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Nitrate Uptake from an Aquifer by Two Plantation Forests: Plausibility Strengthened by Process-Based Modelling

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Abstract: Forest plantations can access water from some unconfined aquifers that also contain nitrate at concentrations that could support hydroponic culture, but the separate effects of such additional water and nitrogen availability on tree growth have not hitherto been quantified. We demonstrate these effects using simulation modelling at two contrasting sites supporting *Eucalyptus globulus* Labill. or *Pinus radiata* D.Don plantations. The APSIM *Eucalyptus* and *Pinus* models simulated plantation growth within 2% of observed growth where the water table was at 4 m depth for eucalypts (height 28 m, MAI 32 m^3 ha^{-1} $year^{-1}$) and at 23 m for pines (height 37 m, MAI 20 m^3 ha^{-1} $year^{-1}$). In simulations without an aquifer, observed growth could only be matched using unrealistically high surface soil nitrogen (N) supply, suggesting this is an unlikely mechanism. Simulated aquifer N concentrations, evapotranspiration, and net N mineralization and leaching (emergent properties of modelling) were similar to measured values. These results strengthen the plausibility that aquifer N uptake by plantations could be contributing to tree growth. This hypothesis warrants further research that quantifies these processes at multiple sites. Simulations included growth of herbaceous and tree weed species, and pasture, which demonstrated the utility of the process-based APSIM modelling framework for dynamically simulating carbon, water and N of plantations and other mixed-species systems.

Keywords: APSIM model; ecosystem; groundwater; *Pinus*; *Eucalyptus*; nitrogen; water; South Australia

1. Introduction

Eucalyptus and *Pinus* plantations are globally significant for wood supply. In Australia, plantation forests in southeastern South Australia, colloquially known also as the western part of the Green Triangle region, grow above an unconfined aquifer and cover approximately 1350 km^2. This area is about 7% of Australia's total plantation estate, and 74% supports *Pinus radiata* D.Don and 26% *Eucalyptus globulus* Labill. [1]. Establishment of pine plantations in the region commenced in 1881 [2], and many of the *P. radiata* sites now support a 3rd rotation that exceeds the productivity of previous rotations [3]. Establishment of significant areas of eucalypt plantations commenced in the 1990s, and, being a shorter

duration crop, some are also now in a 3rd rotation. Mean annual increment (MAI) of *P. radiata* stem wood at these sites can reach 56 m^3 ha^{-1} $year^{-1}$ over 30- to 35-year rotations, which is approximately double that achieved on average in other parts of Australia with comparable annual precipitation of 600–800 mm $year^{-1}$ [4]. This MAI was also 2–3 times greater than could be expected from the relatively low N availability and dominantly sandy soils compared to 50 forested sites in North America for other species [5]. However, regional area and wood supply statistics from the Australian Bureau of Agricultural and Resource Economics and Sciences indicate average productivity across the Green Triangle region is about 21 m^3 ha^{-1} $year^{-1}$ for *P. radiata* and 17 m^3 ha^{-1} $year^{-1}$ for *E. globulus*, which is similar to other plantation regions in Australia (Jim O'Hehir pers. comm.).

High plantation productivities at some sites in the region have been attributed partially to roots accessing water from an unconfined aquifer [1,6], the surface of which fluctuates in space and time and can be 0–25 m below the ground surface [2]. That tree roots of the plantations access such depths is not surprising as they have been observed in caves in the region at 14 m depth in Morgan's cave [6] and at 15 m depth in the Margaret Rose Cave. In contrast, roots of relatively shallow-rooted agricultural crops and pastures in surrounding farmland are assumed not to access this water resource unless the water table rises close to the soil surface, or it is pumped and delivered by irrigation. Aquifer water is a finite resource used for various purposes in the region, and consequently planation establishment is now regulated in South Australia [7].

The aquifer contains N as nitrate, which is a concern for the supply of drinking water to the city of Mount Gambier, South Australia, where concentrations of nitrate-N in incoming groundwater are in the range 4–7 mg L^{-1}, about half the Australian Drinking Water Standard of 11.3 mg L^{-1} [8], which is assisted by local dilution by inflows of fresh stormwater. Concentrations greater than 100 mg L^{-1} have been measured in the aquifer, but most frequently they are less than 10 mg L^{-1} [9–11], and under plantations, range from non-detectable to 8 mg L^{-1} (Jeff Lawson pers. comm.). Research from a part of the region supporting intensive horticulture and using monitoring data, stable isotopes, and process-based modelling, suggested that nitrate came mainly from mineralization of nitrogen that had been fixed by legumes in agricultural and horticultural areas, and from septic systems [9]. Nitrate inputs from plantation areas were minimal. Since plants can take up nitrate-N down to a concentration of c. 0.04 mg L^{-1}, and rapid growth in hydroponic production can be supported by concentrations of c. 0.35 mg L^{-1} [12,13], it would not be surprising if plantations took up nitrate-N from the aquifer. However, the importance of such a process needs to be quantified relative to other N sources. An alternative hypothesis is that some soils in the region might have an atypical ability to supply N and support high growth rates. Measured ranges of soil properties in the region include high values for the concentration of surface soil total N (0.02%–0.20%) and low values for the C:N ratio (13–60), which would promote N mineralization [5,14].

Process-based modelling is useful for simulating agricultural and plantation forest ecosystems including plant growth, plant use of water and nitrogen, and effects on soil. A set of such models are available in the APSIM modelling framework [15] that have been useful for simulating a range of eucalypt [16–18] and pine plantations, agricultural crops, and grazed pasture systems. The APSIM models quantify key pools and fluxes of C, N and water, and have the flexibility to simulate plantation systems on deep soils with an unconfined aquifer.

Denitrification and plant N uptake have long been considered significant pathways for reducing nitrate concentrations in riparian zones with shallow water tables [19,20], and denitrification in such conditions has been simulated using process-based modelling [21]. However, the process-based simulation of nitrate uptake from water tables and its impact on tree growth has received very little attention, and none that we are aware of in the context of broadscale plantation forestry.

Our objectives were to (i) quantitatively determine whether N supply to highly productive plantations in the region could be supplemented by either uptake of aquifer N or by

atypically high soil N supply, (ii) compare literature data with emergent properties of the simulations such as net N-mineralization, N-leaching, evapotranspiration, and nitrate-N concentrations in the aquifer, and (iii) demonstrate the utility of the APSIM modelling framework for simulating fluxes of C, water and N in forest plantations (with weeds) and pasture. This research is highly novel in the context of plantation forestry and the methods used to quantify the hypothesis about the potential effect of the uptake of aquifer nitrate on tree growth.

2. Materials and Methods

2.1. Sites and Data

Although it was desirable to have temporally consistent measurements across the sites, it was impossible to do so because the satellite and modelling technologies used here became available only recently. Instead, we used historic data and compared observed and predicted values where opportunities existed.

Simulations were for two sites: (i) 'Shallow Site' was a *Eucalyptus globulus* plantation 53 km north-northwest of Mount Gambier, South Australia, over a shallow water table (4 m), and (ii) 'Deep Site' was a *Pinus radiata* stand 16 km south-west of Mount Gambier over a deep water table (23 m) (Table 1). The Shallow Site included approximately annual measurements of trees and 6-monthly measurements of water table depth. At the Deep Site, trees were measured prior to clearfelling and the commencement of measurements of the pools and fluxes of soil carbon and N [22,23]. Key details of these sites are provided in Table 1.

Table 1. Site characteristics.

Site Attribute	Shallow Site	Deep Site
Latitude	−37.3615	−37.8842
Longitude	140.6730	140.9497
Elevation (m)	57	45
Mean daily temperature (C) [a]	14.27	13.87
Mean annual precipitation (mm) [a]	613	818
Mean annual pan evaporation (mm) [a]	1350	1290
Soil Taxonomy	Alfasol	Spodic quartzipsamment
Australian Soil Classification	Sodosol grey	Arenosol grey
Previous landuse	Pasture	Uncertain
Year planted	2000	1947
Silviculture	*E. globulus* Labill. establishment weed control, fertilized at age 4 years, unthinned, unpruned	*P. radiata* D.Don no weed control, fertilizer at planting, thinned, pruned
Plantation Measurements:		
Year measured	2010	1984
Stocking initial, final (stems ha^{-1})	1164, 873	1600 [b], 162
Average tree height (m)	28.4	37
Basal area (1.3 m $height_{over\text{-}bark}$, m^2 ha^{-1})	32.1	33.9
Volume (stem $wood_{under\text{-}bark}$ m^3 ha^{-1})	316	756 [c]
MAI_{ub} (stem $wood_{under\text{-}bark}$ m^3 ha^{-1} $year^{-1}$)	31.6	20.4 [c]

[a] 1985–2020 for the Shallow Site, 1940–2020 for the Deep Site. [b] Assumed initial stocking as was common in the region at the time. [c] Includes estimates of wood volumes removed during two thinning operations, and assumes merchantable volume is 86% of total stem volume.

Both sites had nearby fertilizer experiments where plantations responded positively to N fertilizer additions by 3 years of age [23]. A hypothetical pasture scenario was also simulated for the Shallow Site, with and without irrigation. Water table depths and nitrate concentrations across the region were monitored at various intervals by local authorities [24].

2.2. Modelling

The *Eucalyptus*, *Pinus*, Barley and AGPasture (ryegrass and white clover) models of the APSIM Next Generation modelling framework (www.apsim.info, accessed on 9 December 2021) [15] (herein referred to as APSIM or the model) were used to simulate plantations, weeds and pastures. The models have been documented and tested in tropical and sub-tropical plantation systems [15–18] and temperate pastures [25] across a wide range of contexts (climate, soil, management, and genotype) comparable to the current purpose. These models are one-dimensional that maintain a mass balance for water, C and N per unit soil surface area within the system, with an upper boundary notionally set as maximum plant height, and a lower boundary that is the bottom of the deepest soil layer. Carbon, water and N can enter and leave the system, and maximum daily rates of carbon fixation are constrained by various plant factors interacting with the atmosphere and soil. Stem metrics (height, diameter, volume) are based on calibrated empirical relationships with stem biomass.

Although previous tests included temperate *Eucalyptus* and *Pinus* plantations, as in the current study, they did not include unconfined aquifers. These previous tests provided information on model agreement with field data for leaf area index, component biomass, C and N content, water use, and tree stem dimensions. Simulations and documentation for earlier model testing are provided on GitHub (https://github.com/APSIMInitiative/ApsimX, accessed on 9 December 2021). A feature of the models relevant to the current study is that a user does not specify from where in a soil profile (or aquifer) roots take up water or N daily. Instead, potential demand is reconciled with potential supply from anywhere in the system separately for water and N, and they are taken up from soil where they are most readily available, within daily potential uptake rate constraints that are specified for each soil horizon. Weeds were simulated for the *Eucalyptus* plantation as barley and *Pinus* as representations of annual herbaceous and perennial woody weeds, respectively.

Key weather, soil and management inputs to the simulations are provided in Table 1 and Table 2 and Tables S1–S8. The APSIM framework enables use of different genotypes (called cultivars) within the genus of a model, which cater for physiological and allometric differences. Here, the 'globulus' cultivar was used for *Eucalyptus*, and the 'BFG' cultivar for *Pinus*. A cultivar did not need to be specified for ryegrass. Daily weather data (rain, maximum and minimum temperature, radiation) for each site was sourced within the APSIM user interface from the SILO gridded product (https://www.longpaddock.qld.gov.au/silo/, accessed on 9 December 2021), which has a 3 arc-minute (c. 5 km on-ground) resolution. Soil data similarly were sourced within APSIM from the Soil and Landscape Grid of Australia (SLGA, https://www.clw.csiro.au/aclep/soilandlandscapegrid/, accessed on 9 December 2021), which has a 3 arc-second (c. 90 m on-ground) resolution. As the greatest depth provided by the SLGA was 2 m, total soil depth was increased in all simulations by replicating values for the lowest layer down to the bottom of the profile required, which included an aquifer for several simulated treatments.

Fine tree roots were permitted to access the total profile by growing down at the default maximum rate of 10 mm d^{-1}. Pasture roots grew at potentially double that rate, but they were limited to the top 1 m of soil and therefore did not reach the aquifer. The model was parameterized to allow all plants to extract water to c. −1.5 MPa soil water potential. To provide a closed system, simulated drainage was not allowed below the bottom of the profile or laterally, as linking these 1D simulations to 2D or 3D ground water modelling was beyond the scope of the study. At the Shallow Site, roots were permitted to take up water and N from the aquifer or its capillary fringe, but at the Deep Site water and N uptake only from the capillary fringe was permitted because significant water uptake by roots does not occur at such depths [26]. Input values for soil organic C, C:N ratio, and pH were set to measured values at the sites or nearby where available, or else left as the acquired SLGA values. Inputs of N from precipitation [27], non-symbiotic N fixation [28], and rhizosphere priming [29], which are processes not specifically simulated in APSIM and poorly quantified generally, were together set at 10 kg ha^{-1} $year^{-1}$ applied in equal

3-monthly instalments. Seedlings were provided with 40 kg N ha^{-1} at planting as nitrate. In addition, the Shallow Site was fertilized with 125 kg N ha^{-1} as urea at age 4 years, which was simulated to reflect this operation.

Table 2. Key soil input values for APSIM simulations compared to soil attribute values acquired from SLGA. A more detailed comparison of soil attribute values is provided in Tables S1–S8.

Attribute	Shallow Site:		Deep Site:	
	APSIM	SLGA	APSIM	SLGA
C (%, 0–15 cm)	1.93 [a]	2.47	1.20 [a]	4.96
C:N (0–15 cm)	12.5 [a]	32.2	29.0 [a]	39.2
pH (0–15 cm)	5.89 [a]	5.39	6.10 [a]	4.95
Total profile depth (m)	10	2	30.0	2
Maximum root depth (m)	10		22.9	
Depth to aquifer (m)	4 [a]		23.0 [a]	
PAWC [b,c] (mm)	895		1427	
Initial available water [c] (mm)	627		1198	
Initial profile mineral-N [c] (kg ha^{-1})	36		36	

[a] Measured; [b] Plant available water capacity = difference between upper drainage limit and lower plant limit, summed for all horizons; [c] For total profile depth.

Although the *E. globulus* stand was never thinned, natural mortality reduced population density (stocking) over the rotation, which was simulated as thinnings of average trees to match measured values. The *P. radiata* stand was operationally thinned at least twice and likely also experienced mortality, but only the final density was known. Its population density was therefore simulated as 10% mortality and three thinning operations on average trees. To approximate a low level of weed competition at the Shallow Site, herbaceous weeds were simulated by sowing barley for each of the first three years at 100 plants m^{-2}, and to mimic a woody weed *Pinus* was transplanted in the first year at 0.1 plants $m^{-2.}$ Although barley produced 10 t ha^{-1} of biomass during the first year, it produced negligible amounts in the subsequent two years, and *Pinus* produced a maximum of only 0.02 t ha^{-1} as it was rapidly shaded out by *E. globulus*. Hence, weed competition was simulated to be negligible, which was similar to that subjectively assessed by the plantation manager.

Simulated treatments were conducted: (i) without a water table (Control); (ii) with a water table that contained no nitrate (Aq); (iii) with a water table containing nitrate (AqN); and (iv) as for (ii) but including values of surface soil C, C:N and pH highly favorable to net N mineralization [5,14] (AqHiSoilN). For the latter three treatments, a permanent water table was provided at 4 m depth in Shallow Site simulations, and at 23 m in Deep Site simulations, which were generally consistent with regional monitoring and reports [2,24,30] and monitoring near the Shallow Site. Nitrate in the aquifer for the AqN treatment was simulated as 3-monthly additions of nitrate fertilizer at the surface of the water table at a rate calibrated to approximate measured MAI (based on total stem volume over a rotation) and height. For the Shallow Site, simulated and measured MAI and tree height are reported at 10 years of age, which is a nominal age for comparing eucalypt plantation productivity in Australia, but simulations were extended 2 years beyond the actual harvest age of 12 years so that simulated changes in water and N dynamics after harvesting could be compared to patterns generally observed in the literature. For the Deep Site, the simulation was harvested at 37 years for direct comparison with tree measurements at that age. Simulations of hypothetical grazed pastures (irrigated and unirrigated) containing ryegrass and white clover at the Shallow Site, with an intermediate annual rate of N fertilization (applied in 9 instalments), was based on literature [31,32] and used the Agpasture [25] and Stock [33] models available in APSIM.

Satellite-based estimates of evapotranspiration were modelled using the CMRSET algorithm applied to blended Landsat and MODIS surface reflectance data (8 d, 25 m resolution) [34,35]. Data for the period 2001–2014 were obtained from a data set produced for the entire Green triangle [36]. Evapotranspiration simulated in the APSIM model was

calculated as the sum of transpiration, canopy interception, and evaporation from the soil surface, for comparison with these satellite-based estimates.

Depth to the surface of the water table monitored approximately monthly across the region was 0–4.0 m during 1970 to 2004 [2,24,30], and, similarly, 4.25 km to the northwest of the Shallow Site (monitored approximately 6-monthly) was 5.5 m in 2009 rising to 3.5 m by 2019. Hence, an assumed 4 m depth for simulations was realistic at that site. The Deep Site was about halfway between two locations where water table depth was monitored since 1975. In 1984, water table depths were 15–24 m, and dropping at a rate of 0.1 m year^{-1}. To be representative of a deep water table, we therefore assumed a constant depth to the water table of 23 m for this site.

Observed and predicted productivity of plantations (including wood removed during thinning operations at the Deep Site) were compared using height and MAI. Pasture production was calibrated to reflect reasonable values of annual biomass production (15–20 t ha^{-1} year^{-1}). Annual rates of net N mineralization (NNM), and annual cumulative leaching (below 1 m depth) were also simulated, and those at the Deep Site compared with measurements in the second rotation [22,23]. Simulated concentrations of nitrate-N in the aquifer were calculated for comparison with published data for the region generally collected at 1- to 24-monthly intervals since about 1975 [8–10].

3. Results

3.1. Shallow Site

At the Shallow Site, when aquifer water and N were accessed (AqN treatment), simulated *Eucalyptus* MAI and height values were similar to those observed (Figures 1 and 2a,b). The value of MAI was simulated to be 15 m^3 ha^{-1} year^{-1} where roots did not access water from an aquifer (Control treatment). Access to aquifer water increased MAI to 22 m^3 ha^{-1} year^{-1} (Aq treatment), and to 32 m^3 ha^{-1} year^{-1} where nitrate-N was also simulated to be available in the aquifer at a rate of 76 kg N ha^{-1} year^{-1} (AqN treatment). Simulated MAI increased to 37 m^3 ha^{-1} year^{-1} if highly favorable conditions for soil N supply were assumed (AqHiSoilN treatment), i.e., surface soil C was increased from 1.93% to 4.24%, C:N decreased from 12.48 to 8.07, and pH increased from 5.89 to 6.80. Simulated average tree height at age 10 years in the AqN treatment (27.8 m) was 98% of that measured.

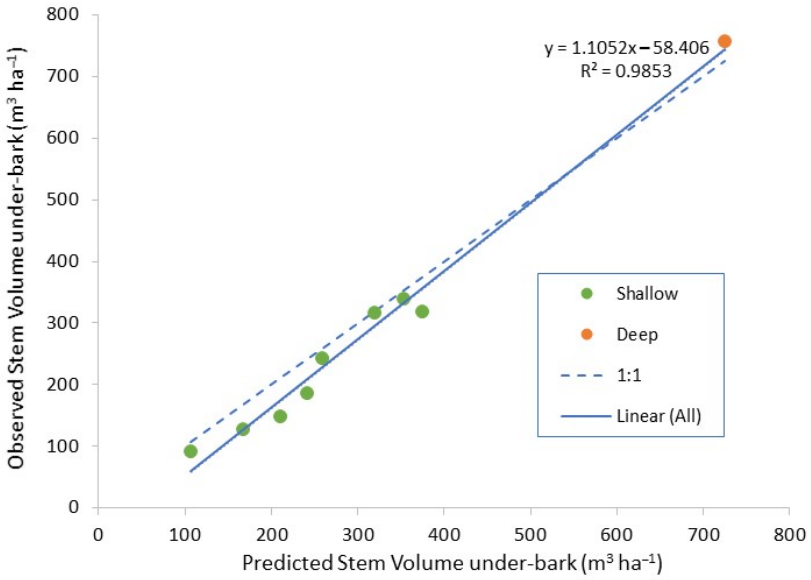

Figure 1. Observed versus predicted comparison of stem volume under-bark values. Multiple values for the Shallow site are for different ages of the plantation, but only end-of-rotation data were available for the Deep site.

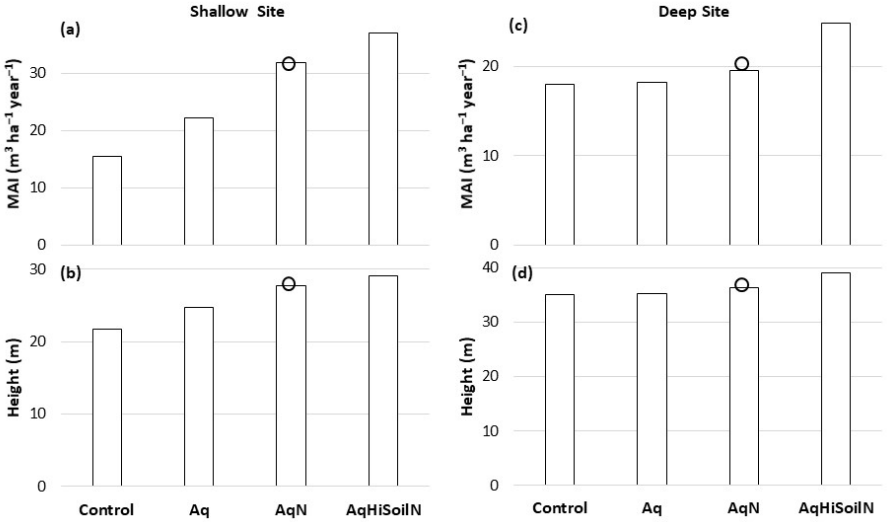

Figure 2. Simulated (bars) plantation MAI (**a**,**c**) and height (**b**,**d**) in four treatments at Shallow (**a**,**b**) and Deep (**c**,**d**) sites, with observed (circles) values placed with the AqN treatment for which simulations were calibrated to match MAI.

Simulated rates of NNM (0–80 cm depth) were in the range 15–85 kg ha^{-1} year^{-1} for most of the rotation where average measured values for soil were used, but they increased to about 100 kg ha^{-1} year^{-1} after harvest (Figure 3a). Rates of NNM simulated with enhanced soil fertility were substantially higher than in other treatments, and in the range 82–253 kg ha^{-1} year^{-1}. Leaching rates below 1 m depth were very low compared to rates of NNM, but also increased after harvesting and were highest at 129 kg N ha^{-1} year^{-1} in the AqHiSoilN treatment (Figure 3b). Cumulative N leaching below 1 m over 37 years reached 6000–8000 kg N ha^{-1} in the pasture systems, which equated to an average of c. 194 kg Nha^{-1} year^{-1}, reflecting the high N inputs in those systems (Figure 4), and there was a more even, temporal pattern of N-leaching with irrigation. Net positive leaching is shown overall, but parts of the trend are negative due to an upward flux that occurs during some periods. Irrigation provided a more uniform pattern of leaching than without irrigation as it took many more years without irrigation for drainage to leach the nitrate-N leaching front below 1 m depth. Simulated concentrations of nitrate-N in the aquifer reached 3.8 mg L^{-1} at 1.5 years prior to roots reaching the aquifer, but later stabilized to c. 1.4 mg L^{-1}, and they increased to 5.7 mg L^{-1} after harvesting (Figure 3c). Simulated rates of water uptake were not affected by the presence of the aquifer until roots were simulated to have reached the depth of the water table and enough time had elapsed to allow an enhanced leaf area in response to an increase in N supply from either or both the aquifer and surface soil (Figure 3d). Thereafter, there were higher rates of simulated water use with an aquifer.

Simulated evapotranspiration for the AqN treatment for the period 2001–2014 (complete years) was on average 71 mm year^{-1} higher (10%) than that derived using a satellite-based method, but less during the early establishment phase (2002) and after harvest (2012–2014, Figure 3d). The deviations from satellite estimates were greater for the Control (21% lower) and AqHiSoilN (29% higher). Of the APSIM simulations, the Aq treatment was in closest agreement with the satellite estimate (6% lower).

Average ratios of P/ET by treatment for the main plantation period (2003–2011) were Control 0.98, Aq 0.77, AqN 0.65, AqHiSoilN 0.57, Satellite 0.76 (Figure 5), suggesting that recharge from precipitation almost met water demand of the Control treatment, that water demand of the other treatments depended on uptake from soil water and the aquifer if present, and that water use from the aquifer was higher in the treatments with higher N availability, i.e., AqN and AqHiSoilN treatments. It was reassuring during this phase of the crop that the satellite product and APSIM simulations generally provided similar estimates of P/ET. However, low ET estimates for all treatments by APSIM in the period 2012–2014 (post-harvest that included some regeneration of trees and weeds) led to high P/ET ratios,

suggesting that patterns of tree and herbaceous weed growth assumed in the simulations for that period might not have been accurate.

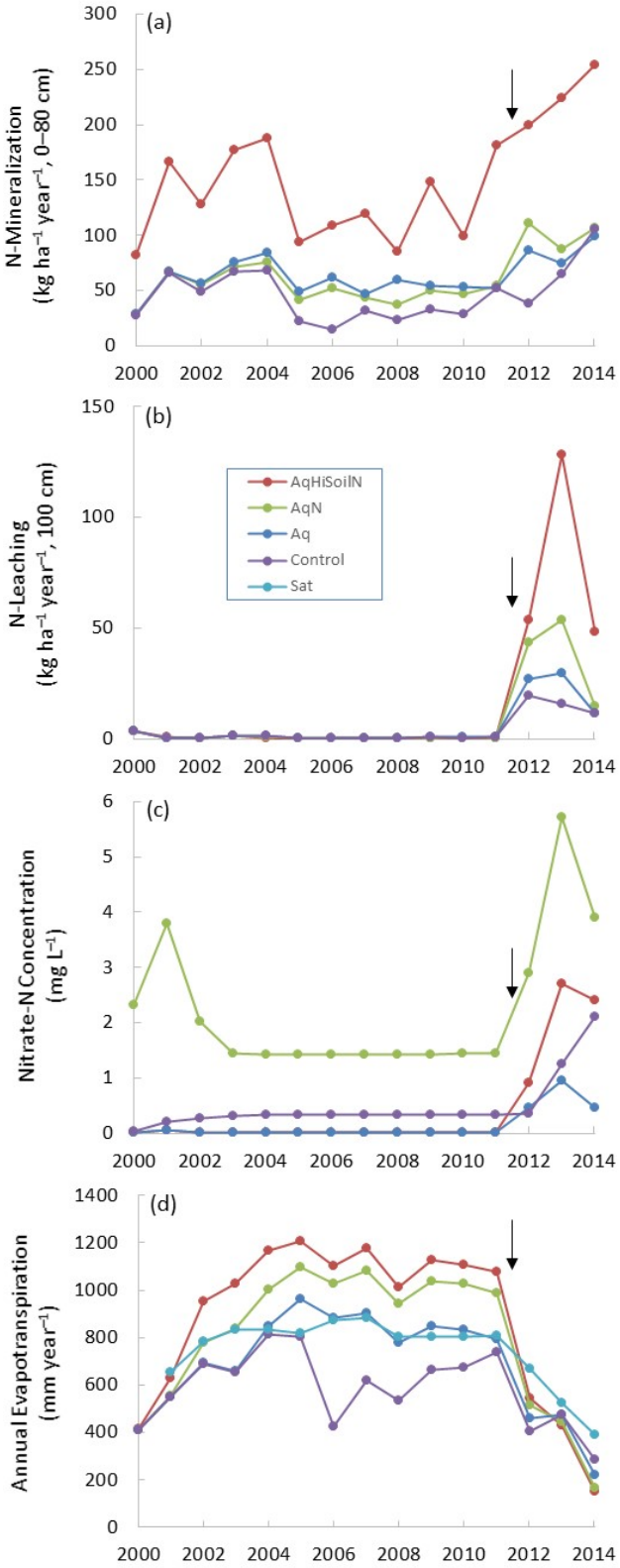

Figure 3. Simulated annual patterns at the Shallow Site of net N-mineralization (**a**), N-leaching below 1 m depth (**b**), N-concentration in aquifer (**c**), and evapotranspiration (**d**). Annual evapotranspiration as estimated by a satellite-based method is also included (Sat). Arrows indicate date of harvest. The legend in (**b**) also applies to all other parts.

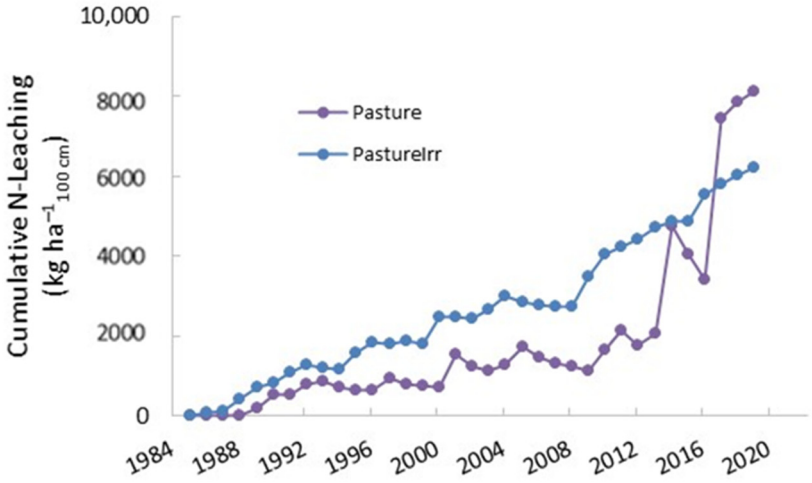

Figure 4. Simulated temporal trend of cumulative N-leaching at 1 m depth under a hypothetical pasture established on the Shallow Site and grown for 37 years with (PastureIrr) and without (Pasture) irrigation.

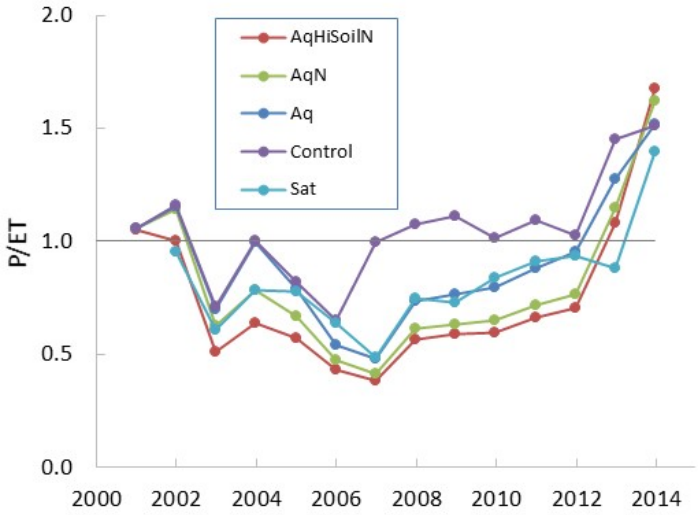

Figure 5. Simulated temporal trend of P/ET ratio for APSIM treatments compared to an estimate based on satellite data. A ratio of 1.0 indicates no net change in soil water storage.

3.2. Deep Site

At the Deep Site, *P. radiata* MAI and height were adequately simulated (Figures 1 and 2c,d). Simulated MAI was 18.0 m^3 ha^{-1} year^{-1} (including thinnings) where roots did not access water from an aquifer. Access to aquifer water in the capillary fringe increased MAI by 1% to 18.1 m^3 ha^{-1} year^{-1}, and to 19.6 m^3 ha^{-1} year^{-1} where nitrate-N was also available in the aquifer. The AqN treatment required 8 kg N ha^{-1} year^{-1} to be added to the aquifer. Simulated productivity increased to 24.9 m^3 ha^{-1} year^{-1} if highly favorable conditions for soil N supply were provided instead of access to aquifer N. Simulated average tree height in the AqN treatment was 98% of that measured. Access to aquifer water and nitrate in the capillary zone at this site provided little simulated benefit to the plantation mainly because fine roots were assumed to be limited to the capillary fringe into which water and nitrate from the aquifer below could only be drawn up by slow unsaturated flow and diffusion processes. This is in contrast to the Shallow site where roots were assumed to grow into the aquifer and could therein directly access water and nitrate. Together, these assumptions and Control treatment cover the full range of possibilities about root access to aquifer water and nitrate, which can only be clarified by further research.

Simulated rates of NNM (0–120 cm depth) were in the range 19–85 kg ha^{-1} $year^{-1}$ where an average of measured values for soil were used, but they reached 272 kg ha^{-1} $year^{-1}$ where conditions very favorable to NNM were assumed (Figure 6a). Leaching rates were much lower than NNM rates, highest during the early few years of the rotation, and highest in treatment AqHiSoilN (Figure 6b). Concentrations of nitrate-N in the aquifer were in the range 0.0–0.2 mg L^{-1} for most of the rotation in the AqN treatment, but they reached 2.8 mg L^{-1} in the AqHiSoilN treatment just prior to roots reaching that depth (Figure 6c).

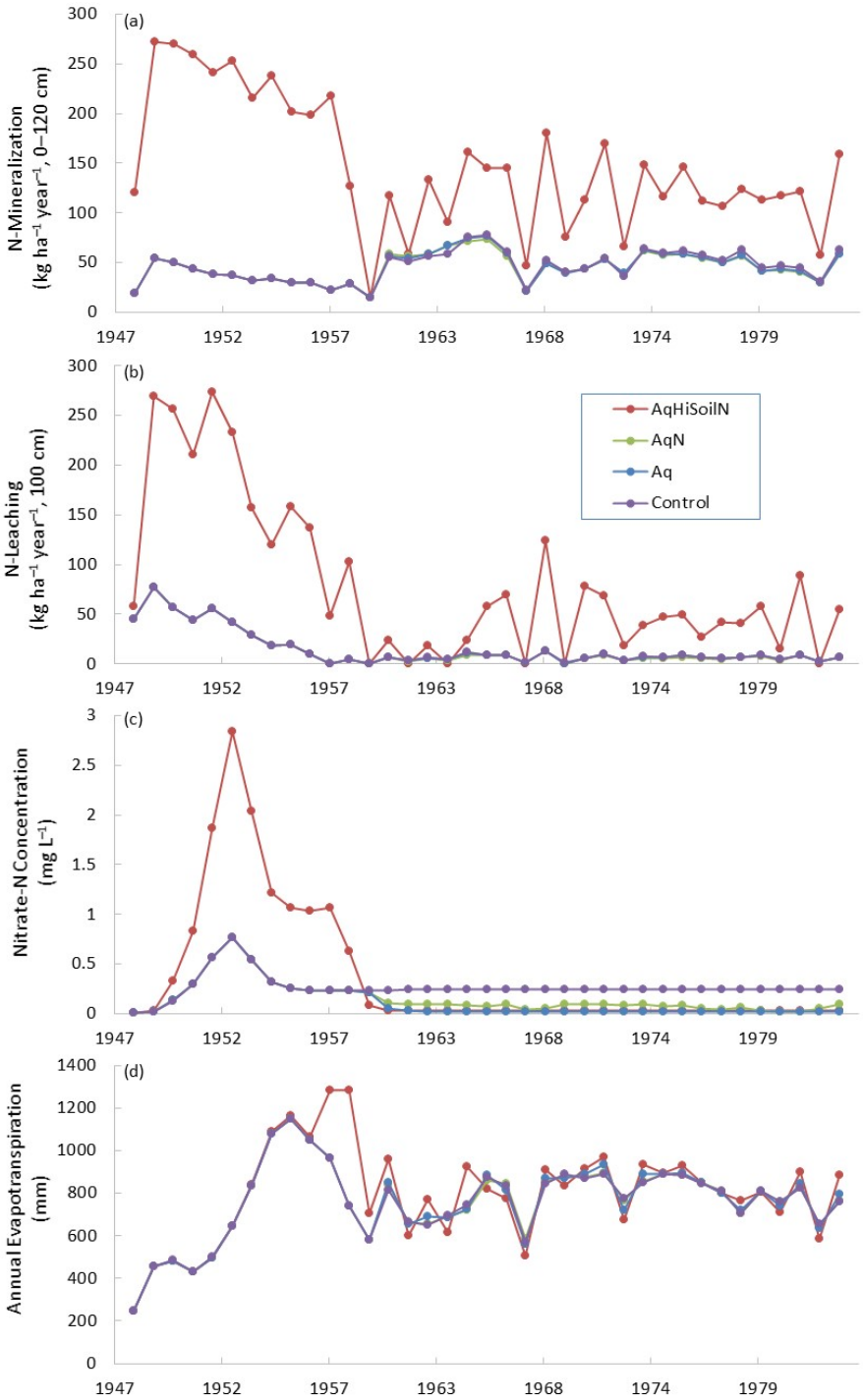

Figure 6. Simulated annual patterns of net N-mineralization (**a**), N-leaching (**b**), N-concentration in aquifer (**c**), and evapotranspiration (**d**) at the Deep Site for the four simulated treatments. Where points and lines for the Aq and AqN treatments are not obvious, they are the same as the Control treatment.

Simulated rates of water uptake were little affected by the presence of the aquifer, as roots were permitted to take up water only from the capillary fringe, which was provided water only very slowly as an upward flux of unsaturated flow (Figure 6d). Ratios of P/ET were across the entire rotation averaged 1.1 in all treatments, inferring net recharge from precipitation into soil and the aquifer, but they were 1.4–1.8 during the first 4 years, 0.5–0.9 at ages 7–10 years, and 0.8–1.4 in all other years. Satellite-based estimates of ET were not available for the period of this simulation.

4. Discussion

Prior research on water uptake by trees from the unconfined aquifer, and nitrate concentrations required for hydroponic growth, suggested that some plantations in this region of South Australia could partially meet their N demand by taking up nitrate from the aquifer. Here we add simulations of the system that quantitatively strengthen that hypothesis. Additionally, these simulations suggest that that this process could be contributing to lower concentrations of N in the aquifer. However, uncertainty about several aspects of the data from measurements and modelling prompt discussion that could affect plausibility and help prioritize future research.

Are simulated rates of evapotranspiration similar to those estimated from a satellite-based method? The 95% confidence interval of measurement for plot-scale measurements of water use by a plantation is 40–300 mm year^{-1} [1], and the RMSE for the satellite method is 354 mm year^{-1} [37]. In addition, a water balance study in the region compared field-based estimates for water balance with a satellite-based product with a lower spatial resolution (MODIS, 8 d, 250 m) to the one used here [38]. The study indicated that the satellite product over-estimated recharge (i.e., under-estimated evapotranspiration) by 45 mm year^{-1}. This analysis of errors infers that the difference between the APSIM and satellite-based estimates of evapotranspiration (Figure 3d) might not be significant. However, periods of consistently higher or lower differences suggest systematic deviations in simulations or satellite estimates for some periods. These comparisons could also be affected by changes in plantation water productivity, which can increase with nutritional status [39].

Plantations in the region where roots can access the unconfined aquifer at shallow depths (<6 m) extract water from it at an average rate of 409 mm year^{-1}, with negligible rates at greater depths [1,26]. For regulatory purposes, plantations in the region growing where the unconfined aquifer is within 6 m of the surface are deemed to be accessing that water at a rate of 166 mm year^{-1} for hardwood and 182 mm year^{-1} for softwood [7]. Fine-scale spatial estimates of actual evapotranspiration were assessed across plantation compartments in the region using the same data set [36] for the period 2001–2014. Averaged across the region for those years, both types of plantations were estimated to have a P/ET ratio in the range 0.7–1.2. Here we sourced these data specifically for the Shallow Site (Figure 3d). Our simulations estimated that water use from the aquifer (when N was also available) was 0 mm during the first two years and as high as 600 mm year^{-1} in 2006, with P/ET values averaging 0.65 for most of the rotation. A comparable range of simulated values for the Deep Site was 539–1221 mm year^{-1} evapotranspiration after the establishment phase and annual P/ET of 0.65–1.4.

Lower rates of evapotranspiration as predicted by the model compared to remote sensing for the Shallow Site have important implications for inferring net recharge of the aquifer by precipitation. These inferred differences in recharge therefore need more detailed study that rely more on site-specific measurements rather than assumptions for both APSIM modelling and remote-sensing estimates. Important estimates would include fluxes of water into and out of the aquifer, detailed soil water balance, plant water use (transpiration) and its role in producing leaf area and biomass, root vertical growth rate and maximum depth, soil evaporation and canopy interception (evaporation), and water uptake rates by trees and understory from all parts of the soil profile. Calibration methods and assumptions for satellite-based estimates also need checking for applicability to specific

locations in the region. Satellite-based estimates are challenging to validate at such fine scales, but they would benefit from external validation that accounts for locality, land cover and plantation species. Calibration and evaluation of the satellite-based method for plantations in Australia have relied on flux towers in other states, and plot-scale water balance studies in the Mt Gambier region [37]. The calibration could be enhanced if a flux tower was also installed in this region.

The measured increase in depth to the surface of the aquifer at the Shallow Site was 2000 mm over 10 years. If this water loss is assumed to be due entirely to water uptake by the plantation, and that the confined aquifer had a specific yield coefficient of 0.1 m recharge per m^{-1} water table [2], this represents a water use rate by the plantation from the aquifer of 10 mm $year^{-1}$. This value is lower than the 186 mm $year^{-1}$ average difference in simulated ET between the AqN and Control treatment. However, neither method accounts for lateral flow in the aquifer into and out of the area during the rotation, which would be required to complete a water balance of the aquifer [38].

Are simulated and observed concentrations of N in the aquifer in agreement? Although nitrate-N concentrations in the aquifer were not measured at either site, simulated concentrations of nitrate-N in the aquifer required to support observed plantation growth were a maximum of 3 mg L^{-1} for pine 6 years after planting and for eucalypt 2 years after harvest, and 0–0.4 mg L^{-1} for most of the rotation at both the Shallow and Deep sites. These values were within the range measured at other locations in the region under plantations, but there could be considerable error due to a lack of knowledge of the gradient of nitrate concentrations in the aquifer at the sampling points and weighted average depth of sampling [2,9,10]. Uptake at concentrations as low as 0.04 mg L^{-1} or less are possible for most plant roots, including *Eucalyptus* [12], and *Pinus* roots probably behave similarly [40]. Active uptake (i.e., independent of water uptake and consuming energy) saturates at 0.7 mg L^{-1}, above which nitrate-N is assumed to flow to the root surface at approximately the same velocity as water. Hence, both measured and simulated concentrations of nitrate-N in the aquifer in the region are consistent with uptake by tree roots. Note, however, that hydroponic growth usually includes mist culture or circulating liquid, which precludes zones of depletion developing around roots. In an aquifer or capillary fringe, very little stirring (dispersion) would occur, which might lead to zones of nitrate depletion developing around roots, and concentrations at root surfaces that are less than those in bulk solution.

Are these results consistent with the observed incidence and magnitude of N deficiency in pine and eucalypt plantations in the region? In this region, soil supply of available N from net N mineralization can exceed the demand by pine plantations [23,41,42], but thereafter deficiencies develop [23,41], especially when in competition with weeds [41,43]. Nitrogen demand by eucalypt plantations is potentially higher than pines (commensurate with higher growth rates), which is also reflected in growth responses to N fertilizer. Indeed, in fertilizer experiments adjacent to the two sites simulated, plantation mangers reported that plantation growth had responded positively by 3 years of age to N applications at establishment [23]. Water use efficiency can also increase with an improvement in N status.

Simulated predictions of N deficiency depended not only on N supply from surface soil by net N-mineralization, but on the timing of roots reaching aquifer N in relation to plant demand. In APSIM, the default value in the model for the maximum rate of downward tree root growth is 10 mm d^{-1}, which is then reduced by root access restriction factors related to plant N and water stress. In these simulations, eucalypt roots took 1.83 years to reach a water table at 4 m depth (6 mm d^{-1}), and pines 11.83 years to reach one at 23 m (5.3 mm d^{-1}). This value for pine is comparable with measurements of 4–12 mm d^{-1} inferred from soil water contents in a deep sand in the region [44]. If roots grew as simulated, there would have been time before reaching the water table for plantations to experience N deficiency on some sites. If vertical root growth or the ability to take up nitrate from it was less than simulated, there would have been further occurrence of N deficiency. Moreover, it is likely that many plantations in the region do not access an aquifer [1,26]. Hence, a

simulated growth response arising from nitrate uptake from an aquifer is consistent with the widespread incidence of N deficiency in the region.

Are simulated rates of net N mineralization and leaching similar to those measured? During the first rotation at the Deep Site that ended in 1984, the average simulated rate of net N mineralization was 32.4 kg N ha^{-1} $year^{-1}$ (0–15 cm depth). This value is not significantly different from the average rate of net N mineralization measured of 36.5 kg N ha^{-1} $year^{-1}$ (standard error 9 kg N ha^{-1} $year^{-1}$, n = 4) during the first four years of the following rotation (1984–1988) [23]. Rates of leaching from this depth in the region, as a percentage of net N mineralization, are known to be very high for the first 3 years after planting due to stimulated mineralization and initially low plant demand that then develops to exceed soil supply during the period of peak canopy development a few years later [23,42,45]. This general pattern was also observed in simulations, and percentages were within the range expected (data not presented). Simulations for pasture indicated high rates of leaching of N from surface soils, but little below 1 m depth without overuse of irrigation. Simulations also suggested that high rates of N input (either by N supply from fertilizer, soils highly favorable to N mineralization, or by access to N in the aquifer) led to higher plantation or pasture biomass production, higher rates of transpiration, lower surface soil water contents and less leaching. These results highlight the complexity of the interactions occurring, and that measurements for validation are very limited as studies that comprehensively measured all of the relevant processes at a single site have not been possible.

How important are errors in soil measurements or interpolated databases? The two sites simulated had contrasting levels of soil sampling and measurement. The Shallow Site drew on the analyses of surface soils in 11 nearby locations (0–10 cm depth), for which mean total C concentrations were 1.93% (range 1.21%–4.24%), C:N 12.48 (8.07–18.43), and pH 5.89 (4.6–6.8). These values had wide overlap with those measured (0–15 cm depth) (n = 39) [14]: C 1.23 (0.39–4.57), C:N 22.5 (14.3–29.6), and pH 5.2 (3.9–6.1), and mean SLGA were similar (Table 2). The same details are not provided for the Deep Site, as soils in those simulations were based on intensive sampling [22,23]. For the Shallow Site, using the ends of the ranges of C, C:N and pH that were most favorable for net N mineralization, rather than those measured nearby, resulted in higher simulated growth than was achieved by enabling access to aquifer nitrogen (Figure 2). This demonstrates several important aspects: (1) the importance of soil data for simulations, (2) that the level of sampling at that site (n = 11 nearby) was acceptable, and (3) that SLGA (mean) values are acceptable default if local measurements are not available. However, SLGA values need careful consideration for use in any simulation because the uncertainty is relatively large and therefore could be grossly inaccurate for an individual site. For example, the 95% uncertainty bounds for soil C in the 5–15 cm depth at the Shallow Site was 0.77%–4.74%, the upper value of which is similar to the highest value measured in plantations in the region used in the AqHiSoilN treatment. An advantage of using the SLGA values as provided within APSIM is that all soil inputs required for a simulation are provided, which can then be adjusted for on-site or nearby measurements, aiding the rapid set-up of simulations. Similar comments are likely to apply to soil data layers from other national soil databases and from the International Soil Reference and Information Centre (ISRIC).

Suggestions for future research: The priority for measurements addressing the current question of the role of nitrate will require non-isotopic methods like those cited here, and isotopic tracer methods (C^{13}, N^{15}) on aquifer water, soil nitrogen and plant nitrogen, which will rely on significant differences between these pools. Knowledge of the profile of nitrate concentrations and water velocities with depth in the aquifer would also be required, with most emphasis near the surface of the water table. It would be useful to determine the source of the differences in evapotranspiration between the satellite-based method, ground-based measurements and modelling at various locations in relation to vegetation (pasture and plantations), management (high and low rates of N fertilization, irrigation and rainfed), and depth to the aquifer. We encourage modelers of dynamic processes in forest ecosystems to seek independent comparisons of estimates across scales, e.g., the

use of satellite-based products. Here, as an example, we have shown how outputs of 1D simulations of a forest ecosystem could be compared to regional knowledge of the depth to surface of an aquifer, its concentrations of nitrate-N, and forest productivity. Earlier use of process-based modelling to predict water use in the region indicated poor accuracy where trees were accessing an aquifer, with the SoilFlux and 3-PG+ models substantially under-estimating water use from the aquifer, and CABALA tending to over-estimate [26], but none took account of the potential effect of aquifer N uptake.

Forest plantations commonly include other vegetation at some time during a rotation, either as unwanted weeds that compete for site resources and consequently reduce crop growth, or as deliberately retained vegetation that has benefits out-weighing the negative environmental and tree growth effects or the costs associated with full weed control. For these systems, as well as agroforestry and highly diverse mixed-species forest systems, we need simulation capabilities that can capture more than monocultures. This need was recognized earlier [46], which led to these capabilities being included in APSIM [15,47]. In the current simulations, herbaceous and woody weeds were included at low density, but their biomass productivity was simulated to decrease to negligible amounts during the first 3 years due to competition from the tree crop for light, water and N (data not presented), which is typical for plantations in this region [41,43]. Tree models currently available in APSIM are Gliricidia, oil palm, and temperate and tropical genotypes of *Eucalyptus* and *Pinus*. There is a much larger range of herbaceous pastures and crops, and the list of crops, pastures and trees available in APSIM is expected to continue to expand. These plant models (N-fixers, non-N-fixers, trees, shrubs and herbaceous) can be included as required in one dimensional simulations of forest plantation systems, and there is also a two-dimensional capability that was developed for agroforestry. APSIM also includes a capability to simulate livestock systems and pest life cycles, but these have not yet been explored in a forestry context.

5. Conclusions

For the first time, research here linked modelling and observations to strengthen the plausibility that forest plantations at two sites in the Mount Gambier region took up nitrate-N from an aquifer that led to increased tree growth. Several lines of evidence were provided. (i) Nitrate-N was present in the aquifer across the region at concentrations adequate for hydroponic culture. (ii) Roots were known to reach the aquifer and take up water. (iii) With a previously validated process-based model, simulated productivity could match that observed only by either including the possibility of N uptake from the aquifer, or, much less likely, by specifying soil conditions much more favorable for N supply from mineralization than measured. (iv) Emergent properties of the modelling were generally consistent with observations: rates of net N-mineralization and N-leaching, concentrations of nitrate-N in the aquifer, and rates of water uptake from the aquifer. Differences in estimates of evapotranspiration across scales (satellite to plot) warrant further investigation. These processes partly explain the observation that nitrate-N concentrations in the aquifer under plantations were observed in some instances to be less than under farmland that was mainly pasture. Simulations demonstrated the utility of the APSIM framework for simulating processes in complex forest ecosystems, but uncertainties about the calibration process meant that its predictions of water and nitrate uptake from the aquifer in this region can only be accepted currently as hypothetical. Future research should quantify the dynamics of aquifer N use by plantation at a range of sites.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/f13020184/s1, Table S1: Unmodified soil physical parameter values sourced by APSIM from the SLGA for the Shallow Site, Table S2: Modified soil physical parameter values as used in simulations for the Shallow Site, including measured values and additional depths, Table S3: Unmodified soil chemical parameter values sourced by APSIM from the SLGA for the Shallow Site, Table S4: Modified soil chemical parameter values as used in simulations for the Shallow Site, including measured values and additional depths, Table S5: Unmodified soil physical parameter

values sourced by APSIM from the SLGA for the Deep Site, Table S6: Modified soil physical parameter values as used in simulations for the Deep Site, including measured values and additional depths, Table S7: Unmodified soil chemical parameter values sourced by APSIM from the SLGA for the Deep Site, Table S8: Modified soil chemical parameter values as used in simulations for the Deep Site, including measured values and additional depths.

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