*: 684-689. https://doi.org/10.1038/s41558-019-0545-2

Wakelin SA, Gomez-Gallego M, Jones E, Smaill S, Lear G, Lambie S. 2018. Climate change induced drought impacts on plant diseases in New Zealand. *Australasian Plant Pathology 47*: 101-114. https://doi.org/10.1007/s13313-018-0541-4

Watt MS, Kirschbaum MUF, Moore JR, Pearce HG, Bulman LS, Brockerhoff EG, Melia N. 2018. Assessment of multiple climate change effects on plantation forests in New Zealand. *Forestry: An International Journal of Forest Research 92*: 1-15. https://doi.org/10.1093/forestry/cpy024

Withers CS, Krouse DP, Pearson CP, Nadarajah S. 2007. Modelling temperature trends in New Zealand. *Environmental Modeling & Assessment 14*: 231-249. https://doi.org/10.1007/s10666-007-9126-2

Yao RT, Palmer DJ, Payn TW, Strang S, Maunder C. 2021. Assessing the broader value of planted forests to inform forest management decisions. *Forests 12*: 662. https://doi.org/10.3390/f12060662