Quantifying interception associated with large-scale plantation forestry in the Northern Territory

March 2012

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Acknowledgements

This project was funded by the Australian Government through the National Water Commission's Raising National Water Standards Program. Many thanks to the owners and property managers for letting us access to mahogany plantation sites. Mr Steven Tickell of the Water Resources Division of NT Department of Natural Resources, Environment, The Arts and Sport provided invaluable advice and data sources for isotopic sampling in Stray Creek. We also thank Michael Brand and Mathew Northwood from Charles Darwin University for their assistance with compiling the various data sets on soils and catchment maps. Thanks to Emma Richter and Ginni Glyde of the National Water Commission for their support throughout the project.

Executive Summary

Introduction

In 2004, the Northern Territory Government signed an Intergovernmental Agreement as part of the Commonwealth's National Water Initiative (NWI). The NWI identified large-scale plantation forestry as an activity which may be undertaken without a water access entitlement (WAE). However, as this has the potential to intercept significant volumes of surface and/or groundwater, under the agreement, the NT Government is required to assess the significance of these activities and apply appropriate planning, management and/or regulatory measures. Research undertaken as part of this report suggest interception of water from non-irrigated mahogany plantations is unlikely to significantly differ from native vegetation or improved pasture water use. However, this finding needs to be treated with caution as results from the modelling are subject to uncertainty, and more work is required to confirm model findings.

In the mid-2000s, an introduction of Managed Investment Schemes (MIS) in plantation forestry resulted in the development of a plantation estate of *Khaya senegalensis* (desr.) A. Juss (African mahogany) in the Douglas-Daly catchment. These non-irrigated plantations have been developed predominantly on freehold lands previously cleared for improved pastures. It is anticipated that there will be an expansion of the African mahogany estate within the Daly River region of the Northern Territory. This report proposes the development of a policy framework for the management of non-irrigated plantations, such as those of the in the Douglas-Daly region, to address elements of the NT's NWI obligations.

Mahogany plantations currently represent only a small proportion of the total catchment area (<1%), however the estate is currently ~13, 000 ha and is anticipated that this area could increase at a rate of approximately 2000 ha^{-1}, potentially up to a total of 50, 000 ha. There are no existing mature and extensive plantation sites to directly measure water balance components. As such, a modelling approach was taken to examine future scenarios and potential impacts where a plantation estate is developed over time.

Water use characteristics of plantations

In order to assess the impacts of African mahogany plantation expansion on the water resources, a preliminary parameterisation of the growth model 3-PG2 was undertaken using literature, existing data and expert knowledge. Water balance of the dominant land types of the Douglas-Daly catchment, native savanna vegetation, improved pasture and mahogany plantations were simulated. The model agreed reasonably well with growth of African mahogany within the region, and was also in reasonable agreement with previous work examining the water balance of tropical savanna vegetation and improved pasture communities within the catchment (TRaCK program). A table of water balance components for the three land uses is given below.

Annual evapotranspiration (ET, total land surface water loss) from mahogany plantations was found to be similar to that observed in the surrounding tropical savanna vegetation and improved pasture, although there were marked differences in the partitioning of total ET and the seasonal dynamics of ET.

Mahogany plantations maintain canopy transpiration rates more than double that of the native Eucalypt trees species of the savanna (Summary Table). Isotopic analyses suggests, that young mahogany trees (~4 yo) are not utilising groundwater to maintain this high rate, and are able to meet transpirational requirements for soil store alone. In land units most appropriate for plantations, water table depth is typically well beyond the anticipated rooting depth (> 15 m). Mahogany tree plantings within 500 m of watercourses where water tables depth is approximately 5m-7 m, isotopic analysis suggested trees were not using groundwater. For trees established in low lying positions in the landscape this result may change as trees mature and root systems become deeper and more extensive.

Tree transpiration dominates ET in plantations, whereas understory transpiration and evaporation dominate the annual water balance of tropical savannas. The shift to higher tree water use on plantations is largely offset by the loss of understory vegetation, in particular, high water using grasses. On managed plantations, at canopy closure, shading results in very low vegetation cover beneath the tree canopy. As a result, up to 400 mm of moisture that would have otherwise been transpired by grasses remains in the soil profile which is available to support mahogany tree transpiration and growth.

Summary of water balance components for contrasting land uses in the Douglas-Daly catchment, NT using the 3PG2 forest growth model. This modelling is described in Section 4 of this report. All units are mm y^{-1}.

Water balance components	African mahogany plantation	Tropical savanna	Improved pasture
Rainfall	1286	1260	1260
Canopy Transpiration	637	270	898
Understory transpiration	n/a	392	n/a
Interception	90	64	56
Soil Evaporation	180	184	191
Total evapotranspiration	907	910	1157
Runoff/drainage	403	379	74
ΔSoil	24	30	-28

Annual ET across the three land covers is similar at ~ 900-1000 mm y^{-1} (Summary table). Higher tree water use may result in significant depletion of soil water stores, particularly in the late dry season. This may reduce deep drainage as ultimately a larger volume of water is required during the following wet season to replenish soil water resources. However, the impact of this dynamic could not be fully explored within the current modelling framework, but this may be an important dynamic in this system as a large component of dry season baseflow in the rivers of the catchment is derived from groundwater discharge. This is an ongoing research question that requires improved modelling.

There is considerable uncertainty in model outputs as there are few existing parameter sets for this species and little data on the growth and water use dynamics for model validation. Estimates of pasture ET are higher than previous measurements. It is also difficult to partition the drainage and runoff terms within the model. Water use monitoring is currently underway and preliminary data support 3PG-2 modelled African mahogany rates as compared with native species. Existing measurement regimes in complimentary projects will reduce modelling this uncertainty in the coming years.

In summary, while tree water use was found to be higher in African mahogany trees when compared with trees of native savanna vegetation, annual water use (evapotranspiration) was similar, at both plot and sub-catchment scale and impacts on water resources was deemed to be low.

This project was led by Charles Darwin University (CDU) and a Steering Committee, with representatives from the NWC, CDU, the NT Government's Dept of Resources and NRETAS. CSIRO was engaged to make a preliminary assessment of the potential impacts plantation establishment and proposed expansion on the water resources of the region using a modelling approach. EcoLogical Australia was engaged to review previous forestry activities in the NT and develop a policy framework in collaboration with NRETAS staff.

Policy recommendations

Given a the low risk of impact on the water resources of the Douglas Daly Basin due to interception by non-irrigated African mahogany plantations, it is recommended that this land use does not require a water allocation licence under the NT Water Act.

Further work is required, however, to reduce the significant uncertainties associated with the outcomes of this research and to continue to inform the policy review process.

This policy applies to non-irrigated African mahogany plantations grown in the Daly basin. Application of the policy to other species requires research and modelling specific to that species. This approach, however, provides a useful and appropriate template for future research and policy development.

Further work is required to improve the modelling and this can be achieved by improvement in data availability such as;

1. spatial variability of rainfall and soil texture with depth within the catchment
2. establishment and regular measurement of a network of monitoring plots of differing age classes within the mahogany estate
3. improved parameterisation of the 3PG and other models, particularly with respect to biomass partitioning and controls on canopy conductance
4. An assessment of the contribution of groundwater to water use by mahogany plantations as trees mature
5. Long-term monitoring of stream flow in sub-catchments where plantation expansion is likely to occur, in particular Stray Creek.

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Acronyms

ARC	Australian Research Council
CDU	Charles Darwin University
CFC	Chlorofluorocarbon
DoR	NT Department of Resources
ET	Evapotranspiration
EPBC	Environment and Biodiversity Conservation
FFPC	Forest and Forest Products Committee
FSC	Forest Stewardship Council
GANT	Greening Australia Northern Territory
GFC	Global financial crisis
GL	Gigalitre
ISO	International Standards Organisation
LAI	Leaf area index
LIDAR	Light detection and ranging
MAR	Mean annual rainfall
TERTHFP	Top End Regional Tropical Hardwood Forestry Project
TRaCK	Tropical Rivers and Coastal Knowledge Research Hu, Charles Darwin University
MIS	Managed Investment Scheme
ML	Megalitre
NWC	National Water Commission
NWI	National Water Initiative
NRETAS	NT Department of Natural Resources, Environment, The Arts and Sport
NTFTPN	Northern Territory Forestry and Timber Products Network
SVAT	Soil vegetation atmosphere transfer
WAE	Water access entitlement

1. Plantation forestry and water resources

1.1 Introduction

In Australia, water is vested in governments that allow other parties to access and use water for a variety of purposes. Decisions about water management thus involve balancing often competing sets of economic, environmental and other interests. The National Water Initiative (NWI, 2004) recognises water resources as being part of "Australia's natural capital" and that management of Australia's water resources is a national issue. As such the NWI aims to:

- Restore sustainable water balance to over allocated systems
- Assess impacts on surface water and groundwater resources
- Increase security of water access entitlements
- Trade water to achieve most profitable use and environmental outcomes
- Address land use change.

A major objective of the NWI is to secure the integrity of water access entitlements and environmental outcomes. As part of this the COAG agreed that landuse change that has the potential to intercept significant volumes of surface or groundwater needs to be addressed. The NWI specifically identifies "large scale plantation forestry" as an example of land use change that has the potential to intercept large volumes of water. However, it is important to recognise that the intention of the NWI framework is not to predetermine whether an activity is a significant interceptor, but instead to determine whether the *volume* intercepted is *significant* in the context of the water systems in which it occurs. Thus the issue of determining whether the interception is significant needs to be considered in the context of each unique regional hydrological balance (Polglase and Benyon, 2009). More specifically, whether the proposed land use change and the associated interception activity is likely to place significant pressure on water resources within the management zone or push a water resource through a predetermined threshold, resulting in the water resources within the management district becoming over-allocated.

Plantation forestry as a landuse change driver is of particular concern because it is well recognised that evapotranspiration from forested catchments is higher than evapotranspiration from grassland catchments (Zhang *et al.*, 2001, Jackson *et al.*, 2005). This difference arises because forests;

- Intercept more radiation and rainfall
- Are aerodynamically rougher and thus well coupled to the atmosphere, and
- Have deeper root systems that allow them to exploit larger soil volumes than grasses.

The impacts of forests on catchment water balance were demonstrated in Zhang *et al.* (2001) who analysed runoff data from over 250 catchments from 28 countries from around the globe. These catchments ranged in size from less than 1 km^2 to over 100 000 km^2 and spaned a variety of climates including tropical, dry and warm temperate. Vegetation within catchments ranged from plantations, native woodlands, open forest and rainforests to native and managed grasslands or agricultural cropping. In their analysis, the most important controls on evapotranspiration were annual rainfall and vegetation cover. They developed relationships between rainfall and annual evapotranspiration for forested and grassed catchments; the "Zhang curves" (Figure 1) and demonstrated that for annual average rainfall above 600 mm, evapotranspiration from a forested catchments is higher than that from a grassed catchments. The analysis has provided a robust framework for analysing the impact of reforestation on runoff, the difference between rainfall and evapotranspiration that can be expected under different vegetation types and for different rainfall scenarios. However, the curves describe the steady state water balance of a system and are not particularly sensitive to as assessing the impacts where landuse change is a continually occurring process in a catchment.

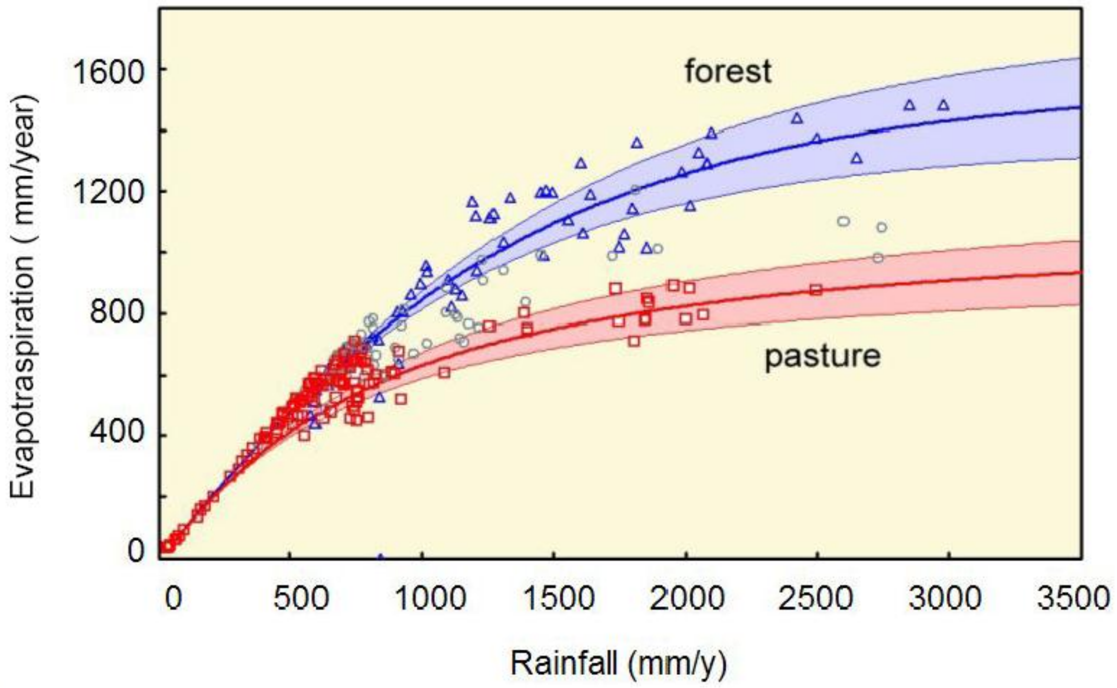

Figure 1 The relationship between annual evapotranspiration and rainfall for forested and grassed catchments (Zhang *et al.* 2001).

The Zhang curves are relatively insensitive to changes in water interception that occur as a result of plantation age, stand management and other external influences such as fire or climate change. As a result there may often be a need for more intensive investigations of the water use of plantations in order to fully assess the impacts of plantations on catchment water resources.

Polglase and Benyan (2009) note that in Australia, the impacts of plantation establishment on catchment water balance have been somewhat overstated, finding that while plantations are likely to have localised impacts, in general plantation forests occupy only a small proportion of catchment area and thus their impacts on catchment water yield are typically less than would be otherwise expected based on conventional wisdom. However, groundwater issues emerged as the most significant issue and they recommended further research to examine plantation water use and its impacts on recharge processes. For a system such as the Daly Basin, this is an important conclusion, as the Daly and associated rivers are sustained by groundwater inflow through the dry season, a period when maintenance of environmental flows is critical to ensure a functioning riverine system. Polglase and Benyon (2009) went onto identify the Douglas-Daly catchment as one where groundwater issues are of ‘immediate concern’ (*Executive Summary, pp iv)* in relation to potential development of plantation forestry.

1.2 African mahogany plantations in the NT

Over the last decade, land and water resources of north Australia, in particular the NT and WA, have been viewed as a potentially exploitable resource, given issues of salinisation, soil acidification, over-allocation of water resources and potentially long-term rainfall decline in south Australian agricultural regions (Petheram *et al.*, 2010). In the NT, plantation forestry has been identified by the NT Government (NTG) as a potential land use, and industry estimates suggest that 30 000 to 40 000 ha or more is required to support an economically viable enterprise. Significant expansion of land and water resources represents a level of management risk if vegetation and soil systems are modified with limited predictive capability regarding potential impacts, in particular, changes to interception. Over the last 6 or more years, afforestation of previously cleared pastures using a fast growing, exotic tree species *Khaya senegalensis* (African mahogany) is occurring. Development opportunities are likely to centre on the Douglas-Daly and Katherine River catchments, which has fertile soils (by NT standards) and good groundwater stores (Begg *et al.* 2001). The benefits could include revenues from a plantation industry producing high quality furniture timber products with potential for carbon sequestration. However, the costs of this LUC also need to be considered, which may include increased GHG emissions associated with establishment of plantations on uncleared lands, and a reduction in environmental flows due to potentially high rates of plantation water use.

Large, established plantations of mature African mahogany trees do not currently exist in the NT and measurements of large trees can only occur on small experimental plots. As such, modelling and scaling will be critical to provide estimates of potential water use at stand maturity (15-20 years of age) to water resource staff of the NT Government's water management agency, NRETAS.

There has been a significant research effort in the Douglas-Daly catchment over the last 5 years via the Tropical Rivers and Coastal Knowledge Research (TRaCK, www.track.gov.au) hub based at Charles Darwin University (CDU). This program has examined a wide range processes within the basin from channel hydrodynamics, biodiversity, indigenous use of water resources to land use change impacts on surface hydrology. This latter project (Project 4.1, Cresswell *et al.* 2011) examined the water balance of uncleared savanna and cleared and improved pasture sites, however, there was no focus on plantation forestry in this project, a significant knowledge gap given the recent expansion of plantation forestry in the catchment. This current project aims to provide a preliminary assessment of issue.

1.3 NT water policy requirements

Sections 55 through 57 of the National Water Initiative (NWI) signed by the Commonwealth and the Northern Territory Government requires this jurisdiction to manage; a) interception activities that are assessed as being significant and should be recorded (for example, through a licensing system), and b) any proposals for additional interception activities above an agreed threshold size, will require a water access entitlement. Interception' as used here is defined by the NWI to mean the measurable diminution of flow or likely flow of water in or into a waterway and/or aquifer at any time within the duration of a water plan or proposed water plan. Large scale plantation forestry is one of only 3 examples listed in NWI as land use change activities that may have potential to intercept surface and/or groundwater. Water allocation planning is currently undertaken in 3 regions in Top End, namely Katherine, Douglas-Daly and Mataranka with a draft plan realised covering the Oolloo aquifer that encompasses these regions (NRETAS, 2012). This project aims to contribute to this long term water resource planning via an improved understanding of impact on plantation forestry, in any, on surface and/or groundwater resources.

Given the current paucity of data and information regarding plantation forestry water use and interception processes, this research is seen as vital to the requirements outlined above and to the ongoing management of water resources in the Northern Territory. Research on forestry water use and impacts in other areas of Australia has shown that forestry can make up a significant component of the water cycle and must be considered during water allocation planning (Zhang *et al.* 2001). This will ensure all components of the water balance are accounted for. It is especially important to understand water use in a wet-dry environment that is subject to high evaporation rates and highly seasonal available water to support environmental flows. This current research gap is considered to be the major missing component in the development of water allocation plans in catchments in the NT where this land use is expanding.

1.4 Research program overview

This project is aimed at developing an initial assessment of water use of non-irrigated plantation forestry in the Daly River catchment, an emerging land use in the Top End of the NT. The project was structured around four Aims; **Aim 1**) assessing the potential groundwater dependence of *K. senegalensis* trees in low lying position in the landscape, **Aim 2**) the establishment of a long-term monitoring plantation at the Department of Resources Douglas-Daly Research Farm (DDRF), **Aim 3**) an initial calibration of the growth model 3PG+ to model plantation water balance relative to natural vegetation and improved pasture and **Aim 4**) the development of a water use planning framework to assist with policy development associated with the land use. These aims are briefly outlined below.

Aim 1 Groundwater dependence of African mahogany – Isotopic analysis of groundwater, soil and plant water assess groundwater dependence of both native and mahogany trees. The oxygen isotope (^{18}O) were used to examine fractions of soil moisture and groundwater to identify the source of transpired water of native and African mahogany tress. Sampling was undertaken in the late dry season when any reliance on groundwater will be evident given the soil moisture store will be at a minimum. This work is described in Chapter 2.

***Aim 2 Establishment of a long-term monitoring plantation* –** For long term monitoring of water use, growth and runoff, an experimental plantation consisting of African mahogany trees was established at the NTG's Douglas-Daly Research Farm (DDRF). Three contoured bays were established to compare runoff, growth and water use of trees at two densities and an improved pasture. In addition, different seed provenances were used to examine growth performance over time. The experimental plantation is described in Chapter 3.

Aim 3 Modelling water balance of savanna vegetation and plantation stands – Given the absence of existing mature plantation stands within the catchment, modelling potential shifts in water balance over the life time of a growth cycle becomes essential to assess potential impacts on water resources. Existing data were assimilated to calibrate a SVAT 3-PG2 to predict water use and soil moisture drainage for native savanna vegetation, improved pastures and African mahogany plantation at both a plot and sub-catchment scales. Models such as WAVES, developed by CSIRO (Zhang *et al.*, 1996) and the stand growth and water use model 3PG+ (Section 4.4) can be used with data collected from this project. 3PG+ can simulate vegetation water use, soil moisture dynamics, deep drainage and recharge as a function of climate, soil and vegetation variables. These models, once parameterised for the soils an vegetation of the catchment will enable us to examine impacts of plantation forestry on interception processes. Modelling is described in Chapter 4 and outputs used to assess risk and provide advice for the development of policy (Aim 4) to manage any future expansion of this land use.

Aim 4 Policy to address forestry water use in the Northern Territory – Currently the NTG has no policy to manage forestry or agroforestry and potential impacts on water resources. This project will provide an initial examination of potential impacts to develop a policy position concerning water resource management as affected by non-irrigated forestry.

The specific areas requiring policy development are the impacts of forestry on overland flow, aquifer recharge and aquifer depletion. Data and modelling arising this project has been used to assist with policy development by determining the potential level of impact on each of these water balance components allowing a risk assessment to be made. While no policy has yet been developed, amongst the options are:

- no discernible impact - policy to allow agroforestry, but to revisit legislation in 5 years (with appropriate legal settings to allow a change in policy, as new knowledge is obtained)

- minimal impact – policy to account for impact in water allocation plans (as part of the consumptive pool, but not granted as an entitlement)
- major impact – policy to require agroforestry enterprises to acquire a license and to operate within a regulatory framework.

In summary, the project will provide ongoing monitoring of growth performance of the target species African mahogany and an initial assessment of the water use characteristics of the species at stand and sub-catchment scales scale to provide a scientific basis for informed policy development.

1.5 Study areas

The study was conducted within the Douglas-Daly catchment (Figure 2), 200 km south of Darwin, a catchment earmarked for agricultural development and since 2006, a region that has the seen the establishment of the Mahogany plantation estate (see Section 5.2). Much of the existing cleared land and mahogany plantation development occurs within the Douglas and Stray Creek sub-catchments () and field sites and modelling were focussed in these sub-catchments. The Oolloo dolostone aquifer is also outlined in Figure 4 as it is an important aquifer within the Daly basin and occurs across much of the Stray Creek sub-catchment. This aquifer maintains environmental flow in the Daly and Katherine Rivers through the dry season as well as providing water resources for consumptive use (NRETAS, 2012). Discharge from the aquifer is largely via springs with a concentration of springs found along Stray Creek (Tickell, 2012) and this inflow is critical to maintain associated riverine ecosystems. The impact of mahogany plantations on the water balance is of interest, in particular of the Stray Creek sub-catchment, given the development of plantation estate in this sub-catchment that provides significant dry season flow to the Daly River.

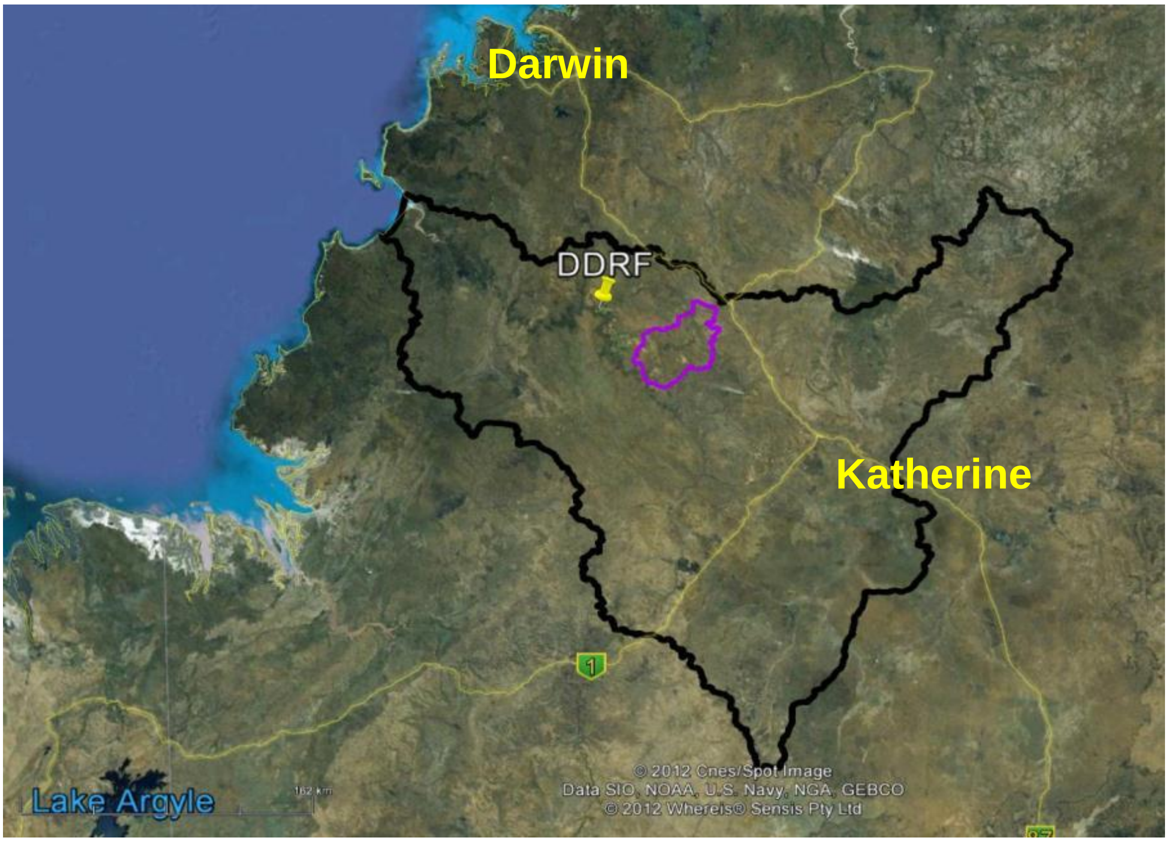

Figure 2 The Douglas-Daly catchment, approximately 200 km south of Darwin. The catchment boundary is marked in black with research sites established at the DDRF and within the Stray Creek sub-catchment, marked in pink. Plantations have been established in the Stray Creek and Douglas River catchment.

Figure 3 Landsat image of the Douglas and Stray Creek sub-catchments showing the distribution of cleared blocks for cropping and improved pastures. Mahogany plantations have been established on cleared blocks since 2006 with the plantation estate currently at ~13 000 ha.

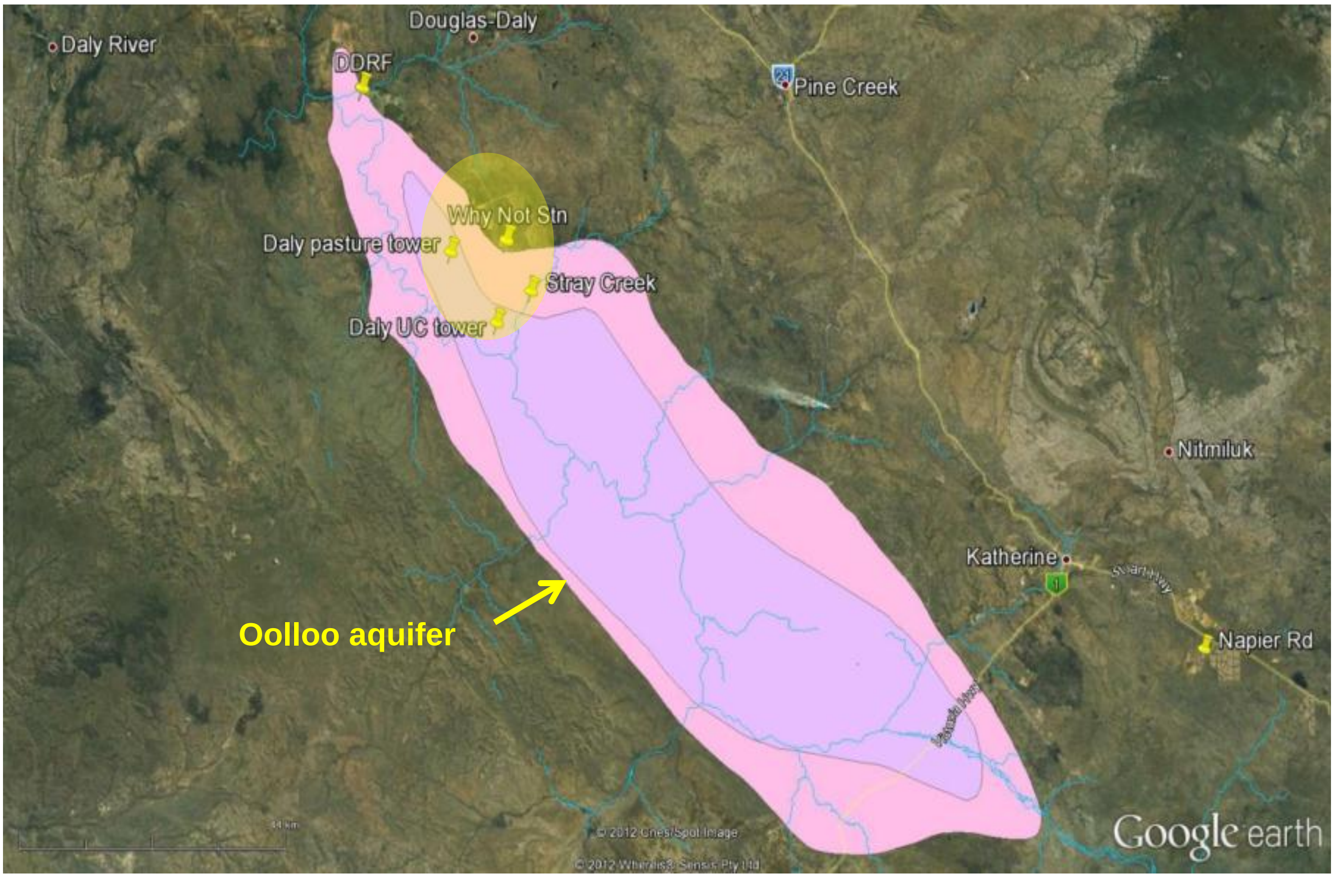

Figure 4 Intensive observation area (yellow shaded area) within the Stray Creek sub catchment featuring flux towers for on-going evapotranspiration measurements of savanna (Daly UC) and improved pasture (Daly pasture) land uses, NRETAS monitoring bores and tree water use monitoring on Mahogany plantations. The Oolloo aquifer is also show, with the boundary taken from Tickell (2012).

2 Potential groundwater usage of mahogany plantations

Lindsay B. Hutley, Mila Bristow, Michael Brand

2.1 Introduction

Natural vegetation reaches an equilibrium with long-term available moisture and replacement of natural vegetation associated with land use change will alter this ecohydrological equilibrium (Eamus *et al.*, 2006). For a comprehensive understanding of the water balance of vegetation, quantifying the sourcing of water for transpiration is required. Water sources include differing soil horizons, or if vegetation is deep rooting and water table shallow, direct uptake from the capillary fringe. Understanding this dynamic is especially important in highly seasonal climates that experience soil water deficits but support perennial evergreen vegetation that requires access to moisture throughout the seasonal cycle.

Differing vegetation systems of the Top End are characterised by differing patterns of water use. For the dominant vegetation, the savanna woodlands, transpired water during the wet season is sourced from the upper 50 cm of soil, whereas dry season water requirements are sourced from between 2 and 8 m depth with little reliance on groundwater (Cook *et al.*, 1998; Kelley *et al.*, 2002). As a result savanna tree water use is relatively aseasonal, with differing soil horizons exploited over the dry season to maintain transpiration all year (O'Grady *et al.* 1999). By contrast, riparian vegetation in this environment, where the water table is closer to the surface, sources up to 50% of its transpired water from groundwater to maintain transpiration into the late dry season (Liddle *et al.*, 2008; O'Grady *et al.*, 2002). Water use of shallow rooted improved pastures tend to follow surface (0-1 m) soil moisture dynamics, with high rates of transpiration observed in the wet season (~6 mm d^{-1}) followed by a rapid decline into the dry season as the shallower rooted grasses and legumes are unable to access deeper water stores in the horizon (Creswell *et al.* 2011). Water use patterns of African mahogany plantations with season and stand age is unknown in the NT.

Quantifying the rate and seasonal patterns of moisture uptake from mahogany plantations is critical to making an assessment of the potential impact of this land use in the Daly catchment. Recent studies of mahogany plantations and groundwater interaction has been undertaken in the Kimberly region of WA, a similar climate zone to that of the Daly. In this study, Carter *et al.* (2010a) examined mahogany water use and the drawdown of a shallow watertable and direct uptake from the capillary fringe was occurring, with the plantation drawing the water table down 7 m over a 10 year period. Annual transpiration rate was ~750 mm per year from plantations with access to the water table. These data suggest high rates of water use are possible and impact on water resources has occurred via the direct uptake of water from the capillary fringe associated with the water table. Alternatively, impact may occur indirectly via increased water use when compared to native vegetation types, leading significant dry season soil moisture deficits and reduced deep drainage and recharge to local aquifers.

As such, the ability of African mahogany to use groundwater directly in a plantation setting of the Stray Creek area (Figure 3) was assessed by examining seasonal patterns of water table depth in the blocks where plantations currently exist and may exist in the future. This provides an indication of seasonal changes of depth to water table and the likely need of mahogany trees accessing this water given their potential rooting depth. The isotope of oxygen, ^{18}O, was used to compare potential water sources transpired by individual trees, namely differing soil horizons vs direct access to the local water table. The use of isotopes as a marker of differing transpired water sources is a standard method to assess groundwater dependence of vegetation (Cook and O'Grady 2006). Isotopic signatures of groundwater, soil water from differing depths and water stored with vegetation tissues provides an indication of the fraction of differing water sources used. Mixing models can be used to quantify these fractions if sources (surface water, soil water, groundwater) have strongly contrasting isotopic signatures.

These approaches were used to assess the current and potential for groundwater use of mahogany plantations established on deep, well drained Blain and associated soils in the Stray Creek sub-catchment. Where available, time series of standing water levels were examined within in the intensive observation area (Figure 5) with isotopic signatures of surface water, groundwater, soil and tissue water for both native and mahogany trees species also sampled.

2.2 Methods

2.2.1 Stray Creek intensive observational area

At present there is a range of ecohydrological observations available within the Stray Creek sub-catchment aimed at examining land use change and impacts on surface and groundwater hydrology (Figure 5). Long-term eddy covariance flux towers have been installed in the Stray Creek sub-catchment, a method that makes real-time measurements of evapotranspiration (ET), surface energy balance, rainfall and soil moisture dynamics. These towers have been installed in contrasting vegetation types, uncleared tropical savanna and an improved pasture with observations ongoing since 2006/2007. Aspects of the these sites and installations are detailed in Cresswell *et al.* (2011) and Hutley *et al.* (2011). These observations provide an understanding of the impact of land use change on water balance and are essential for the calibration of water balance modelling (see Section 4). These data are complimented by the ongoing NRETAS bore monitoring network across the NT, with a concentration of bores within the Daly and Stray Creek catchments. This network consist of both observation bores for spot measures as well as bores with automatic logging of standing water height. This area also features a number of activity managed and expanding mahogany plantations that have been instrumented with sapflow measurements, rainfall and soil moisture monitoring (Figure 5).

2.2.2 Groundwater heights and rooting depth

Depth to groundwater was assessed using data of standing water levels across bores in the intensive observational area (HYDSYS database). This area was considered a typical land system where plantation establishment and expansion has and is occurring. Vegetation is a mix of mahogany plantation blocks with uncleared Eucalypt open forest savanna dominated by *E. tetrodonta*, *E. miniata* and *E. latifolia* and *Erythrophleum chlorostachys* on low undulating plains, classified as vegetation unit 441 using the National Vegetation Information System (NVIS, 2005). Soils types are typically Blain, Kimbyan and Woggaman in this area, which have sand fractions between 80 and 93% and clay fractions of 8% or less (Hutley *et al.*, 2012). Stray Creek is the lowest point in the landscape and dry season flow is largely groundwater discharge and the water level is equivalent to the water table height (S. Tickell, *pers. comm.*). As such height above Stray Creek provides some indication of depth to the water table.

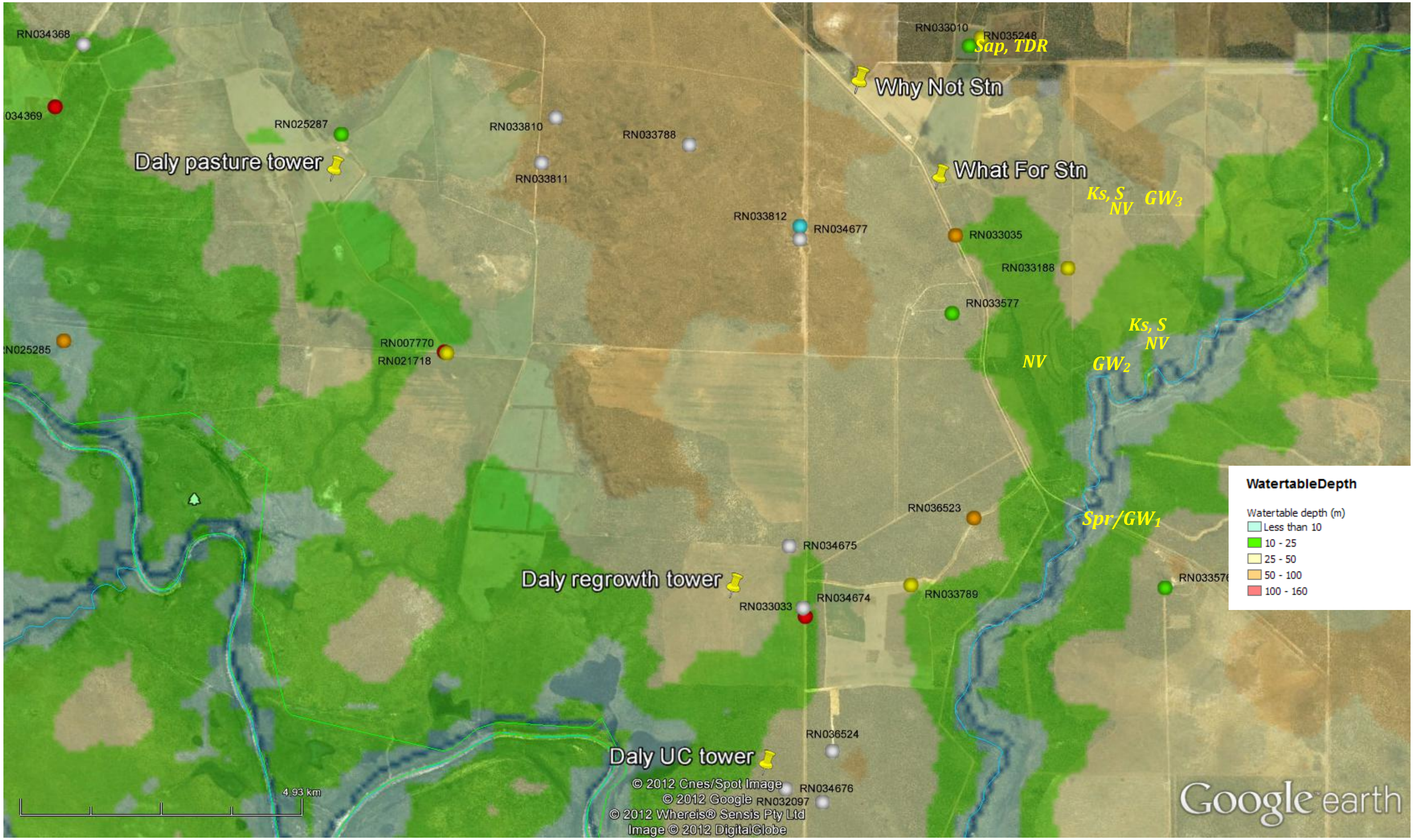

Figure 5 Intensive observation area within the Stray Creek sub-catchment showing flux tower sites, the NRETAS monitoring bore network and sampling locations for isotope analysis. At the flux tower sites there is on-going monitoring of rainfall, ET, soil moisture dynamics and meteorology for tropical savanna and improved pasture. At mahogany plantations sapflow (Sap, marked on map) and soil moisture (TDR). Locations ^{18}O sampling of groundwater (GW1-3), spring water (Spr), soil water (S), native vegetation (NV) and K. senegalensis (Ks) is marked. Also overlayed is a map of depth to the water table.

2.2.3 Isotope sampling

The oxygen isotope ^{18}O samples were taken from groundwater, soil water and vegetation in the vicinity of Stray Creek to examine transpired water sources. Sampling was undertaken in September 2011, the late dry season, a period of the wet-dry seasonal cycle when use of groundwater may occur as soil moisture storage is at a minimum. Groundwater was sampled from a bank spring that was discharging directly into Stray Creek. This water is groundwater from the Oolloo aquifer (Tickell, 2002). To sample groundwater that had not been exposed to the atmosphere, a hole was dug above the discharge point to ~30 cm and groundwater allowed to seep in and immediately sampled (GW_1, Figure 5). Three additional groundwater samples were taken from a seasonal swamp (GW_2) and similarly not exposed to the atmosphere. Further sampling was undertaken at an active bore located 2.56 km north from the creek line (GW_3). The bore was purged for 10 minutes until the flow rate declined, indicating flow was from the aquifer as opposed to water stored within the bore casing. The bore elevation was 110 m, ~40 m above the water table based on the elevation of Stray Creek, which is the height of the water table at this time of the year.

Plant tissue water was sampled within the mahogany plantation stands and from dominant trees species of adjacent savanna sites. Three site groupings were established based on height above the water table at ~5, 10 and 20-25 m. For vegetation (native or plantation sites), three trees were sampled per site with three twigs (~5-10 mm diameter, ~5 cm in length) cut per tree from lower branches. Twigs were stored in sealed plastic containers and transferred to an esky. In the savanna sites, the dominant woody species sampled included *E. tetrodonta* and *E. chlorostachys* with three trees per species selected and three twigs per tree cut and stored in sealed containers. Soil was sampled within the root zone of sampled mahogany trees with three soil pits dug with three replicate soil samples taken at 20 and 50 cm depth. Again these samples were stored in sealed containers in an esky. Extractions of soil water and all isotopic analyses were undertaken at the University Of Western Australia's John de Laeter Centre of Mass Spectrometry, methods after Paul *et al.* (2007) and Wassenaar *et al.* (2008).

2.3 Results

2.3.1 Groundwater heights

Standing water levels have been monitored in the Stray Creek sub-catchment since the late 1980's and a simple appraisal of groundwater heights across the monitoring bore network gives a range of heights from near surface expression to water levels of ~60 m depth below the land surface. Significant interannual variation is evident as is an upward trend in water height since the late 1990's (Figure 6). Mahogany plantations have mostly been established on land units associated with Blain soils which can have depths of up to 8 m (Tickell, 2006). Groundwater water depths in these land systems are between 15 to 30 m below the land surface (Figure 6). Similar depths to the water table is also evident via the observation bores distributed across the catchment, and a number of dry season water levels has been compiled for bores within the intensive observation area (Table 1). Depths range from 6.8 to 62 m due largely to elevation and distance from the watercourse. Based on the NRETAS bore network and hydrogeology, depth to the water table has been mapped across the Oolloo aquifer basin by Tickell *et al.* (2012), an area that includes the Douglas and Stray Creek sub-catchments. For the intensive observation area within Stray Creek, these layers are also given on Figure 5 and show that between 100-400 m from a watercourse, depth to the water table is typically >10 m and up to 50-70 m for a large fraction of the area. Given that the rooting depth of both savanna Eucalypt and mahogany trees is unlikely to be deeper than 8-10 m, this suggests that the potential for trees to directly access the water table across much of the sub-catchment is low.

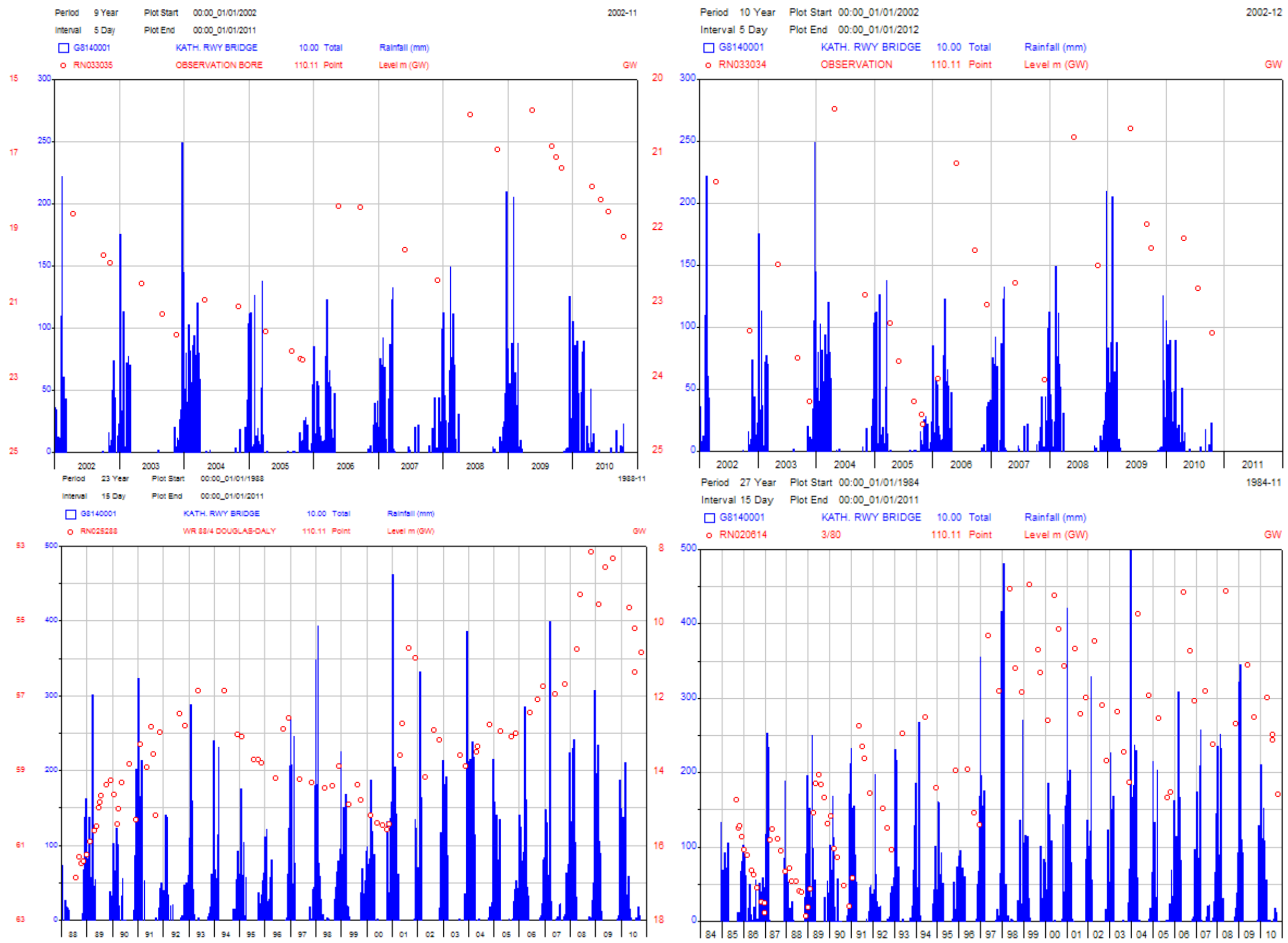

Figure 6 Long-term groundwater heights within the Stray Creek intensive sampling area and Black Bull Yard, Theyona Station. These bore sites are sited within land units with Blain soil types, a soil type where most of the plantation have been and will established. Data from the NRETAS water resources database HYDSYS (http://www.nretas.nt.gov.au/home/nretasmaps).

Table 1 Dry season standing water levels (SWL) in monitoring bores located within the Stray Creek intensive observation area. Data are taken from the NRETAS online bore monitoring database (HYDSYS). All bores were drilled into the Oolloo aquifer except for those marked with an asterisk, which were located in the Jinduckin. The elevation of the creek line ranged from 67 to 52 m.

Bore No.	*End date*	*SWL (m)*	*Elevation (m)*	*Distance to watercourse (km)*
RN033034	20/06/2001	19.6	69	0.9
RN036818	18/11/2009	6.8	65	1.3
RN036817	13/11/2009	-2.0	62	1.3
RN036523	8/05/2009	19.0	84	1.5
RN033789	22/06/2003	18.0	80	1.5
RN033576	25/09/2002	45.0	106	1.9
RN033577	26/09/2002	42.0	106	2.6
RN033011*	17/05/2001	25.1	116	3
RN033035	26/06/2001	16.6	84	3.5
RN033812	3/07/2003	67.0	118	5.6
RN035248	23/07/2006	40.0	108	6.7
RN033010	9/05/2001	39.8	110	6.9
RN025288*	1/06/1988	63.0	124	11.7

2.3.2 Tissue isotopic signature in native and mahogany trees

There are significant areas where the water table can be between 5 and 10 m below the surface (green and blue areas, Figure 5) which support both well-developed stands of Eucalypt open-forest savanna and plantation trees. As such these communities may access the capillary fringe of a local water table at 5 m depth, although within the Stray Creek area, these trees are currently ~4yo and only 4-6 m in height. To examine this possibility, mean values of ^{18}O for both native savanna and plantation trees sampled in low positions in the landscape (within 1 km of a watercourse) were plotted with groundwater and soil water ^{18}O values (Figure 7). This figure presents isotopic values on an x-y scatter plot, with the y-axis representing soil depth. Values for groundwater and vegetation samples are scaled to the x-axis only, which enables comparison using common x-axis values, which is the mean $\delta^{18}O$. The isotopic signature of groundwater and surface water was not significantly different, with a $\delta^{18}O$ value of approximately -6‰ (Figure 7). Shallow soil water (20 cm depth) was more depleted at approximately -7 ‰. Soil water at 50 cm depth was further depleted, but more variable with means ranging from -8 to almost -10‰. Mean values for mahogany tree tissues was -9 ‰ and were the least variable. This mean was significant different from groundwater, but was not different from 50 cm soil water. Native vegetation was intermediate and similar to 20 cm soil water.

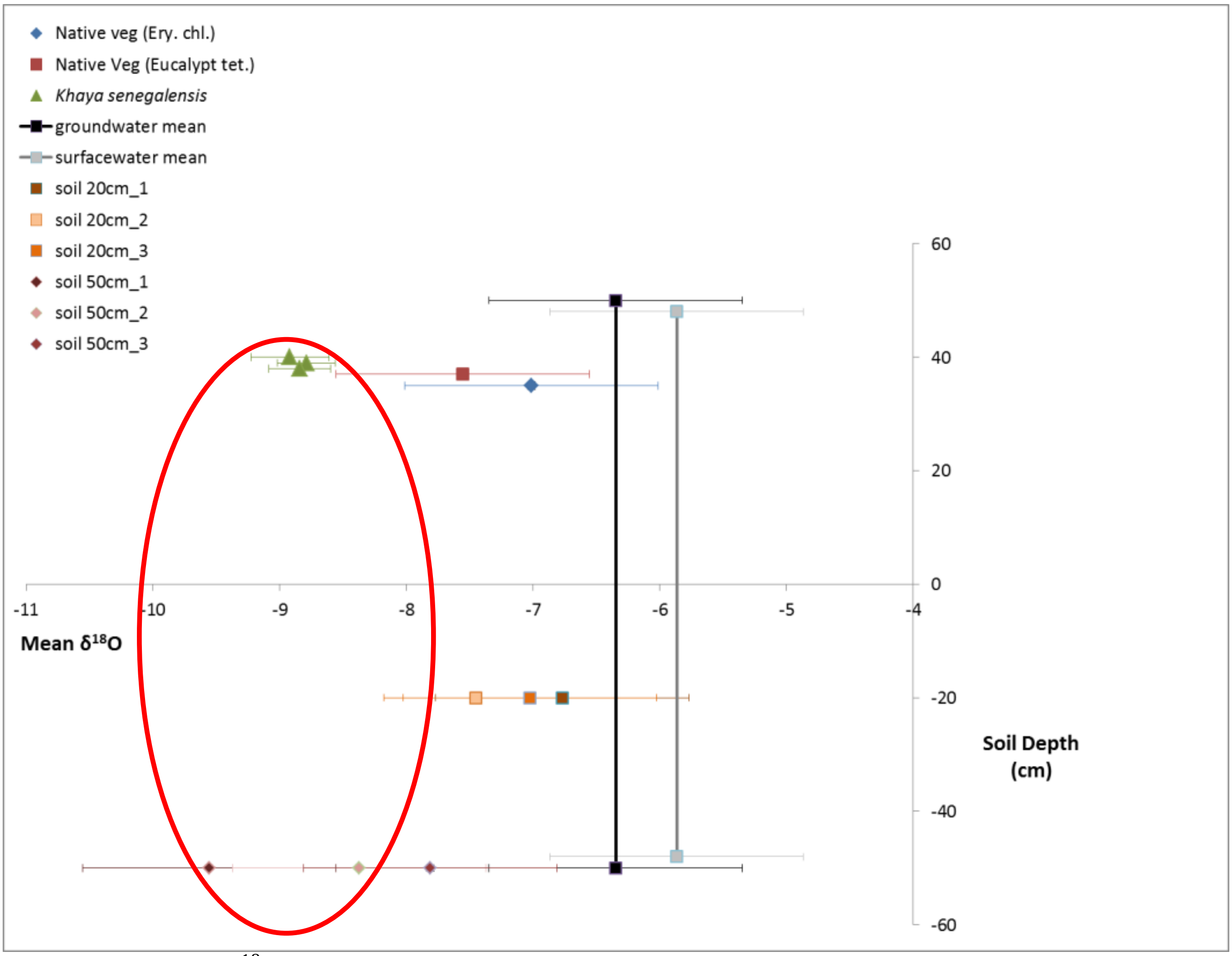

Figure 7 Values of $\delta^{18}O$ for sampled groundwater, creek water (surface water), soil water (20 and 50 cm depths), and twigs sampled from mature, common savanna tree species *E. chlorostachys*, *E. tetrodonta* and plantation trees in lower elevations of the estate near Stray Creek. Mean ^{18}O of soil at 50 cm was not significantly different to that twig water of mahogany trees.

2.4 Discussion

Water table depths observed across land systems typically utilised for mahogany plantations were in excess of 10 m, and more typically 15 to great than 40 m. It is unlikely that significant root growth will occur to these depths given the depth of Blains soils of 2-8 m (Tickell, 2006), with this soil volume likely to supply the transpirational moisture requirement through the dry season. Within the intensive observation area (Figure 5), seasonal patterns of soil storage of a Blain soil type supporting Eucalypt open-forest savanna is being monitored to 5 m depth at the Daly UC tower site. Soil moisture data for the period of isotope collection (Sep 2011) is available and these data, when combined with soil retention curves for this soil from this site (Cresswell *et al.*, 2011; Kemei *et al.*, 2012), provides a means to examine available water at the end of the dry season with depth (Figure 8). At the end of the dry season, there is available moisture between 0.5 and 1.8 m of the profile. Integrating these water contents suggests that by the end of dry season, there is still ~105 mm available moisture over a 5 m profile with this water available within the root zone of woody vegetation, native species or mahogany. As such this soil type is likely to supply the transpirational needs for mature Eucalypt stands and there is no reliance on the water table for moisture. It is likely that the current immature mahogany plantations will behave similarly, although it is unknown how the profile make look under a mature stand, an issue to be addressed in the water balance modeling section (Section 4).

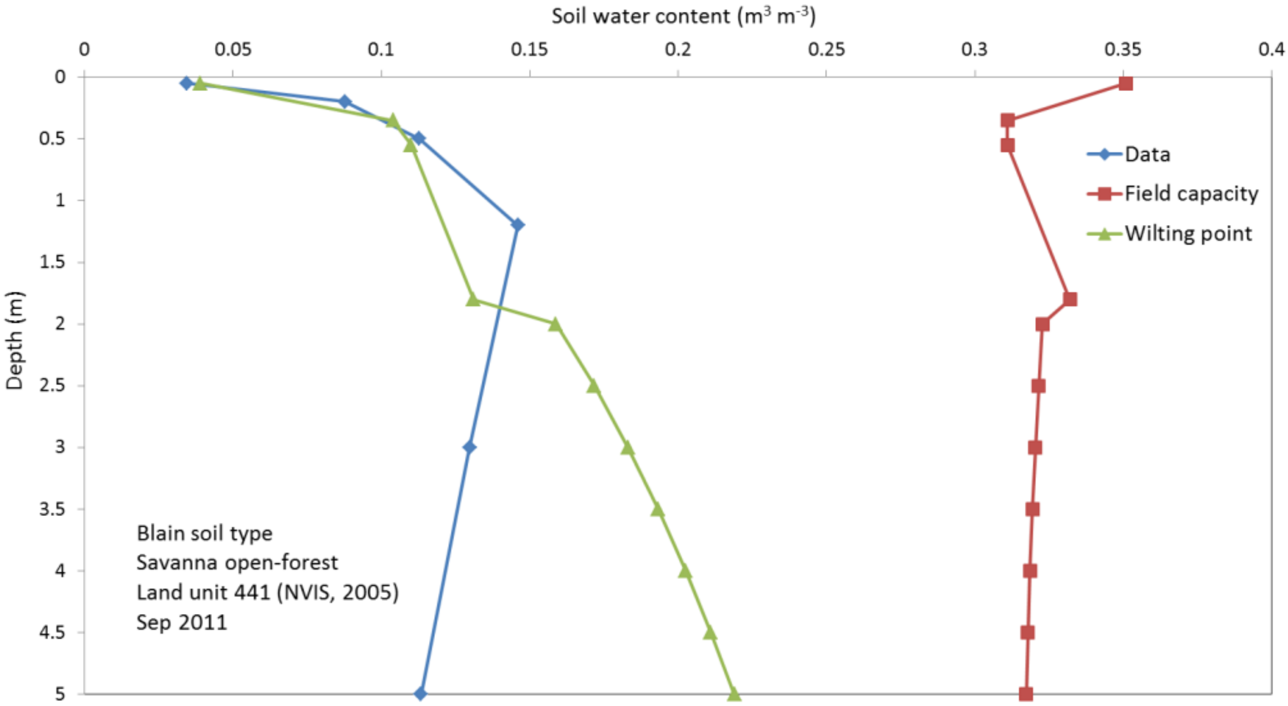

Figure 8 Soil moisture profile at the end of the dry season 2011 at the Daly UC flux tower site. Moisture content data is plotted with estimated water content at wilting point (a soil matric potential of -1.5 MPa) and field capacity (matric potential of -0.01 MPa). Water release data (WP and FC) are from Kemei *et al.* 2012 for soils sampled at this site.

Isotope data also suggested transpired water was being sourced by trees from soil as opposed to the groundwater, especially for mahogany trees, with ^{18}O values identical to soil at 50 cm depth and distinct from the groundwater (Figure 7). Soil ^{18}O values were depleted, at approximately -9 ‰, which was distinct from groundwater and more likely to represent the previous wet season monsoon, which was a record rainfall across north Australia (since records have been kept). For the Stray Creek area, the 2010/2011 wet season rainfall was between 1900 and 2000 mm, almost 1000 mm above average. Seasonal fluctuation in ^{18}O of rain water is significant, ranging from ~0 to -10 ‰, with -10 typical of monsoonal rainfall of southern Asia and north Australia (Hoffmann and Heimann, 1997). This suggests we are seeing relictual soil moisture storage form the previous wet season and this exercise needs to be repeated for more average rainfall years.

In conclusion, data describing typical groundwater depths in land units likely to support mahogany plantations were beyond the expected rooting depth of these trees and soil moisture is likely to be the sole source of the transpired water, not groundwater. This was supported by isotopic analysis which suggested that in areas where the water table was at 5 m depth, tree water use was derived from soil moisture. However, this sampling was undertaken after a record wet season with potentially higher than average soil moisture and from trees which were immature at 3 to 4 yo. Mature canopy stands (12-15 yo) are likely to have triple the canopy leaf area and would have developed more extensive root systems, especially in these deep sandy soils. As such plantations established within 300-500 m of a watercourse, depending on topography, may require on-going monitoring to quantify the fraction of groundwater extracted.

3 Establishment of a long-term monitoring plantation

Don Rilley, Bruce Sawyer, Lindsay B. Hutley

3.1 Introduction

As a component of this project, an experimental plantation consisting of African mahogany trees was established at the NT Department of Resources (DoR) Douglas-Daly Research Farm (DDRF). The plantation consists of two planting densities and an adjacent improved pasture bay. It is situated on Blain soils types at the DDRF and provides a site to better understand the growth potential of second generation seed varieties of African mahogany in the climate zone and soil environment the plantation industry is developing in. Having seedlings of known pedigree will allow the site to be converted to a seed production area (SPA) that will provide higher performing seed for the plantation industry. In addition to growth measurements, water use, deep drainage and run-off can be assessed over the life of a harvest cycle. Run off-flumes will be established for the measurement of runoff characteristics from a plantation as trees mature and canopy develops. Run-off characteristics for a range of pastures and crop types have been previously established at the DDRF by Dilshad *et al.* and this plantation site will add to this existing knowledge relating to the land use and hydrology for these soils. DDRF staff manage a BoM meteorological station on site which provides long term climatology to support this monitoring. The experimental plantation will contribute to long-term growth, water use studies and run-off studies and enable comparisons between plantation stands and improved pasture.

3.1.1 Methods

3.1.1.1 Planting design

The experimental plantation consists of two, 0.5 ha bays of two tree planting densities, one at a 2.5 m plant spacing and a 4 m row spacing (high density planting at 1000 stems ha^{-1}), and a second bay at a 5 m plant spacing and 4 m row spacing (low density, 500 stems ha^{-1}). The high density bay is further divided into 20 plots, each 24 x 10 m and containing 24 seedlings. Seedlings were sourced from 24 different seed lots from the Howard Springs seed orchard (SO) and from Darwin street trees (DST). Within each of the 20 plots, all 24 seedling lines were randomly planted giving 20 replicates of each seedling type across the bay. Seedlings 1-14 were from the Howard Springs seed orchard and the remainder sourced from Darwin street trees. Planting occurred on the 21 and 22 December 2010, prior to the onset of the wet season to enable establishment over the 2010/2011 wet season, which proved to be a record wet season. Weed control was undertaken to ensure good establishment (Figure 9) and dead seedlings were replaced. There is a number of other African mahogany and other trees species previously established in blocks adjacent to the experimental plantation and these plus the new plantation developed for this project creates a precinct of trial plantings of different potential timber species of different ages (1, 3-4, 6 and 16 yo) at the DDRF.

Adjacent to the two tree bays an identically sized improved pasture block was established that will be used as a non-tree control block. All three bays were contoured with earth works to manage and collect any runoff that will be measured via flumes installed at the lowest point of each bay.

Figure 9 Plantation as of October 2011, with good tree establishment, with the automated soil moisture logger and soil chambers in place for on-going evaporation, CO_2 and methane emission measurements. Previously established plantation blocks can be seen in the background.

Figure 10 Well established sapling in the late dry season, October 2011 during a plantation wide tree height and stem diameter measurement run. Initial weed control was effective and mortality modest with replacement plantings undertaken to ensure a constant experimental planting density for the two density treatments.

3.1.1.2 Instrumentation

Two automated soil moisture monitoring systems have been installed in the high density planting bay and at the pasture bay. At the high density bay three soil moisture probes were buried at 5 cm and a profile of probes at 20, 50, 100 and 290 cm depth installed. Bulk density was sampled at each probe depth with three replicates per depth taken. A similar design was used at the pasture block with surface probes and a profile of 5, 20, 50, 70 and 100 cm probes installed. These probes are logged using a second solar powered datalogger on site. Rainfall data is provided by the Bureau of Meteorology's weather station that is operational at the DDRF which provides long term climatology to support this monitoring. A time series of the data collected to date is given in Figure 12, showing daily rainfall and wetting fronts moving through the profile. Even at 1.5 years old differences in soil moisture dynamics are evident, with the end of wet season drying more evident at the plantation site when compared to the pasture bay (Figure 12). Dry season soil moisture balance equates to evapotranspiration as with no rainfall, runoff and an assumed zero deep drainage, differences in daily soil moisture is due to plant water use alone. Moisture storage integrated over 1 m depth for each profile was summed and daily ET calculated as the difference between successive profile storages. At the end of the wet season (April), pasture water use was up to 5 mm d^{-1} compared to the young mahogany tree bay that was using ~4 mm d^{-1} at this time (Figure 13). Pasture water use then declines rapidly and is near zero by July, whereas ET from the tree bay continues throughout the dry season between 1 and 0.5 mm d^{-1}. The young trees are able to establish deeper roots and continue to use water through the dry season. Dry season water use for the plantation bay was 140 mm as compared to 109 mm for the same period at the pasture bay. Despite the young age of the trees, differing water use patterns compared to pasture are already evident. Such trends can be monitored over the coming decade as a function of climate and stand canopy development.

Figure 11 High density planting bay at the DDRF as of March 2011 during soil moisture pit installations. Probes were inserted in the pit wall which was then backfilled. Each soil pile was

labelled and repacked in the hole to attempt to maintain soil structure. Soil probes are logged every 1 hour via a solar power automatic datalogger. The 6 yo mahogany stand is in the background.

Runoff from tree and improved pasture bays will be monitored over time as the trees grow, providing estimates of changes to runoff as the canopy matures as well as enabling an assessment of erosion potential of plantation sites as the favoured soil type Blain is highly erodible. Flumes will be established at the lowest point in each of the 3 bays to capture runoff from these defined area bays. A smooth-concrete stationary crest v-flume will be used instrumented with an ISCO 4230 bubble level flow meter. An event rainfall logger will also be installed as the DDRF meteorological station provides 30 min rainfall totals. Rainfall runoff characteristics for a range of pastures and crop types has been previously established at the DDRF by Dilshad *et al.* (1994) and Dilshad *et al.* (1996). This work was conducted on heavier texture red loam soil (Tippera loams), soils that are unlikely to support extensive plantations as there are few properties available for plantation establishment in the region with this productive soil type. This will add to this existing knowledge relating to the land use and surface hydrology for these soils and climate system.

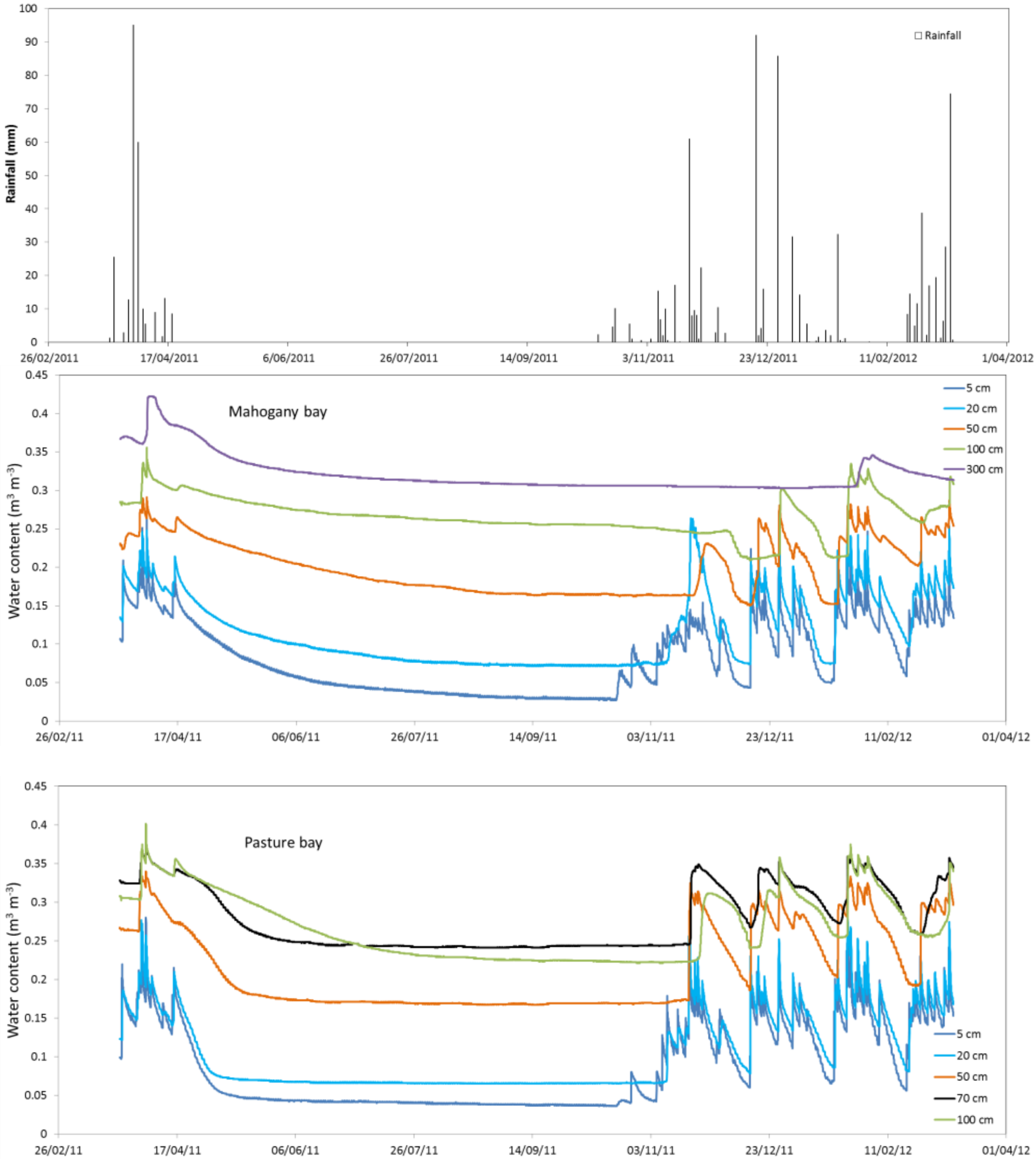

Figure 12 Time series of daily rainfall total and mean daily soil moisture with depth, March 2011 to March 2012. Data are form the two soil profiles established at the high density mahogany experimental plantation and the adjacent improved pasture bay, DDRF. As the trees age, differences in rates and depth of moisture extraction will change relative to the shallower rooted pasture site.

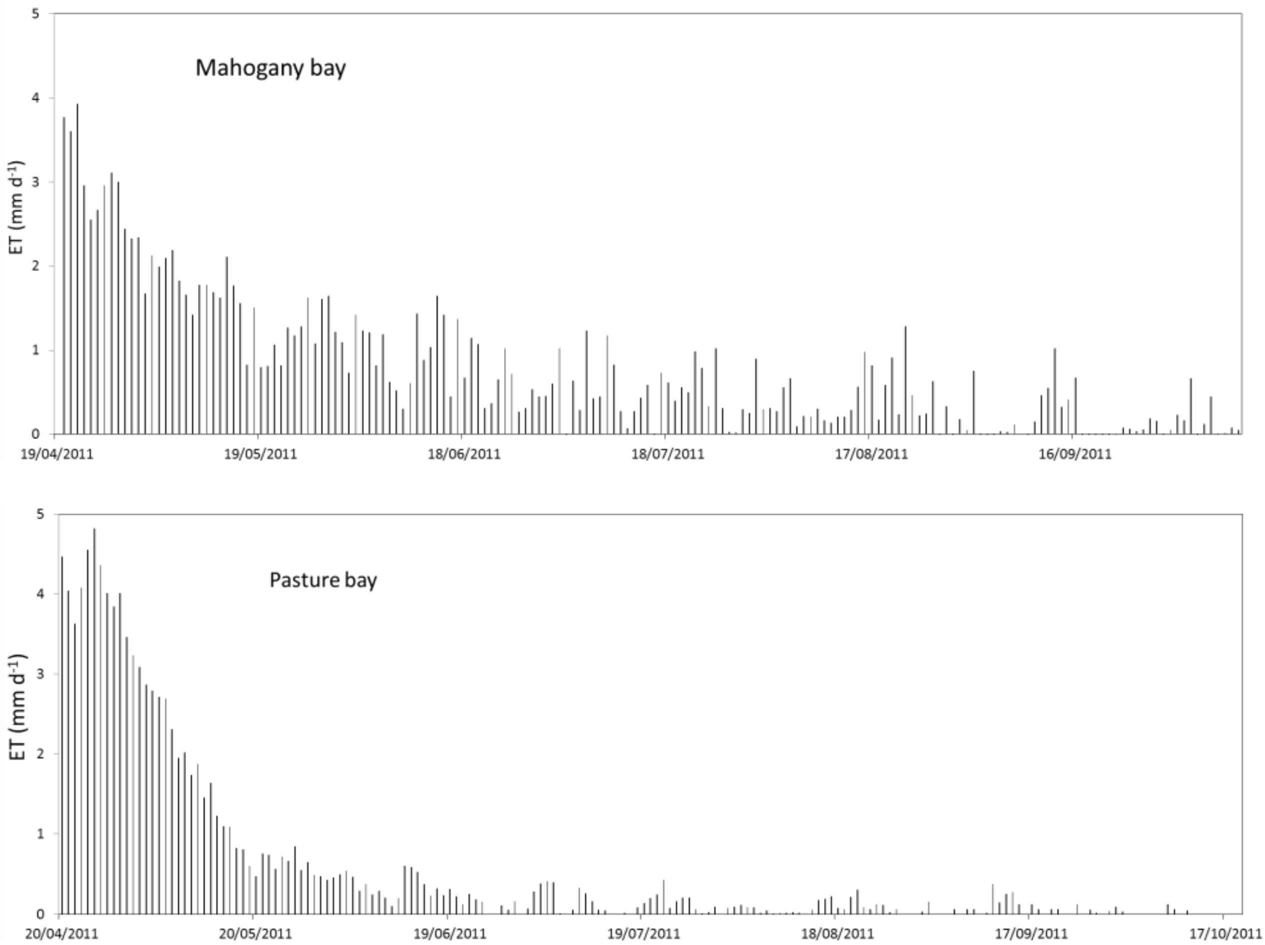

Figure 13 Evapotranspiration (ET) for the dry season 2011 for the African mahogany and improved pasture bays at the DDRF. ET was calculated using soil moisture data given in Figure 12 as during the rain free dry season, with no runoff and assuming no deep drainage losses, daily changes in profile storage are equal ET.

4 Preliminary assessment of the water balance of *Khaya senegalensis* plantations in the Daly River Region, Northern Territory

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4.1 Introduction

In recent years there has been rapid expansion of African mahogany plantations in the Daly River region of the Northern Territory. In 2006 it was estimated that there were approximately 200 ha of planting in the Northern Territory (Reilly, 2006), however rapid expansion of the area of these plantations since 2007 has seen this increase to approximately ~13,000 ha in the Daly River region alone. Continued expansion of the mahogany industry could see up to 50,000 ha of mahogany plantations established. Further details of the history of plantation forestry in the NT is given in Section 5.2.1.

The Daly River has a number of well recognised cultural and natural values, and is one of only a few large perennial river systems in Northern Australia, with dry season flow rates being sustained by significant groundwater inflows (Erskine *et al.*, 2003). There are concerns that further expansion of these plantations in the Daly River could have significant impacts on local or regional hydrological processes. As a result there is a requirement to develop a better understanding of the growth and water use of these mahogany plantations to better assess the potential environmental impacts of this expansion.

Under natural conditions African mahogany occurs in tropical regions of central Africa (Bristow and Skelton, 2004) (Nikles *et al.*, 2008). The tree typically grows to about 30 m and has a wide crown, although under cultivation can grow to more than 35m and attain diameters up to 1.5 m. African mahogany is an important multipurpose tree in Africa. It is an important fodder crop for cattle, provides wood for fuel and is believed to have important medicinal properties. It seeds provide oils which are rich in oleic acid which is used in cooking and in cosmetics (Arnold, 2004). *Khaya senegalensis* is also well known for its capacity to produce high value timber (Armstrong *et al.*, 2004), and as a result has been promoted in northern Australia for its potential to provide an alternative high value timber product for landholders and indigenous communities. While its potential has been long recognised, establishment of an extensive plantation industry in northern Australia has been slow to emerge, but is now expanding. *Khaya senegalensis* was introduced into the Northern Territory in 1959. During the 60's its potential as a plantation species began to be recognised and trials aimed at domesticating and improving the species were established near Darwin and on Melville Island (Nikles *et al.*, 2008). In the 1990's another wave of trial plantings were established in the Northern Territory, north eastern Queensland and in the Ord River of Western Australia (Nikles *et al.*, 2008; Dickinson and Kelly, 2006; Carter *et al.*, 2010). Commercial scale planting of African mahogany in the Northern Territory and in particular in the Douglas Daly region began in 2006 (Reilly, 2006). By 2011, there were approximately 10,000 ha of African mahogany plantations established in the Daly River region and plans to establish a further 40,000 ha, taking the total area in the Daly River region to approximately 50000 ha (D.F. Reilly pers. comm.)

Despite this history of establishment trials, there remains a lack of understanding of the factors limiting productivity of this species. There have been few systematic surveys of the growth and survival of this species across northern Australia. (Dickinson and Kelly, 2006) surveyed the productivity of African mahogany plantations and trials established in north Queensland finding that although the lack of intensive silviculture has probably limited growth rates, mean MAI of up to 8-10 m^3 ha^{-1} yr^{-1} are possible on good sites and with good stand management. Generally the growth and productivity of this species is poorly understood, both in Australia and internationally.

4.2 Hydro-climatic setting of the Daly River Region

A detailed description of the physiography of the Daly River region is given in (Tickell, 2012), ecological condition was described in detail by (Faulkes, 1998). Here we provide a brief summary of the hydro-climatic conditions in the region as contextual background.

The catchment of the Daly River consists of a number of important tributaries including the Katherine River, Flora River, King River, Fergusson River, Edith River and Douglas River. The main valley of the Daly River is a broad undulating area bounded by ranges to the south west and north east. The township of Katherine is the largest town in the catchment although smaller towns and settlements occur within the catchment (Faulkes, 1998). The principal land use in the catchment is associated with grazing although increasingly, large scale mahogany plantations are becoming an important component of the landscape.

The climate of the Daly River region is dominated by a distinct monsoonal wet season occurring from October until April and a winter dry season extending from May to September. The summer monsoons are driven by low level westerly flows that switch to a low level easterly flow during winter resulting from the west to east passage of high pressure systems in southern Australia (Cook and Heerdegen, 2001). The transitional periods before and after the monsoons are an important feature of the climate in the region. During these periods, rainfall is driven by local convective thunderstorms that can contribute up to 30% of annual rainfall (Cook and Heerdegen, 2001). These periods are also characterised by changes in humidity and vapour pressure deficits (VPD) that are important determinates of plant function (Duff *et al.*, 1997). Mean annual rainfall with the region is highly variable and increases in a south to north direction. Mean annual rainfall at Katherine is approximately 980 mm and this increases to approximately 1100 mm at the Douglas Daly research farm. Annual rainfall within the region has been higher than the long term average since 1996 and this has had a significant impact on the water balance of the region (Tickell, 2012). Temperatures remain high throughout the year, although temperatures are generally higher during the wet season than the dry season. Mean annual daily maximum and minimum temperatures are shown in Table 2. Annual pan evaporation is approximately 2300 mm and is relatively evenly distributed throughout the year, although maximum evaporation rates occur in October when daily with maximum temperatures are also high (~ 38ºC) (Tickell, 2012).

Table 2 Mean annual maximum and minimum temperatures for Darwin and the Daly River region (O'Grady *et al.*, 2002)

Site	Average Annual daily maximum temperature (ºC)	Average Annual daily minimum temperature (ºC)
Katherine	34.0	20.3
Wooliana	33.8	19.6
Mango Farm	34.1	20.6
Darwin	32.0	23.2

The geology and landforms of the Daly River region have been mapped by several authors (Baker and Pickup, 1987; Christian and Stewart, 1952; Northecote, 1968). Dominant features include the Arnhem Land Plateau, comprising Komolgie Sandstone, steep ridges, undulating plains and extensive floodplain system extending up to five kilometres from the banks of the Daly River (Faulkes, 1998; O'Grady *et al.*, 2002).

Three major limestone formations form the aquifers that provide water for the Daly Rivers strong dry season baseflow; the Jinduckin, Tindal and Oolloo. Recently a forth formation, the Florina has been identified and mapped (Kruse *et al.*, 2012). The Tindal limestone formation is 150-200m thick and consists principally of limestone with thick interbeds of mudstone. This aquifer is general high yielding and has high water quality. The Tindal aquifer is overlain by the Jinduckin formation consisting of mudstone beds up to 450 m thick interlaced with limestone. Water yields and quality from this formation are variable. The Oolloo formation consists principally of dolomite formations up to 200 m thick and tends to be high yielding with high quality water (Faulkes, 1998; O'Grady *et al.*, 2002). The Florina formation is the youngest of the Daly Basin and is restricted to the upper reaches of the Daly River and to a few isolated localities away from the river. The formation is up to 167 m thick and consists of a sequence glauconitic sandstone and limestone with minor shale and dolostone (Tickell, 2012).

There is strong connectivity between surface waters and groundwater. During the wet season aquifers are recharge by runoff events. Groundwater levels decline during the dry season principally as a result of groundwater discharge in rivers and streams and via evapotranspiration (Lamontagne *et al.*, 2005; O'Grady *et al.*, 2006). Groundwater levels also vary considerably on an annual basis, reflecting the length, duration and pulse strength of the preceding wet seasons (Jolly, 2001). By the end of the dry season many of the smaller tributaries stop flowing and at this point, base flows in the larger rivers are dominated by groundwater discharge. For a more detailed description of the hydrogeomophology of the region refer to Tickell (2012).

4.3 Water Balance of the Daly River catchment

There have been several assessments of the water balance of the Daly River region. At a catchment scale, a major feature of the water balance of the catchment is the highly variable nature of annual rainfall which results in large variation in runoff and groundwater recharge (Jolly, 2001) both within the catchment and between years. Average rainfall for the period 1957-2000 across the catchment was 970 mm, although this ranged from 500 mm to 1620 mm. As a result groundwater recharge varied from 0 to 300 mm yr^{-1} (mean 90 mm) and runoff varied from 50 to 590 mm yr^{-1} (mean 220 mm yr^{-1}, Jolly (2001). In this analysis Jolly reports understory ET and transpiration by large trees to be 510 and 150 mm respectively. These estimates of tree transpiration were derived by adapting the estimates of tree water use in the savannas near Darwin (O'Grady *et al.* 1999, Hutley *et al.* 2000) to the lower rainfall and tree densities of the Daly River region. These numbers highlight the importance of understory ET to total ET in the tropical savannas of northern Australia.

The most comprehensive study to date is that of Cresswell *et al.* (2011a) as part of the TRaCK program. This study provided as assessment of the impacts of land clearing on the water balance of the Daly catchment. Detailed measurements of evapotranspiration were made using the eddy covariance method (Hutley *et al.*, 2000) and soil moisture monitoring were conducted in conjunction with hydrological modelling using the WAVES model (Zhang *et al.* 1996) to assess the impacts of land clearing on the water balance. on uncleared, regrowth and pasture sites in the Daly region (Creswell *et al.* 2011). These studies showed that clearing resulted in a change in diurnal and seasonal evapotranspiration patterns, as well as a reduction in annual evaporation rates and an increase in the amount of water available for drainage and overland flow. Evapotranspiration from the natural savanna was estimated to be approximately 900 mm yr^{-1}, and clearing reduced ET by approximately 130 mm, which closely approximates the estimates of tree transpiration of (Jolly, 2001).

Evapotranspiration rates in the improved pasture site showed high seasonal variability, with the highest wet season rates of all three sites and a reduction to zero by the end of the dry. The uncleared savanna site maintained water use all year round via deep-rooted evergreen trees, while the regrowth site also maintained dry season water use at rates above the pasture site, but had the lowest wet season ET due to a low leaf area index (LAI). While the pasture site had the highest rates of evapotranspiration during the wet season (due to a high LAI and predominance of high water using grasses), the annual evaporation rate in 2008 in the uncleared savanna site (888 mm) was approximately 25% more than that for the improved pasture (719 mm) and regrowth (691 mm) sites (Creswell *et al.* 2011).

The TRaCK project used these data to parameterise the WAVES soil-vegetation-atmosphere-transfer (SVAT) model for these land uses to quantify the impacts of clearing on recharge by partitioning the excess water component of rainfall (derived from the reduced evapotranspiration) into potential recharge and overland flow. This part of the study determined that potential recharge on the pasture site was about twice that of potential recharge on the native vegetation sites, given the low (< 2 %) slopes and insignificance of lateral flows and the low rates of overland flow and relatively high infiltration rates of the Kandosol soils.

The WAVES model was also used to model the water balance for 3500 unique hydrogeomorphic units (HGUs) across the Daly catchment to produce estimates of surface runoff, recharge and ET (Creswell *et al.* 2011). This modelling was integrated with nine years of remotely sensed actual evapotranspiration (AET) data derived by the CSIRO using MODIS-Terra. A detailed summary of the measured and modelled water balance components for savanna and pasture sites in the Daly region is given in Table 3.

Table 3 Summary of the water balance components for a savanna and pasture site in the Daly River region of the Northern Territory (Cresswell *et al.*, 2011).

Parameter	Uncleared site		Pasture site	
	Depth equivalent (mm/yr)	Percentage of gross rainfall (%)	Depth equivalent (mm/yr)	Percentage of gross rainfall (%)
Gross Rainfall	1030	-	1061	-
Overstory Interception	85	8%	67	7%
Understory Interception	34	3%	-	-
Net Rainfall	911	88%	920	87%
Soil Evaporation	133	13%	105	10%
Overstory Transpiration	395	38%	593	56%
Understory Transpiration	255	25%	-	-
Total ET	902	88%	771	73%
Lateral Fluxes	0	0%	0	0%
Overland Flow	7	1%	55	5%
Potential Recharge	116	11%	235	22%

4.4 Parameterisation and validation of 3-PG for African mahogany

Aim 3 was to develop a preliminary parameterisation of the growth model 3-PG for African mahogany that could be used to assess growth and stand water use of these plantations and therefore help to assess the potential impacts of an expanding plantation estate on the water resources of the Daly river region. More specifically the project aims were to:

- Conduct a literature review to compile growth and water use characteristics for African mahogany
- Parameterise the 3-PG model to provide preliminary estimates of forest growth and the water balance of African mahogany plantations
- Conduct a preliminary assessment of the water use of African mahogany plantations at the plot and sub catchment scale to enable a comparative assessment of the water balance of these plantations with existing natural savanna and pastoral land uses, in order to make a preliminary assessment of the water interception activities of African mahogany plantations in the Daly river region.

The model 3-PG model (Physiological Processes Predicting Growth, (Landsberg and Waring, 1997) has been used widely around the world to estimate productivity and water use in plantations at the plot and catchment scales (Almeida *et al.*, 2004; Almeida *et al.*, 2007; Battaglia *et al.*, 2007; Marcar *et al.*, 2010), (Almeida *et al.*, 2010). A detailed description of the model is presented in several publications (Landsberg and Waring, 1997), (Sands and Landsberg, 2002) (Almeida *et al.*, 2004). Briefly however, the 3-PG model uses a simple radiation absorption model to calculate the photosynthetically active radiation (APAR) intercepted by a forest stand. The intercepted radiation is converted to gross primary production using the canopy quantum efficiency constrained by various environmental factors such as vapour pressure deficit, temperature, soil water availability and nutrient status (Almeida *et al.*, 2004). The mechanistic nature of the model has seen it widely applied for predicting the impacts of plantations on catchment water balance (Almeida *et al.*, 2010; Almeida *et al.*, 2007; Marcar *et al.*, 2010). A more recent version of the model allows partitioning of ET into contributions from trees, understory and pasture- a more detailed description of which is presented in Section 4.5.

The forest process-based model 3-PG2 was used to estimate potential forest production. The model has been previously parameterised and validated for *Pinus radiata*, *Eucalyptus globulus* (Sands and Landsberg, 2002), *E grandis* (Almeida *et al.*, 2004) *E. cladocalyx* and several mallee eucalypts (Carter *et al.*, 2008) (Polglase *et al.*, 2008)**.** Data required to run 3-PG2 include; monthly climate data (air temperature, vapour pressure deficit (VPD), solar radiation, rainfall and the number of rain and frost days); site factors (latitude, soil texture, maximum available soil water storage and soil fertility rating); initial partitioning of biomass and stocking rates; and management conditions (e.g. fertiliser application, irrigation and thinning). Parameters in 3-PG2 determining growth include canopy structure and quantum efficiency, partitioning of biomass, basic wood density, litterfall and root turnover rates. Various environmental variables, called modifiers, have the potential to affect the optimum wood production such as temperature, VPD, fertility, stand age, frost and soil water. These modifiers are all species dependent. The model runs on a monthly time-step and its primary outputs are NPP (net primary production), standing biomass in foliage, stems, branches and roots, stem number, transpiration and available soil water (Sands and Landsberg, 2002). 3-PG2 provides a more robust method for calculating the water balance and consequently plant-available water, stand water use, biomass partitioning and inclusion of understory as opposed to modelling only a single stratum of trees (Almeida *et al.*, 2007). The spatial version of 3-PG2 (3-PG2S) was used to estimate forest growth in our study regions. To date there have been no parameterisations of 3-PG2 for *K. senegalensis*. Furthermore, there have been no comprehensive surveys of the growth and physiology of *K. senegalensis*, making parameterisation of the model a difficult task. Here we develop a preliminary parameter set for analysis of the growth and water balance of African mahogany plantations in northern Australia. The parameterisation has been conducted via a combination of literature review and expert knowledge. A comprehensive parameterisation of the model is beyond the scope of this project. However, further detailed investigations would reduce uncertainty in model outputs. Table 4 provides a summary of the required data sets for this task. A complete list of model parameters and their definition are given in (Sands and Landsberg, 2002). Some preliminary field measurements and growth across a range of sites in the existing plantation estate were conducted to provide some background data sets for validating growth estimates.

Table 4 Data sets required for the parameterisation and validation of 3-PG2.

Data	Scale/format	Need
Soil		
Depth	At plot and catchment scale (xls and shape files)	Essential
Texture		
Water holding capacity		
Field capacity	At plot and catchment scale (xls and shape files)	Desirable
Wilting point		
Saturation		
Tree growth		
Tree age (year)	Plot scale, many plots representing variability in time series	Essential
DBH (cm)		
Tree height (m)		
Basal area (m2 ha-1)		Desirable
Volume (m3 ha-1)		
MAI (m3 ha-1 yr-1)		
LAI		
Physiology		
Stomatal response to VPD - gsmax x VPD curve (1/mb)	Tree	Desirable
Canopy conductance	Tree	Desirable
Max, Min and Optimum Temperature for growth (ºC)	Tree	Desirable
Mortality rate (tree/ha)	Plot scale	Desirable
General		
Stocking (tree ha^{-1})	Plot scale	Essential
Age canopy cover (year)	Plot scale	Essential
Specific leaf area mature tree (m^2 kg^{-1})	Tree	Essential
Specific leaf area young tree (m^2 kg^{-1})	Tree	Essential
Canopy quantum efficiency (molC $molPAR^{-1}$)	Plot scale	Desirable
Wood density in different ages (t m^{-3})	Plot scale	Essential
Litterfall rate	Plot scale	Essential
Allometry		
Equation DBH x wood biomass	Plot scale	Essential
Max and min fraction of NPP to roots	Plot scale	Desirable

Data	Scale/format	Need
Initial biomass (Wf, Wr, Ws) (t ha-1)	Plot scale	Desirable
Water balance		
Soil moisture (mm)	Plot scale	Essential
Canopy rainfall interception (mm)	Plot scale	Desirable
Groundwater level (m below ground)	Plot scale	Desirable
Understory LAI	Plot scale	Desirable
Climate data		
Monthly or daily rainfall (mm), maximum, minimum and average temperature (ºC), solar radiation (MJ), number of rain days (month-1)	Plot scale	Essential

4.5 Description of the water balance in 3-PG2

The soil water balance model in 3-PG2 combines forest and understory transpiration and soil evaporation under the generic term *evapotranspiration*. This is computed by applying the Penman-Monteith equation, driven by solar radiation and VPD above the canopy considering rainfall losses by canopy interception. The water balance model in 3-PG2 separately calculates forest and understory rainfall interception and transpiration, and soil evaporation. It takes into account the solar radiation intercepted by each component, shading by higher components, reduces VPD with accumulated LAI to simulate reduced atmospheric mixing within the canopy, and a more realistic model of rainfall interception is used. In addition, the 3-PG2 water balance model can run at a daily time step.

When the water balance is based on monthly data, rainfall interception and soil evaporation are modelled on a rainfall event basis. Each event in a month is assumed to have the same rainfall $R_e = R/d_R$, where R is total monthly rainfall, and d_R is the number of days of rain in the month.

4.5.1 Rainfall interception

Rainfall interception in 3-PG2 is modelled using a leaf water-retention model, and assumes all rainfall occurs as single daily events. In a rainfall event, rain first wets leaves up to a maximum thickness of retained water, and any subsequent rain becomes throughfall. During a rainfall event, retained water is evaporated at the wet-surface rate, and following an event all retained water is evaporated. Interception loss is thus the amount of evaporation during the event, plus all water retained on the leaf at the end of the event. Total monthly interception losses are obtained by summing individual events.

If the amount of rain in a rainfall event is R_e, its duration is assumed to be $t_i = R_e/r$ where r is the typical rainfall intensity. The interception loss I_{Ri} by a canopy of leaf area index L in an individual event is:

$$I_R = \begin{cases} R_e & R_e \le L\delta_{wx}/(1-e_0/r) \\ L\delta_{wx} + e_0 \mathrm{R_e}/r & R_e > L\delta_{wx}/(1-e_0/r) \end{cases} \quad (1)$$

where δ_{wx} is the maximum thickness of water on leaves, and the evaporation rate e_0 is computed using the Penman-Monteith equation for a wet surface. Note that δ_{wx} (mm) should be the sum of the

thicknesses of the water layers on both sides of the leaf. If e_0 exceeds rainfall intensity, all rainfall is lost due to leaf interception and evaporation. If r is unknown, the term e_0/r is omitted in Equation (7), and rainfall interception will be reduced. This can be compensated for to some extent by increasing δ_{wx}.
In the monthly water balance model, R_e is the total monthly rainfall divided by rain days; in the daily model it is the day's rainfall.

4.5.2 Tree transpiration

Transpiration by the forest canopy is modelled using the Penman-Monteith equation. This is driven by the canopy conductance, solar radiation intercepted by the canopy, and VPD above the canopy. Canopy conductance can be optionally modelled as in the original 3-PG or using a model described by (White *et al.*, 1999). Understory transpiration is modelled similarly, but driven by understory canopy conductance, solar radiation intercepted by the understory, and VPD below the forest canopy. The understory conductance is affected by environmental conditions using the same modifiers as applied to forest canopy conductance.

Atmospheric mixing is low within a forest and this reduces the VPD relative to that above the canopy. The VPD below a canopy with leaf area index L is assumed to be given by:

$$D(L) = D_0 e^{-(\ln 2) L / L_{D0}} \tag{2}$$

where D_0 is the VPD above the canopy and L_{D0} is the accumulated LAI required to reduce VPD by 50%. Pasture transpiration is determined similarly, but possible environmental and management effects on pasture conductance are ignored (i.e. no growth modifiers are applied) and the pasture is exposed to full sun.

4.5.3 Soil evaporation

Soil evaporation is confined to a single shallow soil layer. This layer acts as a barrier to further evaporation as the soil dries. Evaporation is high when the soil surface is wet after rain, and declines as it dries out, the so-called, two-phase Ritchie model (Ritchie, 1972**).** The Ritchie model was originally empirical, but can be derived from physical principles after some simple approximations (e.g. following (Choudhury and Monteith, 1988). The key parameters E_{S0} and E_{S1} are then expressed explicitly in terms of various physical properties of soil determined by soil texture. Evaporation from bare soil, and soil below the canopy, understory or pasture, are modelled in 3-PG2 using this model.
In Phase 1 (immediately after a wetting event) the rate of soil evaporation - e_S - is the wet-surface rate, e_0. Phase 2 commences once accumulated evaporation - E_S - exceeds an amount E_{S1}, and e_S is then assumed to decline hyperbolically with increasing evaporation accumulated above that in Phase 1. The rate of decline is described by the parameter E_{S2} which is the amount of evaporation in Phase 2 required to reduce e_S by 50%. Accumulated soil evaporation at a time t since the last wetting event is given by:

$$E_S(t) = \begin{cases} e_0 t & t \le t_{S1} \\ E_{S1} + E_{S2}\left(\sqrt{1 + 2(e_0 / E_{S2})(t - t_{S1})} - 1\right) & t > t_{S1} \end{cases} \tag{3}$$

where $t_{S1} = E_{S1}/e_0$ is the duration of Phase 1 evaporation. The wet-surface rate e_0 is calculated using the Penman-Monteith equation, driven by radiation incident at the soil and VPD above the soil. The analogue of canopy conductance is very large, but aerodynamic conductance g_{As} is much smaller than canopy aerodynamic conductance, e.g. $g_{As} \approx 0.01 g_{Ac}$. VPD and incident radiation take into account the presence of a canopy, and that prior to canopy closure part of the understory or soil is directly exposed to sunlight.

The 3-PG2 model tracks the accumulated net evaporation E_S from the soil, as this determines subsequent soil evaporation. Because of this, there is no need to explicitly consider a separate surface soil layer in the model. When a rainfall event occurs, E_S is reduced by the amount of rainfall (subject to $E_S \geq 0$). This forms the initial condition E_{S0} for subsequent period of soil evaporation, and Eq (9) is inverted and solved for an equivalent initial time t_0. If the time to the next rainfall event is t_R, soil evaporation in the intervening period is $E_S(t_R+t_0)–E_{S0}$. The user must supply values for E_{S0} and E_{S1}, and for the aerodynamic conductance g_{As}.

4.5.4 Runoff and drainage

If rainfall is sufficient so that the volumetric soil water content q exceeds saturation (q_{sat}), then excess above saturation is deemed to be surface runoff. The remaining water is available for transpiration and evaporation. If q subsequently exceeds field capacity (q_{fc}) the excess soil water is available for drainage. Drainage is assumed to proceed at a rate proportional to the excess, where the rate constant k_{Drain} (d^{-1}) is a texture-dependent soil property. Drainage D_D over a time period t days is given by:

$$\Delta_D(t) = (\Theta_0 - V_{Soil}\theta_{fc})(1 - e^{-k_{Drain}t}) \qquad (4)$$

where Q_0 is the initial amount of water in the soil, V_{Soil} is the volume of the soil profile, and q_{fc} the volumetric soil content at field capacity. In the daily model this is applied with t = 1, and in the monthly model with t = number of days between rainfall events.

Total runoff or drainage is the sum of runoff or drainage from the forest and pasture. The user is required to provide a value for k_{Drain}, and this will normally be available through the soil properties database.

4.6 Soils of the Daly catchment

Soils of the region have been extensively characterised. The existing plantation estate is situated mostly on red earths (Kandosols) characterised by deep sandy soils, and in particular the Blain, Woggaman and Oolloo soil types. Future plantation establishment is likely to be focused particularly in the Blain soil types (Hutley, L. pers comm.). Surface textural information is available for most of the soil types within the Daly River region (Tickell, 2012). Moisture release characteristics have also been measured for surface and 30 cm depths for a range of soil types. Table 5 presents the textural and moisture holding characteristics for a range of soil types in the Daly Region. Wherever possible, we use measured data from field sampling, however where needed, we have in-filled missing data using Saxtons soil hydraulic properties calculator based at: http://www.pedosphere.ca/resources/texture/worktable_us.cfm .

Blain and Oolloo soil types are typically very deep (often more than 5 m). There have been very few characterisations of soil texture and moisture holding characteristics with depth, although Kemei *et al.* (unpublished data) provide a detailed water release curves, bulk density and hydraulic conductivity to 1.8 m depth. However, surface properties have been used in this parameterisation to describe soil profiles. However, mahogany plantations are deep rooted (potentially up to 5 m pers. obs.). Here we extrapolate these soil properties to these depths.

Table 5 Soil moisture characteristics for the major soil types in the Daly River region used in plot scale and catchment scale 3-PG modelling. Data taken from Hutley *et al.* (2012). Numbers in red are calculated values based on soil textural properties using Saxton's soil hydraulic properties calculator at www.pedoshere.ca/resources/texture/worktable_us.cfm. Soil textural classifications are based on textural properties in (McDonald *et al.*, 1998).

Soil Type	Depth	Bulk density	%Clay	%Silt	%Sand	%Gravel	Classification	θs	Field capacity	Wilting Point	Drainage	K_{Sat}	K_{Us}
		g cm^{-3}						m^3 m^{-3}	m^3 m^{-3}	m^3 m^{-3}	m day^{-1}	m day^{-1}	m day^{-1}
Banyan	surface	1.36	7.9	8.6	83.5	0.17	LS	0.39	0.16	0.08		1.02	3.39
	depth	1.37	10.4	14	80.3	0	LS	0.4	0.17	0.09		0.65	5.73
Beemla	surface	1.79	9.2	14	76.9	21.12	LS	0.39	0.17	0.08		0.77	0.60
	depth	1.85	20.2	8.7	71.2	23.17	L	0.45	0.22	0.13		0.16	0.62
Bend	surface	1.6	9.05	12.9	78.1	1.48	L	0.35	0.17	0.08		0.77	1.24
	depth	1.58	24.5	13.3	62.2	0.74	L	0.46	0.24	0.15		0.10	1.17
Blain	surface	1.45	5.8	1	93.2	0	S	0.33	0.08	0.03		1.74	15.6
	depth	1.59	6.8	3.9	89.2	0	LS	0.37	0.14	0.07		1.34	13.5
	surface	1.45	5.8	1	93.2	0	S	0.35	0.08	0.03		1.74	15.6
	depth	1.59	6.8	3.9	89.2	0	LS	0.37	0.14	0.07		1.34	6.20
Cully	surface	1.55	10.5	7.2	82.3	11.25	SL	0.46	0.17	0.09		0.65	0.50
	depth	1.72	30.3	8.8	60.9	15.67	CL	0.48	0.26	0.17		0.06	0.53
Jindara	surface	1.51				4.1						0.19	0.75
	depth	1.65				2.1						0.07	0.18
Kimbyan	surface	1.34	8.38	12.5	79.1	27.82	LS	0.46	0.17	0.08		1.02	2.66
	depth	1.35	25.1	10.5	64.5	35.15	CL	0.39	0.24	0.15		0.16	1.69
Soil Type	Depth	Bulk density	%Clay	%Silt	%Sand	%Gravel	Classification	θs	Field capacity	Wilting Point	Drainage	K_{Sat}	K_{Us}
		g cm^{-3}						m^3 m^{-3}	m^3 m^{-3}	m^3 m^{-3}	m day^{-1}	m day^{-1}	m day^{-1}
Tagoman	surface	1.63	9.37	8.51	82.1	1.85	SL	0.40	0.17	0.08		0.78	5.05
	depth	1.67				1.05							6.82

Tolmer	surface	1.53	14.8	4.9	80.3		SL	0.42	0.19	0.11		0.33	2.52
	depth												
Woggaman	surface	1.61	8.6	4.6	86.8	7.25	LS	0.35	0.16	0.08	21.6	2.72	3.73
	depth	1.61	3.9	5.4	90.7	5.67	S	0.35	0.08	0.03	20.1	0.88	10.08
Wriggley	surface	1.53	9.03	10.6	80.37	0.36	LS	0.40	0.17	0.18		0.81	1.64
	depth	1.61	27.1	11.03	61.8	0.18	CL	0.47	0.25	0.16		0.08	0.61
Yungman	surface	1.6	5.11	7.22	87.7	7.6	LS	0.36	0.14	0.06		0.77	3.96
	depth	1.76	11.6	7.09	81.3	27.8	SL	0.41	0.18	0.09		0.97	12.5
Birrimbah	surface	1.72				13.54							3.34
	depth	1.64				16.29							8.24
Larrimah	surface	1.56				4.33							
	depth	1.49				2.55							
Oolloo	surface	1.64	10.7	1.9	87.4	0	SL	0.37	0.08	0.06	2.32	0.65	2.43
	depth	1.44	9.87	3	87.2	0	SL	0.40	0.16	0.08	2.37	0.75	2.15
Mason	surface	1.42	4.8	5.8	89.9		S	0.35	0.08	0.03			
	depth	1.51	5.8	7.8	86.5		S	0.37	0.14	0.06		1.53	7.46
Dashwood	surface	1.42	24.1	45.3	30.6	6.5	SC	0.47	0.08	0.21		0.16	
	depth	1.51	50.3	25.6	24.1	12	C	0.53	0.42	0.29		0.04	0.61
Soil Type	Depth	Bulk density	%Clay	%Silt	%Sand	%Gravel	Classification	θs	Field capacity	Wilting Point	Drainage	K_{Sat}	K_{Us}
		g cm^{-3}						m^3 m^{-3}	m^3 m^{-3}	m^3 m^{-3}	m day^{-1}	m day^{-1}	m day^{-1}
Cahill	surface							0.32	0.08	0.05			

4.7 Tree growth-visits to existing African mahogany plantations

A visit to African mahogany plantations growing in the Douglas/Dally region was conducted in July 2011. The aim of these visits was to collect additional data that could be used at for parameterising and validating 3-PG2. A number of sites were visited (Table 6) that ranged in age from less than 1 year to approximately 12 years old.

4.7.1 Tree growth

At each site a measurement plot consisting of 7 x 7 rows of trees was established. Growth characteristics of these sites are summarised in Table 7. The height (m) and diameter of each tree within the plot was recorded using a tape and height pole.

Table 6 African mahogany sites visited during July 2011.

Site	Plot	Lat	Long	Soil type
Napier Rd	sapflow	-14.5905	132.4774	Waggaman
Napier Rd	4			Waggaman
Napier Rd	3			Waggaman
Napier Rd	2			Waggaman
Flemming Rd	1	-13.9516	131.3679	Oolloo
Flemming Rd	2	-13.9956	131.3895	Waggaman
Flemming Rd	3	-13.9969	131.3875	Oolloo
Why Not Station	4	-14.0553	131.413	Blain
DPI research farm	5	-13.8422	131.1824	Blain
DPI research farm	6	-13.8424	131.1823	Blain
DPI research farm	7	-13.8438	131.1829	Blain

Table 7 Plot growth characteristics measured during July 2011 for African mahogany plantations in the Daly River region.

Site	Plot	Stand Age (year)	Avg. height (m)	Basal Area (m^2 ha^{-1})	Vol (m^3 ha^{-1})
Napier rd	sapflow				
Napier rd	4	12	14.5	25.5	127.6
Napier rd	3	12	13.8	27.6	129.2
Napier rd	2	12	14.3	27.7	142.1
Flemming rd	1	2.5	3.5	2.1	2.9
Flemming rd	2	2.5	1.8	0.1	0.1
Flemming rd	3	3.6	4.9	5.1	8.8
Why Not station	4	5	6.7		
DPI research farm	5	0.5	0.5		
DPI research farm	6	0.5	0.4	12.6	28.9
DPI research farm	7	3	2.8	1.7	1.8

4.7.2 Leaf area index

Leaf area index of the plots was estimated using a combination of digital canopy cover photography and hemispherical photography. During the July visit, digital canopy cover photographs were used to assess LAI of each of the measurement plots. Within each plot, 36 photos were taken at the centre point of each row and column intersection using a Nikon Coolpix S8000, 14 megapixel digital camera following (Macfarlane *et al.*, 2007). Photos containing direct sunlight were discarded before analysis, leaf area index (LAI) of the canopy was estimated using the algorithms in (Macfarlane *et al.*, 2007). Leaf area in index at Napier Rd and at Why Not stations have been assessed periodically using digital using hemispherical photography. Hemispherical photos were taken using the same sampling procedure as that used for the digital photography. Photos were analysed using the Hemispherical photo analyser developed by the CRC for Forestry http://members.forestry.crc.org.au/cgi-bin/doc.pl?rm=view_doc&doc_id=2866. A summary of the growth plot LAI estimates is shown in Table 8.

Table 8 Leaf area index of growth plots in July 2011 estimated using digital photography and hemispherical photography.

Date	Site	Plot	LAI (Digital photo)	S.E.	LAI (Hemispherical)
19/07/2011	Napier rd	sapflow plot	3.6	0.08	2.68
19/07/2011	Napier rd	4	4.0	0.06	
19/07/2011	Napier rd	3	3.9	0.10	
19/07/2011	Napier rd	2	4.0	0.08	
20/07/2011	Flemming rd	1	0.3	0.20	0.00
20/07/2011	Flemming rd	2			
20/07/2011	Flemming rd	3	1.2	0.16	1.17
20/07/2011	Why Not station	4	1.1	0.09	0.97
21/07/2011	DPI Research farm	5			
21/07/2011	DPI Research farm	6			
21/07/2011	DPI Research farm	7			

Leaf area index in the wet and dry season was measured using periodic hemispherical photography and the hemispherical analysis software described above (Bristow M, unpublished data). Regular seasonal sampling is ongoing but the existing estimates of LAI were used as an index of litterfall in the mahogany plantations, calculated as:

$$L_F = \Delta LAI_{(t1-t2)} \times LMA \qquad (Eq.\ 5)$$

Where L_F is litterfall (kg m^{-2} day^{-1}), ΔLAI is the change in leaf area index from measurement time 1 (t_1) to measurement time 2 (t_2) (m^2 m^{-2}) and LMA is leaf mass area (the inverse of specific leaf area). We note that this is an oversimplification of litterfall as litterfall that occurs during a period of increasing LAI would not register in this index, however in the absence of actual data on litterfall we believe that this at least gives an indication of seasonal litterfall rates. Seasonal patterns of litterfall for the growth plots are shown in Figure 14.

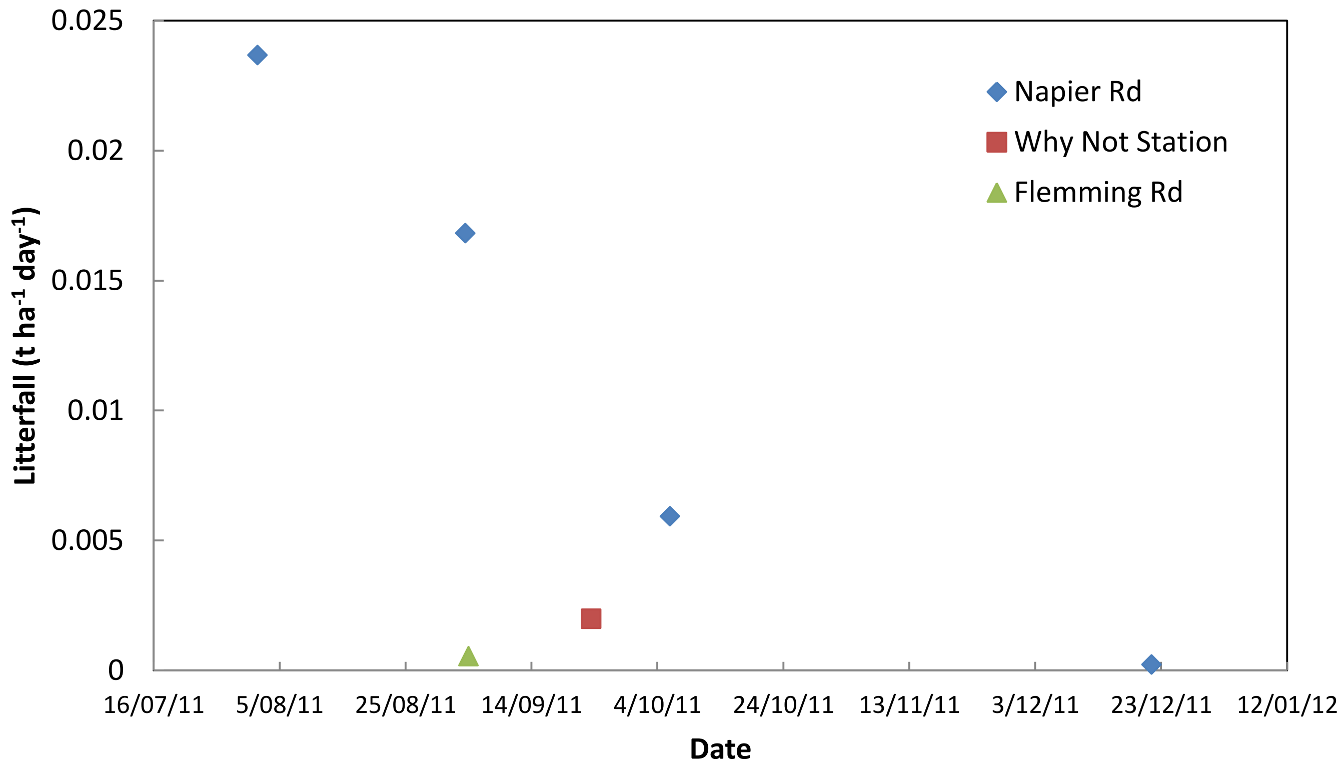

Figure 14 Seasonal estimates of litterfall in mahogany plantations based on an index of changing LAI (Eq. 6).

Photo: Canopy cover at Napier Rd mahogany plantation sapflow site, July 2011. This site is ~11 yo.

4.7.3 Tree scale allometry

The 3-PG model requires inputs of allometric data to enable partitioning of gross primary production among the biomass components as the stand ages. There have been no detailed assessments of the biomass partitioning for African mahogany trees within Australia, and very little information exists for this species globally. While some harvesting trials have been conducted and estimates of bole volume exist (Dickinson and Kelly, 2006), more detailed allometry has not yet been conducted. We have reviewed international literature to provide some preliminary allometric equations for *K. senegalensis*. An estimate of above ground biomass for African mahogany Africa is given by (Henry *et al.*, 2011) as:

$$Y=2.2598-3.4804x+1.6684x^2 \qquad (Eq.6)$$

Where Y is above ground biomass in kg and x is circumference in meters. Basic density for mahogany is 637 kg m^{-3} and varies from 533 to 704 kg m^{-3} (Armstrong *et al.*, 2006).

4.7.4 Physiology

There have been no comprehensive studies of physiological parameters in *K. senegalensis*, thus we have estimated these parameters. There is currently no studies where of stomatal sensitivity to vapour pressure deficit, canopy conductance, max or min temperatures or mortality rates. There has only been one study of water use in this species. (Carter *et al.*, 2010) has examined sapflow in African mahogany in the Kununurra. A however leaf area of the trees studied was not reported thus we could not convert the volume fluxes of water to a canopy conductance for this species. However canopy transpiration in this species is high, with Cater *et al.* (2010a) reporting rates of annual canopy transpiration up to 753 mm $year^{-1}$. Additional data on water use for this species is currently being collected in the Daly River region; however, the parameters required to interpret the sapflow data are currently not available, inhibiting direct comparisons for these sites.

4.7.5 Climate

The model was run using monthly climate surfaces using the SILO data drill. Monthly average minimum and maximum temperature (T_{min} and T_{max}), total rainfall (mm), number of rain days and solar radiation 1990 -2011. For future scenarios the data were looped for the 1990-2011 climate frequency. Seasonal rainfall in the Stray creek catchment is shown in Figure 15.

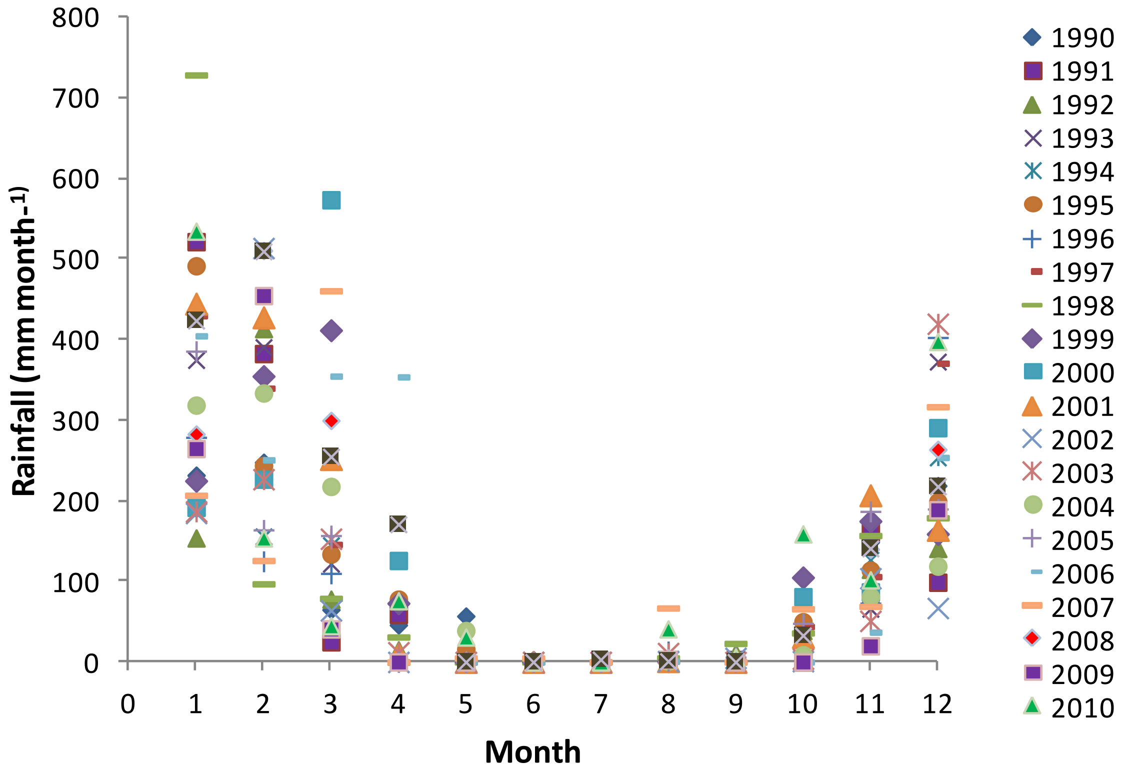

Figure 15 Monthly rainfall from 1990 to 2011 in the Stray Creek catchment.

4.8 Plot scale modelling of African mahogany plantations

4.8.1 Tree growth

The model was parameterised and run for each of the sites visited during July 2011 (Table 6). Simulations of growth over a 20 year period were conducted at each site from the estimated date of planting, 20 years being an estimate of the rotation length for this species in the Northern Territory. Furthermore, for the model runs simulated here, a thinning regime of thin to 700 stems. ha^{-1} was implemented at age 7 and further thinning to 400 stems ha^{-1} at age 14 was implemented based on silvicultural practices that might be employed by the companies during plantation rotation (D. Reilly pers. comm.). A summary of the growth characteristics for the model runs is shown in Figure 16.

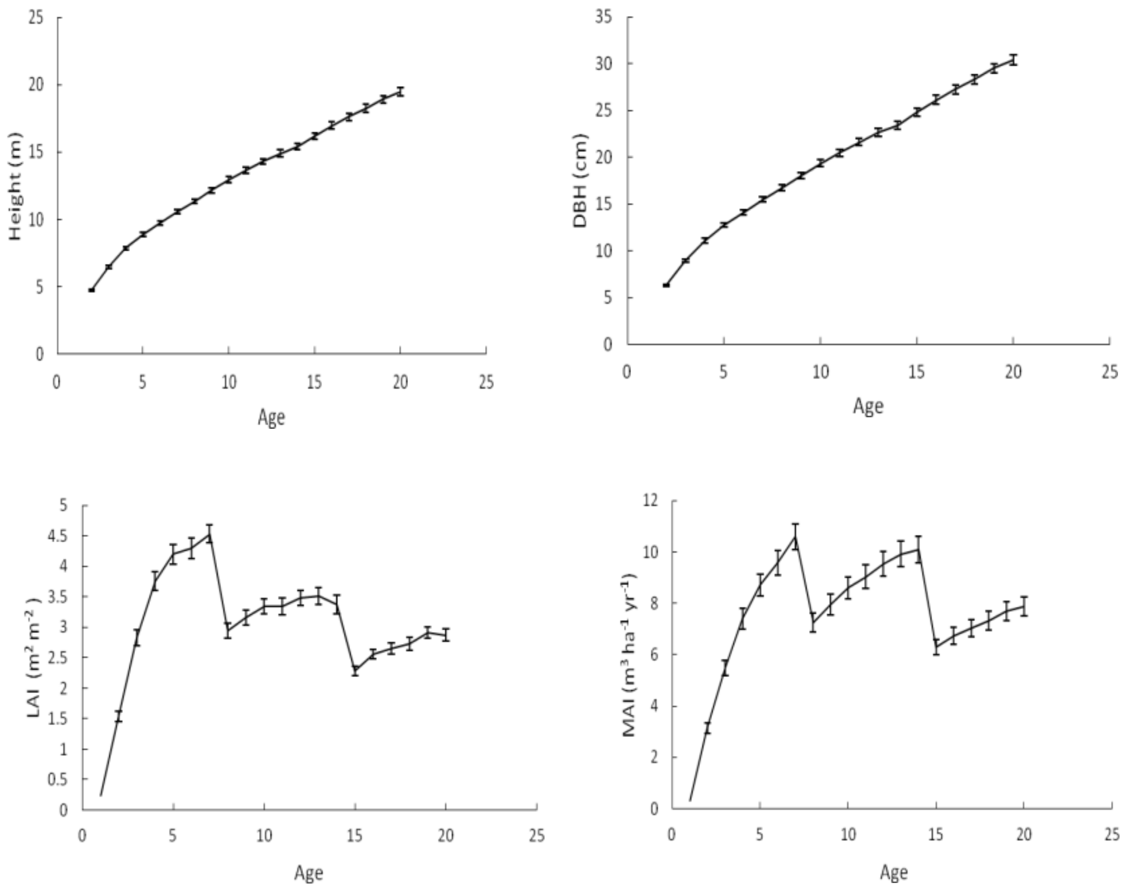

Figure 16 Growth outputs for African mahogany in the Daly River Region. Data are the mean growth curves for 7 sites. Error bars represent the standard error of the mean.

Leaf area index and mean annual increment peaked at about 6 years at around 4.5 and 10 $m^3 ha^{-1} yr^{-1}$ respectively. There is little variability in the modelled estimates between sites, this is largely a function of the low spatial variability in the climate among the sites being modelled and low variability in the parameters that describe the soil textural and physical properties, the plantations in the region have largely been established on Blain, Waggaman and Oolloo soils types that have very similar textural characteristics, predominantly sandy soils. The estimates of growth predicted by the model suggest that in the context of African mahogany plantations in Australia, the plantations of the Daly River region are reasonably productive plantations. Modelled estimates are within the upper range of estimates of growth predicted for this species on productive sites in Queensland (Dickinson and Kelly, 2006). These high productivities might be expected as the soils in the Daly River region are characteristically deep and well drained soils with little in the way of impeding layers. Furthermore rainfall in the climate scenario used in the modelling is above the long term average (1286 mm for the model runs compared to ~900 mm LTA).

A detailed evaluation of model performance was not possible due to the lack of data for validation, however there was good agreement between model predictions and growth data collected during the July 2011 trip. In particular the model predicted quite closely the height and diameter of trees at the Napier Rd site (Figure 17), however the model over predicts the early growth phases of the model, with estimates of height and DBH at Fleming Rd site two and at the DPI research farm being considerably higher than the observed values. The Fleming Rd sites highlight the particular difficulty of validating the model with limited growth data.

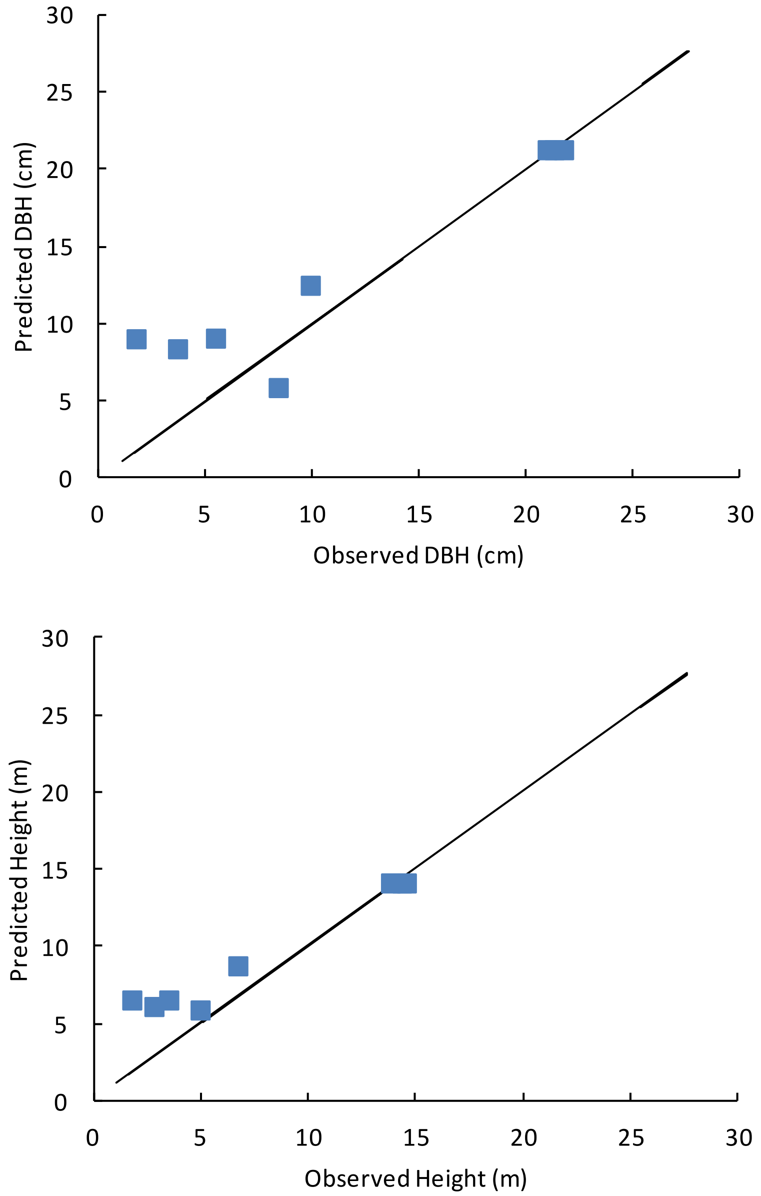

Figure 17 Relationship between observed and predicted mean height diameter for African mahogany trees in the Daly River region

The plantations at Fleming Rd were both established in 2009 on Blain soils with similar climate. However measured heights and diameters at these two sites varied considerably. Measured mean height and diameter were 3.5 m and 1.8 m and 5.5 cm and 1.7 cm at Fleming road sites 1 and 2 respectively. Accounting for such variability without an understanding of the spatial and temporal controllers on growth responses, previous management history and survival post establishment is very difficult.

Figure 18 shows the temporal dynamics of stand growth at the Napier Rd site. The figure demonstrates that growth is highly seasonal. Leaf area index varies seasonally with variation of up to 0.5 to 1.0 m^2 m^{-2} from the end of the wet season to the end of the dry season. This variation is consistent with the seasonal variability estimated using periodic LAI assessments (M. Bristow unpublished data). Despite this variation and based on observed and modelled data, African mahogany plantations maintain a higher LAI throughout the dry season than the LAI of the surrounding savannas. Thus the main constraint on growth appears to be soil water availability.

High LAI accompanied by dry season transpiration rates may considerably deplete soil water reserves by the end of the dry season (These dynamics are discussed in more detail in section 4.9).

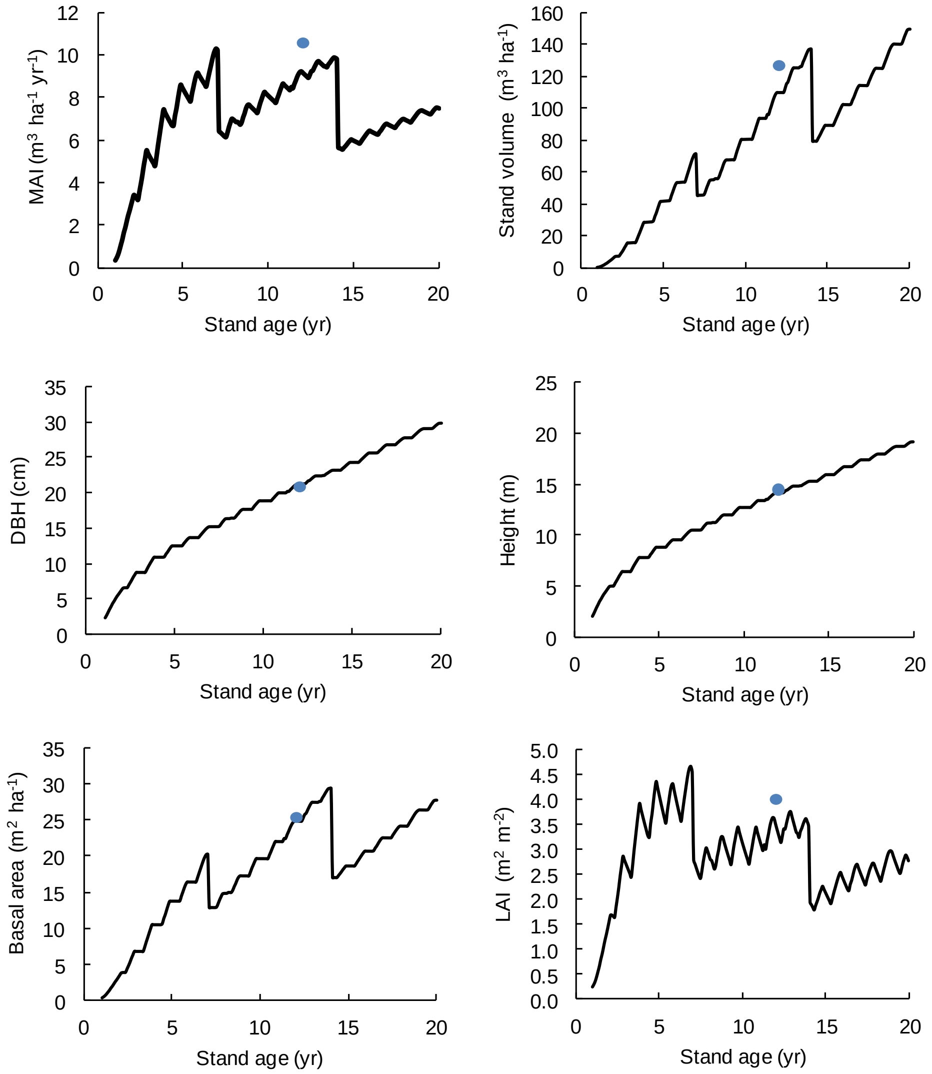

Figure 18 Model output of the temporal dynamic of stand growth at the Napier Rd site

Leaf area index plays an important role in the water balance and productivity of plantations because it determines the amount of light intercepted and also determines the volume of water transpired by the canopy (Landsberg and Waring, 1997). The model predicted the LAI of the Napier Rd sites (3.8 and 4.0 measured and predicted respectively) reasonably well. However, it significantly over estimates the LAI of the younger plantations. The problems that arise for estimating the water balance of a matrix of plantations of different ages are discussed in more detail in section 4.10

4.9 Characterisation of African mahogany plantation water balance

Evapotranspiration and the water balance of the savanna and the pasture communities have been extensively characterised with both modelling and measurements (Cook *et al.*, 1998), (Hutley *et al.*, 2000) (Wilson *et al.*, 2006) (Schymanski *et al.*, 2009) (Cresswell *et al.*, 2011) (Whitley *et al.*, 2011). A summary of measured ET and other components of the water balance for both pasture and savanna in the Daly river region are presented in Table 3. In this section we present, what we believe to be the first assessment of the water balance of African mahogany plantations. However, we stress that there are no comprehensive data sets with which to validate these numbers. Thus our validation is limited to comparing estimates of ET derived from the model for savanna and pasture systems with the measured data for these systems presented by (Cresswell *et al.*, 2011) (Table 3). Here we use the rationale that if we can model these systems reasonably well we can have some confidence in the estimates of key water balance components derived for the African mahogany plantations.

The summary of water balance for the African mahogany plantations over the 20 year plantation cycle is shown in Table 9. Total evapotranspiration from the African mahogany plantations varied from 846 mm yr^{-1} to more 1076 mm yr^{-1}. Drainage under these systems varied from 340-465 mm yr-1 and this is similar to the drainage occurring under the savanna system (Table 10). In the current simulations understory transpiration in the plantations was not considered. On the whole understory vegetation was largely absent from the plantations visited during July 2011. However, understory evapotranspiration dominates total evapotranspiration in savanna systems and can represent up to 60% of total evapotranspiration (Hutley *et al.*, 2000), and is an important component of the water balance of the tropical savannas. Thus despite understory vegetation being suppressed in older plantations, understory grasses may contribute significantly to total evapotranspiration in the plantations during the establishment and early growth phase prior to canopy closure (6 to 7 yo) although this is not explored in this analysis.

Table 9 Summary of the water balance components for African mahogany plantation sites in the Daly River region of the NT. Data represent the mean of the model output over a 20 year rotation length*.

Site	Rf (mm yr^{-1})	T (mm yr^{-1})	I (mm yr^{-1})	E_{soil} (mm yr^{-1})	ET (mm yr^{-1})	Δsoil (mm yr^{-1})	D (mm yr^{-1})
Napier 4	1159	603	75	168	846	-28	340
Napier 3	1159	603	75	168	846	-28	340
Napier 2	1159	603	75	168	846	-28	340
Fleming 1&2	1530	757	131	188	1076	-11	465
Fleming 3	1361	631	92	194	917	-23	466
DPI 3	1349	627	90	193	910	-25	465

*Rainfall = Rf, Canopy Transpiration = T, Interception = I, Soil evaporation = E_{soil}, Total evapotranspiration= ET, Change in soil moisture = ΔSoil, Drainage/Runoff = D.

Comparison of the African mahogany water balance with the savanna and pasture systems is shown in Table 10. Note that this table summarises the main components of the water balance and does not show changes in soil moisture or understory et in the savanna (see table 1). Canopy transpiration in African mahogany contributed the largest component to total evapotranspiration (70 ± 0.0 % of ET) and is within the range of estimate reported by Carter *et al.* (2010a) for mahogany plantation in the Kununurra region. This is in contrast to the savannas were canopy transpiration contributes a much smaller contribution to ET (~30%, (Cresswell *et al.*, 2011)) and understory ET dominates total ET at the annual scale. The components of the water balance compare well with those presented by (Cresswell *et al.*, 2011). Total evapotranspiration represented 88% of rainfall. In the simulations presented here total ET was approximately the same as that reported in (Cresswell *et al.*, 2011) but represented a lower proportion of gross rainfall, approximately 72%. As a result estimates of drainage from 3-PG2 (379 mm) were higher than those reported by (Cresswell *et al.*, 2011), 123 mm, although rainfall in this modelling study was also higher than that reported by Cresswell *et al.* (2011).

Modelling the savanna woodlands with 3-PG2 is a particularly challenging task. 3-PG2 is primarily a growth model and well suited to modelling the growth of plantations. The model is less well suited to modelling native forests. Therefore to constrain growth within the savanna simulations we had to "force" the seasonal patterns of overstory and understory LAI (0.8-1.2 and 0.5-1.5 for over story and understory respectively). While these LAI values are within the range of values previously reported for savannas (O'Grady *et al.*, 2000) it is unlikely that these numbers reflect the natural inter-annual variation in LAI. Furthermore the model predicts much higher growth than is otherwise observed in these systems. The structure and function of the savannas is maintained by high frequency fire regimes that cannot be replicated in 3-PG2.

Table 10 Comparison of the main components of the water balance of African mahogany plantations with savanna and pasture systems modelled using 3-PG2.

Component (mm yr^{-1})	*K .senegalensis plantation*	Savanna	Pasture
Rainfall	1286 ± 63	1260	1260
Transpiration	637 ± 24	270	898
ET	907 ± 36	910	1157
Interception	90 ± 9	64	56
Soil Evaporation	180 ± 5	183	191
Runoff/Drainage	403 ± 28	379	74

Despite these issues, the model did a reasonable job of predicting the seasonal dynamics of overstory and understory ET for the savanna (Figure 19). As discussed above, on an annual basis, total ET of the savannas is dominated by understory ET. Canopy water use exhibits a remarkable consistency throughout the year despite the large seasonality in rainfall (O'Grady *et al.*, 1999), with the modest seasonal variation in the overstory transpiration driven by the seasonality of the semi- and full- decidous trees species that co-occur with the evergreen Eucalypt species (Hutley *et al.* 2000). Seasonality of canopy transpiration is considerably reduced compared to the seasonality of the understory. Furthermore transpiration from the understory during the dry season is similar to that of the canopy, and this is consistent with observed results (Hutley *et al.* 2000).

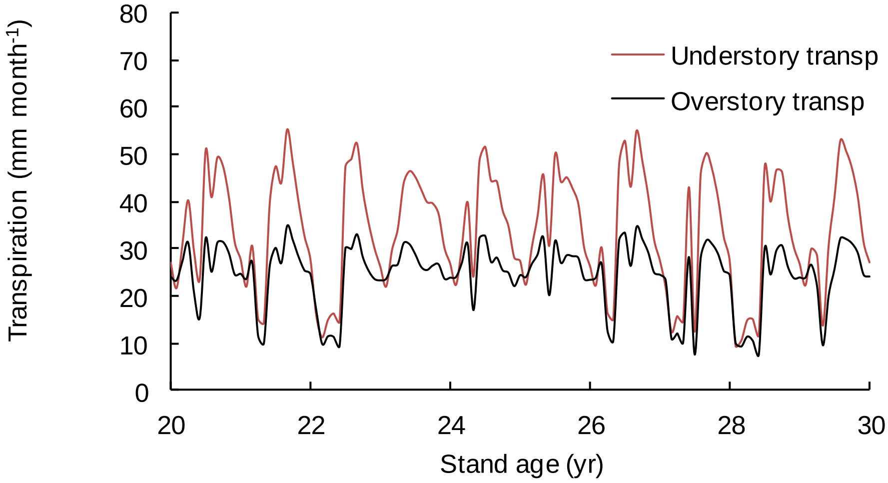

Figure 19 Seasonal dynamics of overstory and understory transpiration in savanna predicted using the 3-PG2 model.

In contrast to the seasonal dynamics exhibited by the savanna system, African mahogany plantations exhibited strong seasonality in canopy transpiration (Figure 20). The model predicts that plant available water in the soil profile to a depth of 5 m is fully depleted by the end of the dry season, a response that drives canopy transpiration to zero in stands where the leaf area index is higher than approximately 2.5. Currently we do not have detailed sapflow data to fully validate this response (either the transpiration data or the soil moisture data to 5 m) but this response represents an important dynamic that differentiates the African mahogany plantations from the savanna systems.

At the time of writing, preliminary tree sapflow data is available with monitoring occurring at a range of tree ages (5 and 12 yo) and soil types. At the Napier Road trial plantation (12 yo, Waggaman soil type), 8 trees have been monitored from April 2011 using heat ratio and heat field deformation techniques (ICT International, Armidale), but with data gaps due to instrument failure. However, data is available for an 11 month period spanning the end of the wet season 2011 (April) to the mid wet (January 2012). These observations, like the model output, demonstrate the high level of seasonality evident for mahogany trees, with at least a 3 fold decline wet to dry seasons evident. This also matches observed 2 fold decline in LAI wet to dry season at this site. However, tree water use did not drop to near zero fluxes as implied from the modelling (Figure 20), an unrealistic outcome, due to a lack of data describing rooting depth and soil physical properties at depth. The modelling also suggests African mahogany tree water use is approximately double that of the Eucalypt dominated savanna canopy (Table 10) and this result is also supported by preliminary sapflow observations at the Napier Rd site, with rates ranging from 8 to 19 l d^{-1} (Figure 21, Figure 22), compared to Eucalypt water use of between 1 and 8 l d^{-1}, wet or dry season (Figure 22).

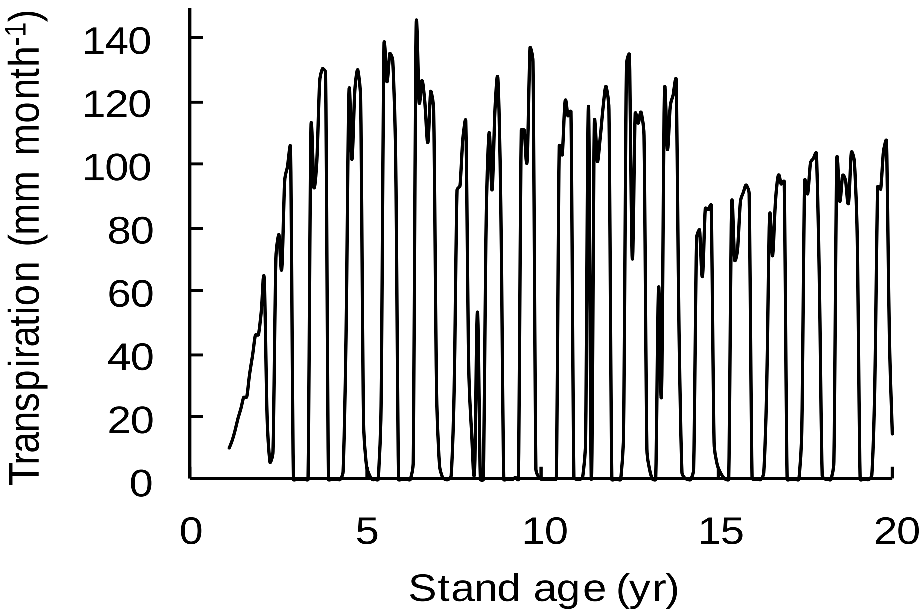

Figure 20 Modelled seasonal dynamics of canopy transpiration in *K .senegalensis* based on soils and stand structure of the Napier Road trial plantation site.

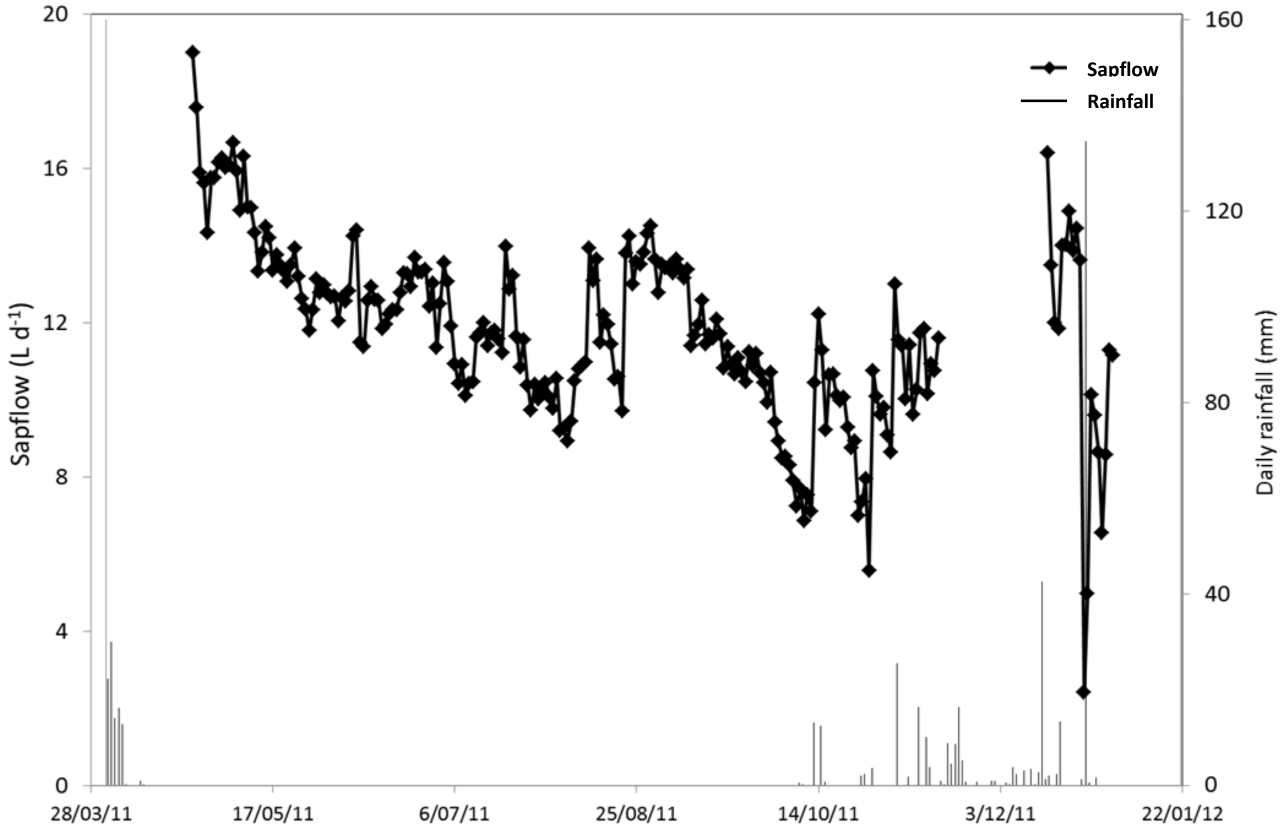

Figure 21 Seasonal patterns of sapflow from a African mahogany individual (21 cm DBH) at the Napier Road trial plantation site. The heat field deformation technique was used to make these sapflow measurements as described by Nadezhdina *et al.* (2008). Probes were manufactured by ICT International, Armidale.

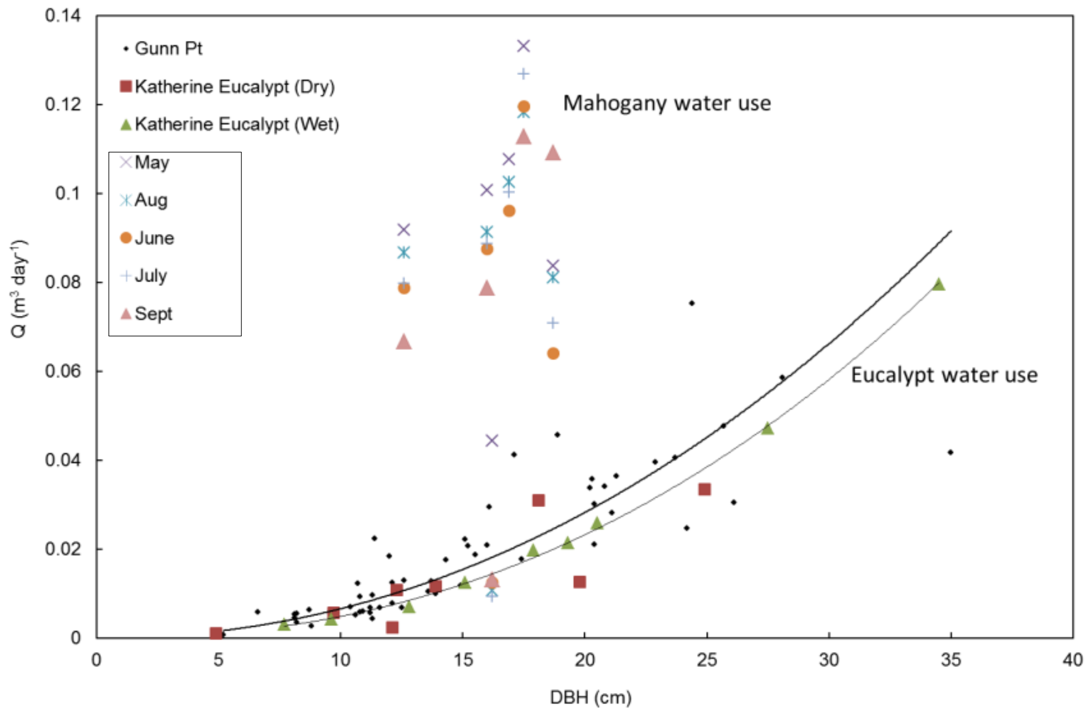

Figure 22 Comparison of Eucalypt sapflow Q (m^3 d^{-1}) (dry and wet season) with African mahogany sapflow (dry season, symbols in box). Units are comparable with Figure 21 by x 1000 to convert m^3 of sapflow to litres per day.

From a water balance perspective, given the larger extraction of soil water from mahogany tree transpiration, a larger proportion of annual rainfall is required to recharge the soil profile in the plantations each wet season when compared to the native savanna and this results in approximately 10% reduction in drainage under the mahogany plantations (Figure 23). This is offset by the loss of high water using grasses at canopy closure (~ 200-300 mm y^{-1}). Although annual rainfall in these savannas is generally high and sufficient to recharge the soil profile, annual rainfall is also highly variable. Low wet season rainfall may make the African mahogany plantations vulnerable to severe drought should there be a succession of low wet season rainfall, or the wet season arrives later in the year. Interestingly, total ET in the savanna and the plantations and pasture systems were relatively similar. This response is not altogether surprising as rainfall and radiation represent the main drivers of evapotranspiration (Budyko, 1974), however the seasonal dynamics of the contributors to ET varied among the three systems.

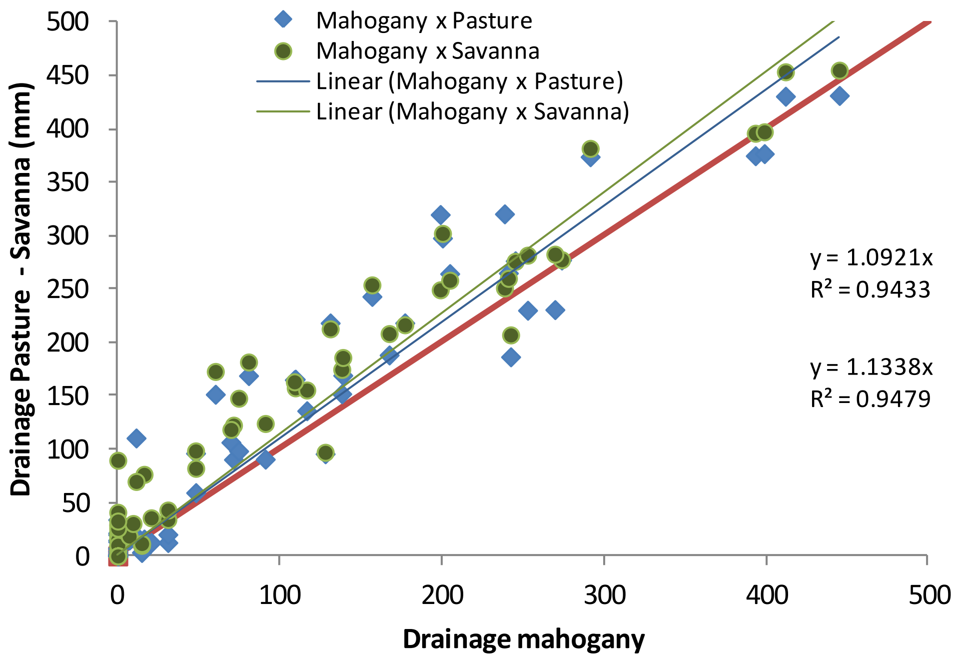

Figure 23 Relationship between drainage under mahogany plantations and under savanna.

4.10 Uncertainty in model parameterisation

This project represents one of the first attempts to model the growth and water balance of this species. However it is important to recognise that there is considerable uncertainty in the modelling presented here. Indeed there is uncertainty associated with all modelling processes (Hayes, 2011). The parameterisation of 3-PG2 was based on information derived from literature reviews and limited field measurements conducted during the course of this project. Where we were not able to find good information on parameters we have had to use expert knowledge in relation to how we think parameters vary, thus there is uncertainty in the parameterisation of the model. Given that there is very little real growth and water balance data with which to validate the model we acknowledge that there is a high level of uncertainty associated with the outputs of the model. This is not necessarily a problem, but this uncertainty needs to be acknowledged if the outputs of this project are to be extended into policy outcomes.

The principal aim of this project was to develop a preliminary parameterisation of 3-PG and assess its performance against observed field data in the region. The collection of field data for both the growth and water use of the African mahogany is ongoing in related projects. Thus improvements to the model parameterisation and validation will be ongoing, and this will act to reduce uncertainty associated with preliminary modelling. In Table 11 we identify important uncertainties likely to impact the modelling outcomes at both the plot and catchment scale. The aim here is to identify where future work might most profitably reduce uncertainty in modelling outcomes and to optimise and prioritise data collection to constantly improve the calibration and validation of the mode.

Table 11 List of inherent uncertainties in the current parameterisation of model scenarios

Uncertainty	**Impact on water balance estimation (low, middle or high)**	**Description**
Climate	High	The climate data used were extracted from SILO data drill for the region. Although climate variability over the region is low, inter-annual and spatial variation in rainfall in particular can have a large impact on the water balance. For future climates we looped the existing the climate record thus in effect we project the historical climate record into the future. Future climate regimes are not accounted for in the current modelling scenario. The future scenario uses the climate record starting from 1990, thus the year 2012 had the same climate as 1990
Soil properties	High	Where possible we used existing soils information. The bulk of this represented the soil physical and textural properties of surface soils. Mahogany plantations are potentially deep rooted. Surface soil properties may not necessarily reflect the physical and textural properties of the whole soil profile Where there were gaps in knowledge of soils we used coarse resolution data available through ASRIS and generic equations for converting soil texture into soil physical properties Defining accurate soil depths is a particularly important parameter as this in combination with soil texture defines the size of the plant available water pool-detailed information of soil depth is not available across the catchment
Physiology	High	There have been no measurements of stomatal or canopy conductance in this species, nor it relationship with D. Allometry in this species is extremely limited, of the information that was available for this species were for wild trees in their native environments. These may or may not reflect the allometry of the trees growing in the Northern Territory. Of particular importance is the partitioning of biomass to leaf, branch stem and root pools as these directly affect the growth and resource capture capacity

4.11 A comparison of ET from mahogany, savanna and pasture within the Stray Creek sub-catchment

To begin assessing the impacts of landuse change on the water resources in the region we ran the spatial version of the 3-PG2 model, 3-PG2S using the Stray Creek sub-catchment as a case study. This was done because this catchment has a high proportion of the favoured Blain soil type within the sub-catchment. The scenario used to assess the impact of plantations establishment on water resources was based on establishing 2000 hectares of plantations per year up to a target 40,000 ha. This scenario is based on realistic scenarios of the future growth of the industry in the Daly River region, although we acknowledge that all of this future planting may not be just restricted to the Stray Creek sub-catchment. A more distributed planting throughout the Daly River basis would most likely reduce the overall impacts on the water balance (i.e. the plantations would be less concentrated over a larger area than the scenario considered). Despite this, the scenario may be realistic as a concentrated planting scenario as modelled would potentially reduce capital and ongoing costs associated with managing an expanding plantation estate.

The spatial version of the model requires input of spatial layers of soils, monthly climate (rainfall (mm), maximum and minimum temperature (ºC), solar radiation (MJ m^{-2} day^{-1}), and number of rain days in the month). An attribute table has been created to establish the values of soil saturation, wilting point, field capacity , drainage, hydraulic conductivity for each soil type present in the catchment. The soil map was produced based on ASRIS available information (Level 4) (http://www.asris.csiro.au/index_ie.html). The climate time series used in the simulations were the observed climate for 2010 to 2011 and from 2012 to 2029 we used a series starting in 1990 to 2009. Using a historical climate time series reproduces natural variability between years and is more likely to minimise potential overestimation of forest growth and water use that can happen using average monthly series (Almeida *et al.*, 2010).

4.12 A case study of the Stray Creek sub-catchment

The distribution of soils types in the Stray Creek sub-catchment are shown in Figure 24. Expansion of the plantation estate is expected to target the Blain soil types (L.B. Hutley pers comm.). In the current modelling scenario, 2000 hectare bocks were established on an annual basis. Initial plantings targeting previously cleared land on Blain soils. The extent of existing cleared land within the catchment was identified using a data layer provided by Charles Darwin University (

Figure 25). Other major land use types within the catchment were identified by combining the existing distribution of the cleared land with the current extent of the existing mahogany plantations (provided by African Mahogany Australia) and image classification of Landsat images. Cleared land and mahogany represent only small proportions of the current landuse activities (10% and 1% respectively). Using this combined approach we classified three main land uses, pasture (cleared land), savanna and African mahogany plantations. The extent of already cleared land mapped as pasture in the Stray Creek sub-catchment is shown in

Figure 25. The African mahogany planting scenario is shown in Figure 26. By 2029 the proportion of the catchment that is occupied by plantations under this scenario increases from 1% to approximately 33% of the total catchment area. Given that only a small proportion of the catchment is currently cleared, our scenario predicts that most of the increase in the plantation estate will occur on land currently classify as native savanna vegetation.

The spatial impacts of the expansion of the plantation estate was assessed by running 3-PG2S at a monthly time step for 20 years with plantation area increasing from January 2009. The model was initialised to tree one year old tress and the new plantations were established in January of each year. Only one parameter set for each vegetation type was established (*K. senegalensis*, savanna, pasture) and used based on the classification performed above.

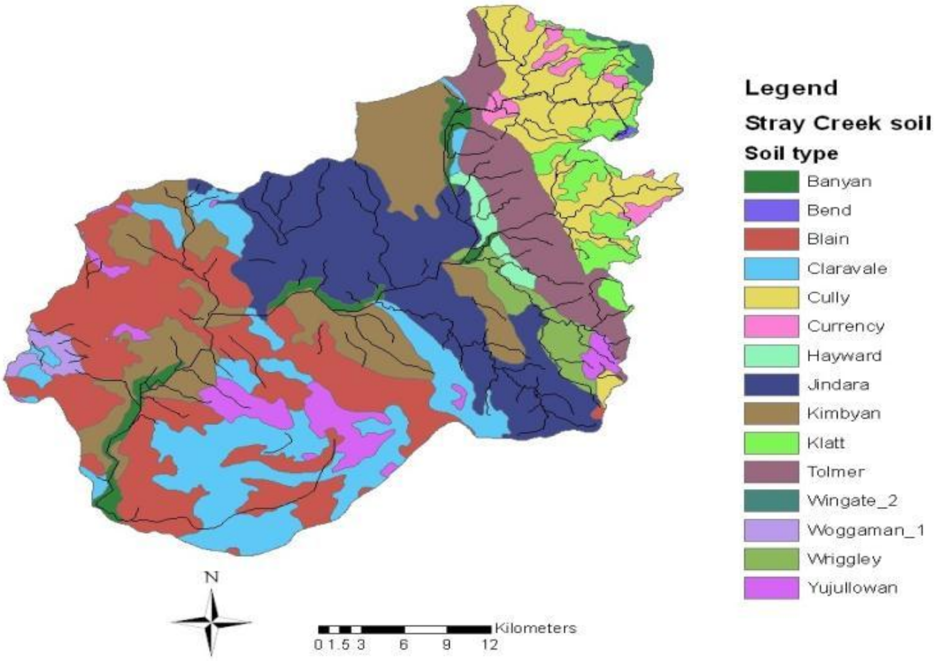

Figure 24 Distribution of major soil types in the Stray Creek sub-catchment.

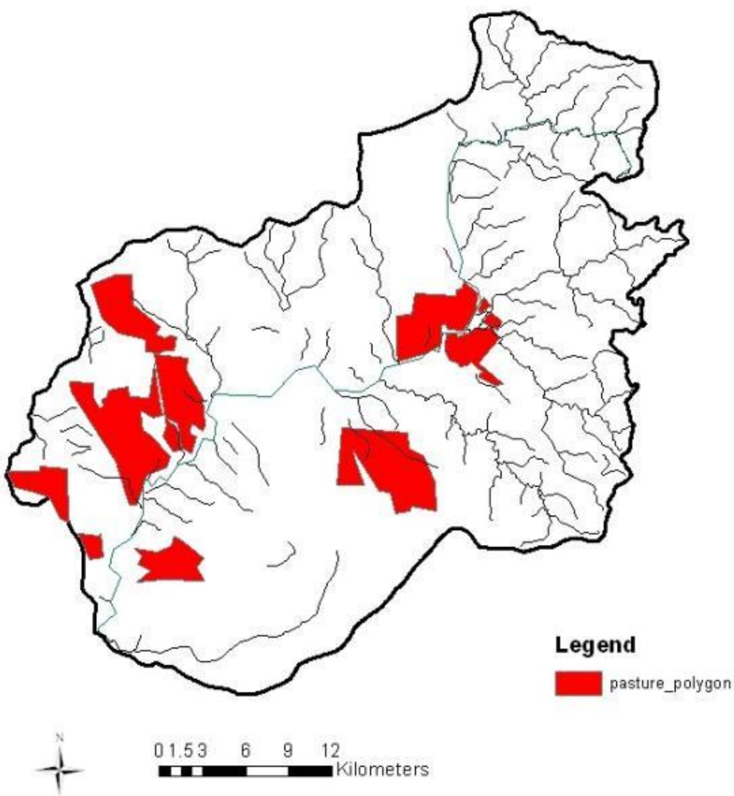

Figure 25 Spatial extent of existing cleared land in the Stray Creek catchment.

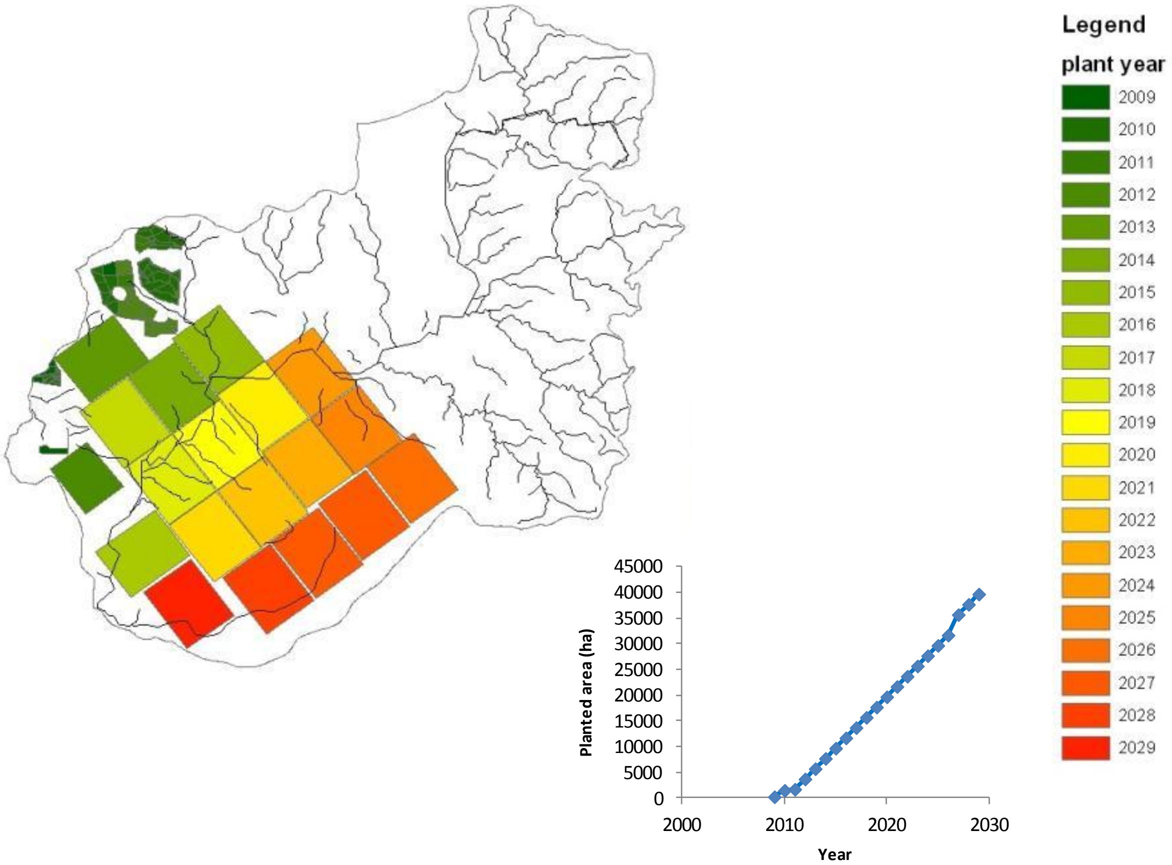

Figure 26 Distribution of the actual and simulated establishment of African mahogany in the Stray Creek catchment for the period 2009-2029.

4.13 Catchment scale estimate of ET and drainage

Figure 27 and Figure 28 show the spatial extent of predicted evapotranspiration and drainage within the Stray Creek catchment at 5 year intervals over the period 2010 to 2029. It is important to note that these figures represent the annual ET associated with that year, and not a cumulative or average of the intervening period. However the two figures demonstrate that there is considerable spatial variability in both ET and drainage. Climate is relatively uniform across the catchment, thus the main driver of the variation in ET and subsequently drainage, is soil properties. A synthesis of the estimated cumulative water balance for the entire catchment is presented in Table 12.

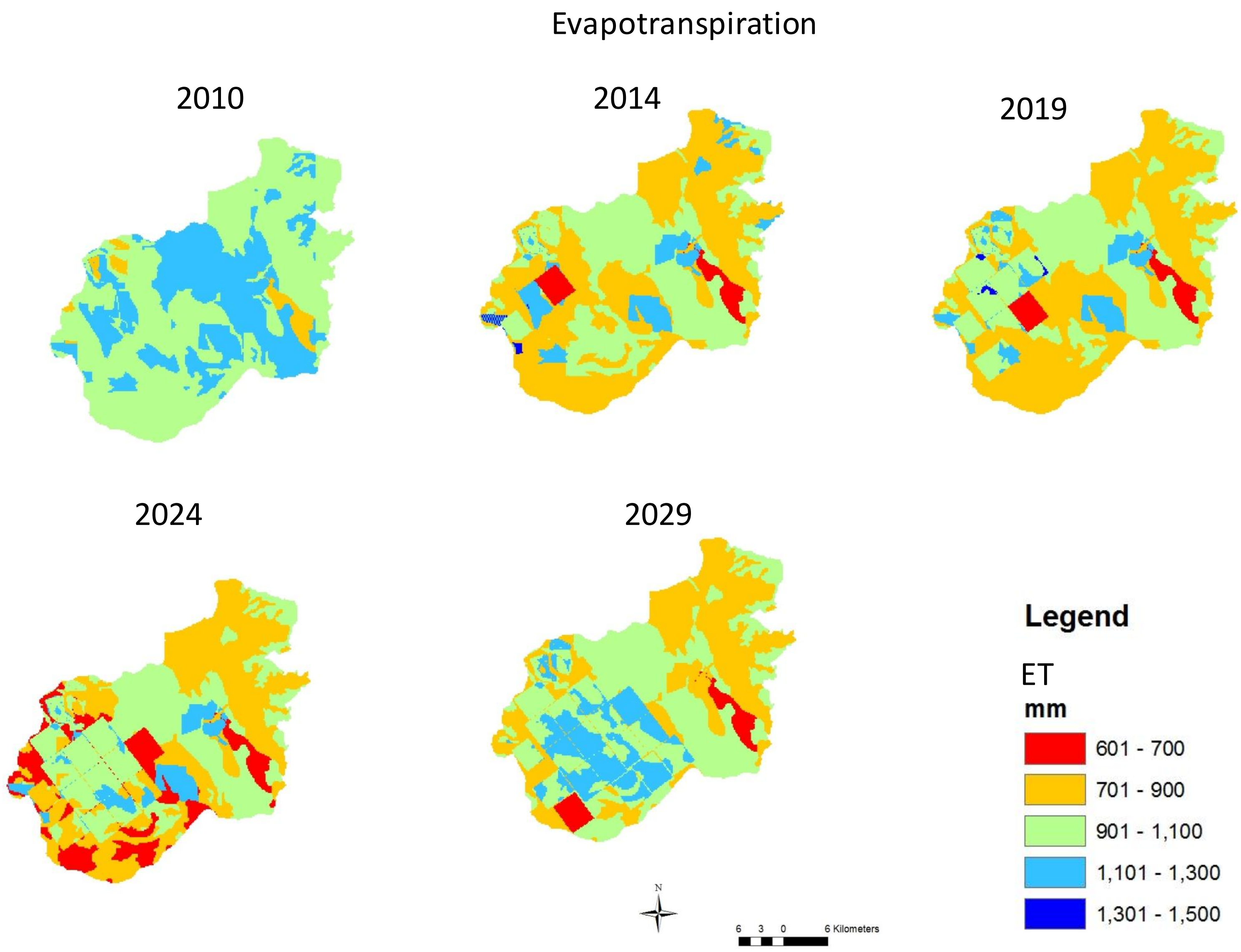

Figure 27 Predicted annual evapotranspiration at five-year intervals of the plantation establishment scenario in the Stray Creek sub-catchment

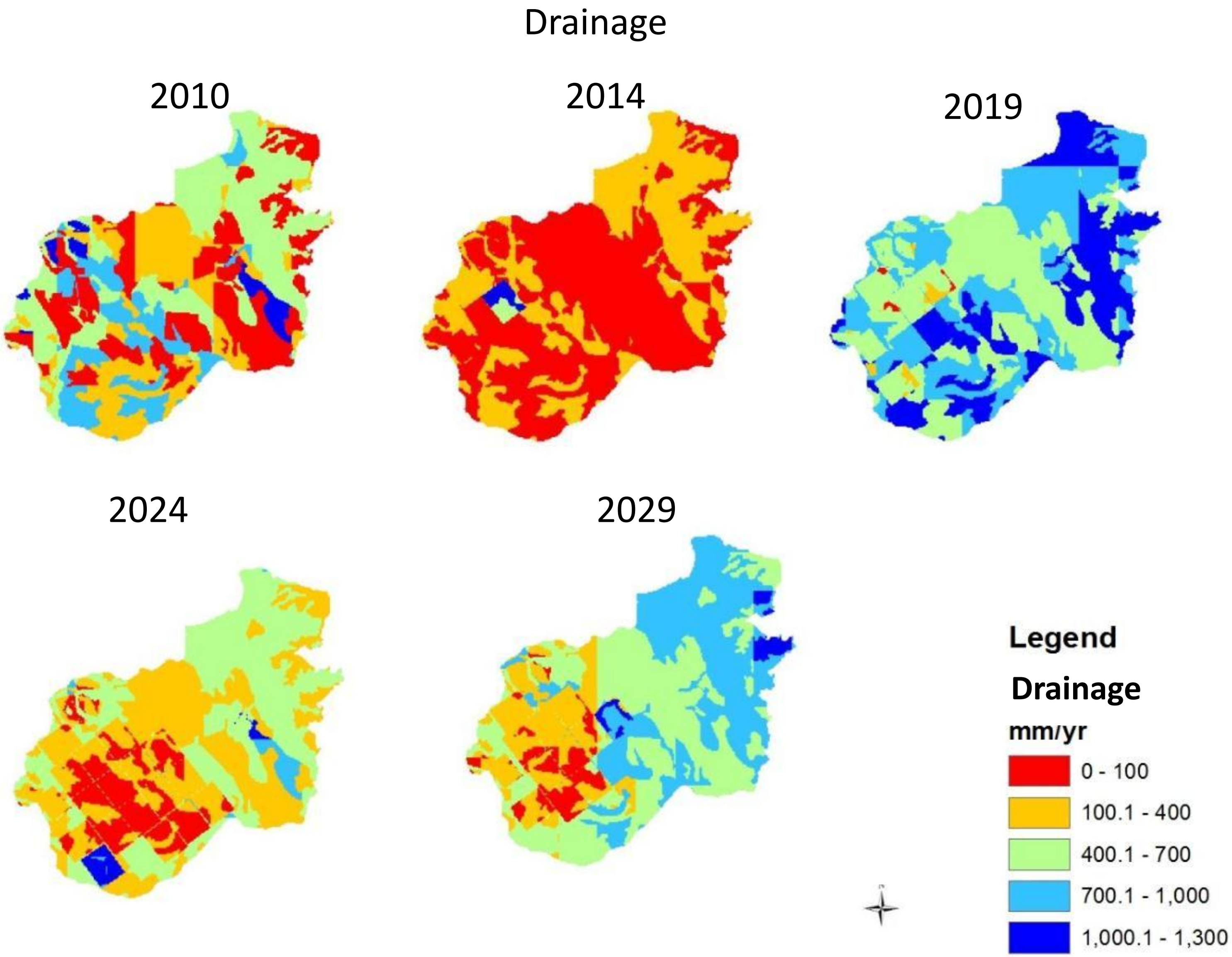

Figure 28 Predicted annual drainage at five-year intervals of the planned plantation establishment scenario in the Stray Creek sub-catchment.

Table 12 Cumulative water balance for the Stray Creek sub-catchment incorporating an increasing area of African mahogany plantations over the growth cycle until 2029. Components are given in mm and as a fraction of total rainfall.

Component	*Value (mm)*	*%*
Rainfall	25,755	100.0
Discharge	7,822	30.4
ET	17,933	69.6
Soil Evaporation	3,851	15.0
Interception	1,376	5.3
Transpiration	12,706	49.3

There is considerable inter-annual variability in rainfall during the model scenario time period (Figure 29). Despite this and an increasing area of mahogany plantations over this time period, catchment scale evapotranspiration is relatively uniform. As a result inter-annual patterns in catchment scale drainage are largely a result of inter-annual variability in rainfall (Figure 29).

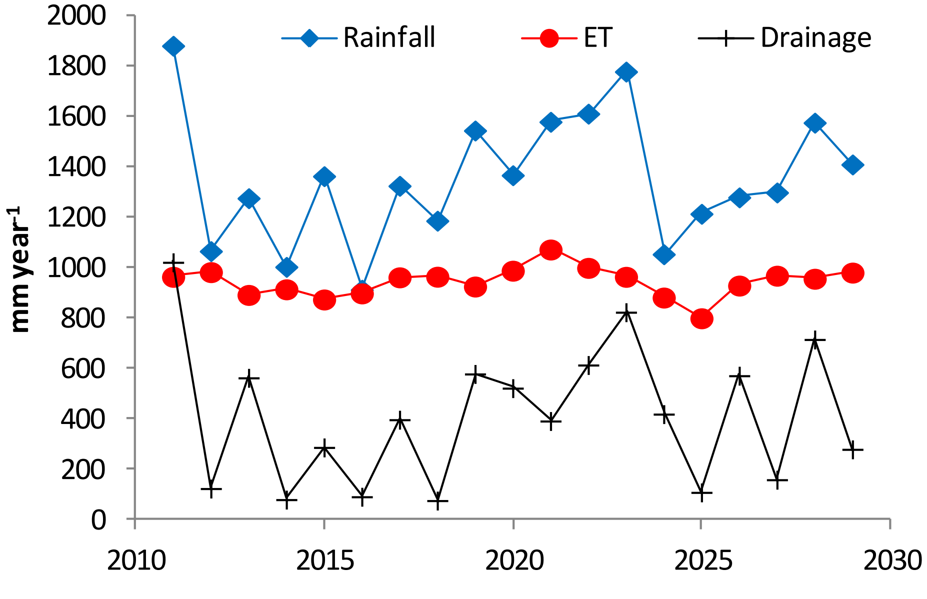

Figure 29 Mean rainfall, ET and drainage for the Stray Creek sub catchment for the period 2011 to 2029. The area of plantations increase in the catchment at a simulated rate of 2000 ha^{-1}

The relatively uniform sequence of ET for the Stray Creek sub catchment, despite an increasing area of mahogany plantations within the catchment suggests that mahogany plantations are potentially having a modest impact on catchment water balance. To explore this outcome further we examined the cumulative impact of plantation establishment on the water balance of the catchment for the period 2010 to 2029. To do this we ran two scenarios. In the first, we took the land use mosaic present in 2010 and calculated total ET and drainage for the catchment on an annual basis.

We compared this to the projected land use change scenario of progressively increasing plantation area of mahogany plantations (Figure 26). We used a cumulative analysis to normalise the effects of inter-annual variability in rainfall and isolate the direct impacts of plantation expansion. Thus in this scenario both land use patterns see the same climatic record at within the same year. The results of this analysis are shown in Figure 30 and demonstrate that the impacts of establishing an extra 40,000 ha of mahogany plantations on the water balance of the Stray Creek catchment are small. This was a somewhat surprising result. However, this outcome occurs for two reasons:

- most of the plantation expansion would replace existing savanna forests as there is only a small area of existing cleared land within the catchment on Blain soils

- and secondly the total area of the catchment occupied by plantation by the end of the expansion phase is still relatively small, approximately 30% of the total catchment area.

This outcome does not mean however that there may not be localised impacts on small drainage lines or tributaries to Stray Creek itself, but suggests that overall there appear o be minimal risk to water resources in the region posed by expansion of the mahogany plantation industry.

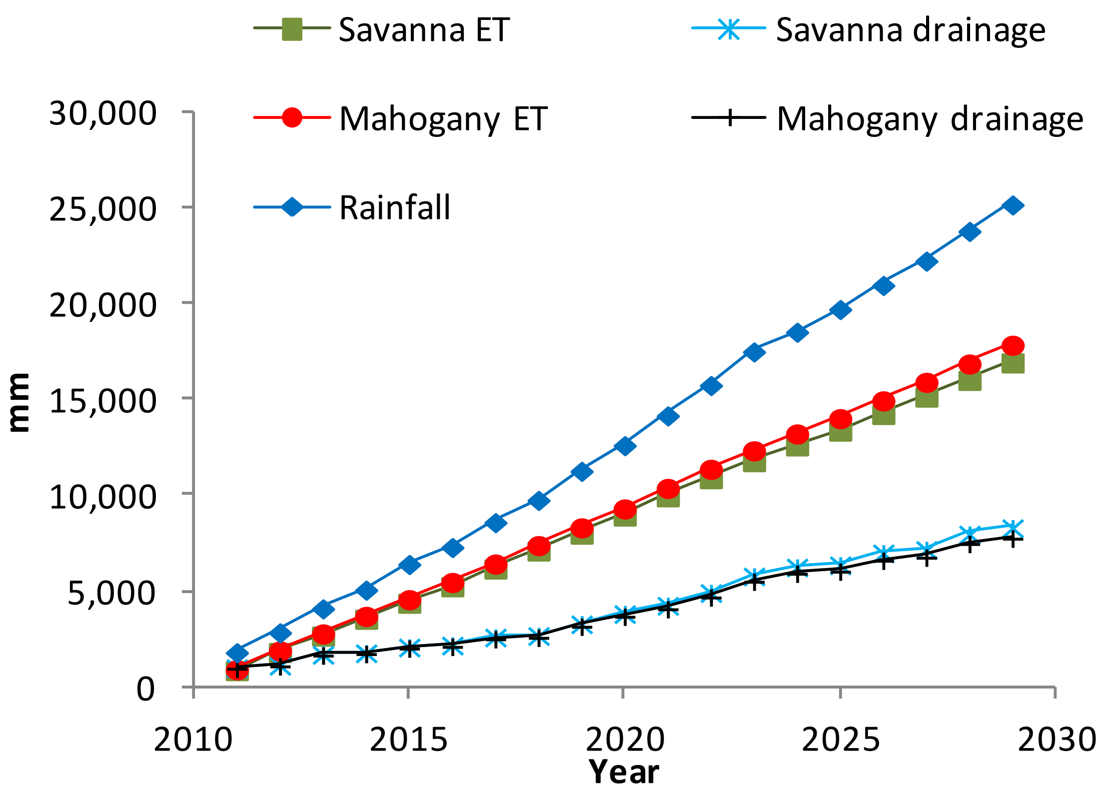

Figure 30 Cumulative rainfall ET and drainage for the Stray Creek sub-catchment over the period 2010-2029, for two landuse scenarios; with plantation progressive establishment and without plantation establishment.

4.14 Discussion

Assessing the impacts of plantations on water resources has received considerable national and international attention (Gilfedder *et al.*, 2010; Jackson *et al.*, 2005; Marcar *et al.*, 2010; Polglase and Benyon, 2009; Zhang *et al.*, 2001; Zhang *et al.*, 2007). There is little doubt that a change in landuse from pasture or grasslands to forests results in an increase in evapotranspiration from the catchment and results in reduced stream flow out of the catchment. The extent of this impact is a function of both the mean annual rainfall and the proportion of the catchment converted to plantations (Zhang *et al.*, 2001). However, the debate surrounding these impacts needs to focuses on whether the impacts are significant within in context of the catchments water resources. From this perspective the intent of the National Water Initiative appears to have greater emphasis on predicting whether the plantation expansion is likely to have a significant impact within the context of the water resources under consideration rather than to focus inherently on changes in evapotranspiration or runoff. For example, a small increase in evapotranspiration resulting from landuse change from pasture to plantations may be considered significant if this change results in water resources becoming over allocated or important downstream environmental assets becoming threatened. Conversely a large change in ET may not necessarily be significant if water resources are largely unallocated and there are no significant risks to environmental assets within the catchment.

The "Zhang curves" provide a robust preliminary framework for assessing the impacts of converting catchments from grasslands to forests. Applying the analysis outlined by (Zhang *et al.*, 2001) to the Daly River region predicts that ET from a completely forested catchment with a rainfall of approximately 1100 mm is approximately 900 mm. This is close to the measured (Wilson *et al.*, 2006), (Cresswell *et al.*, 2011) and predicted (this report) values of ET within the region. Furthermore, if the catchment was completely pasture the Zhang analysis predicts that planting replacing 40 % of the catchment with plantations would result in an increase of 96 mm in catchment wide ET (~0.96 ML ha^{-1} yr^{-1}). This preliminary assessment of the impacts of land use change on the water resources of the regions provides some useful boundary conditions within which we can explore the impact of an expanding mahogany plantation estate. However, two qualifiers should be noted for the study here:

- The Daly River catchment is dominated by riparian forests, savanna open-forests and woodlands. Cleared areas represent only a small proportion of the total catchment area (e.g. <10% for the Stray Creek sub-catchment)
- As a result, for the most part, the modelling scenarios presented in this report replace existing savannas with plantations, rather pastures and grassland with plantations.

Thus the potential impacts of conversion would be considerably less than what might otherwise be predicted from a simplistic Zhang curves analysis.

4.14.1 Plot scale modelling of African mahogany growth and water balance

The principal aim of this study was to establish a preliminary parameterisation of the growth model 3-PG2 for African mahogany in the Daly River catchment area. Model outputs, principally growth (DBH, height volume and MAI) were then compared with growth attributes measured at a number of sites within the region. In general, the model predicted growth of older African mahogany plantations reasonably well and this outcome provides some confidence that the model is capable of providing reasonable estimates of the water balance for these plantations. The model tends to over predict the growth of younger plantations (<5 yo). This would result in increasing uncertainty in estimates of the various water balance components for these younger plantations and most likely result in and over estimate of ET and underestimate drainage from these plantations.

Although there are only small differences in the annual totals of ET between the savanna and mahogany forests, there are important differences in the partitioning of ET and in the seasonal dynamics of ET. Canopy transpiration in the mahogany plantations was considerably higher than measured and predicted values seen in savannas. Annual ET in the savanna forests is dominated by understory fluxes during the wet season associated with the strong seasonal growth of the predominately Sorghum understory (Hutley *et al.* 2000) In contrast canopy transpiration in the savannas varies little through the year (Eamus *et al.*, 2000; O'Grady *et al.*, 1999). The model predicts that leaf area index and as a result canopy transpiration in the mahogany plantations have much larger seasonal variation. These fluxes have the potential to significantly reduce plant available water under these plantations during the dry season, and the impacts of this response on the water balance cannot be fully explored using this model framework. However, it suggests that more rainfall is required in the following wet season to replenish soil water reserves. It also suggests that mahogany plantations may become vulnerable to severe drought stress if there is a sequence of low rainfall wet seasons, outside of the range of rainfall amounts captured in this modelling scenario. An improved understanding of the seasonal dynamics in ET from these plantations will be important in future detailed water balance assessments and for assessing factors that would constrain the productivity the expanding plantation estate.

Results presented here are a preliminary assessment of the productivity and water balance of these plantations, as there is an almost complete lack of quantitative data on seasonal growth dynamics and seasonal patterns in key water balance components (i.e. soil evaporation, canopy transpiration, changes in soil water storage and ET) to allow a detailed assessment of model performance. There is currently an increased effort to address some of these shortcomings via on-going ARC funded research addressing these issues. Thus model parameterisation can be improved incrementally over time as new data sources for validation become available.

The region has reasonably good information on soil textural and physical characteristics. Despite this, there is little resolution in these properties with soil and rooting depth. Soil structure and depth play a critical role in determining the volume of plant available water that can be held within the soil profile. In the current model simulations we used soil textural and physical properties for predominantly surface soils (Tickell, 2012). However the soils of the region are typically deep and clay content increases with depth (Hutley *et al.* 2012). Thus, potentially we underestimate the volume of plant available water within the soil properties and this would tend to result in an overestimate of drainage.

There is considerable uncertainty surrounding a number of key physiological parameters within the model. We could find no allometric information that would allow us to partition gross primary production to the various biomass pools. This information is important because changes in the partitioning of biomass within forests can have direct and indirect impacts on the water balance. An increase in partitioning to leaf area not only increases the evaporating surface are of the forest but can increase total rainfall interception and reduce soil evaporation, through fall and soil infiltration. While there have been a number of assessments of stem volume for this species (Reilly, 2006), (Dickinson and Kelly, 2006) future harvesting could significantly improve our understanding of biomass partitioning if harvests focussed on improving our understanding of the allometry associated with leaf, branch, stem and below ground biomass. Similarly there is almost no quantitative information on stomatal responses to vapour pressure deficit for this species. An understanding of maximum stomatal conductance and its response to atmospheric conditions is important for parameterising the transpiration fluxes within the model. Studies of whole plant water use that are currently being conducted in this species will help to improve our understanding of these dynamics, if the data are collected within an appropriate framework. There are also a number of techniques available for extracting this information from sapflow data (O'Grady *et al.*, 2008; Whitley *et al.*, 2012).

4.14.2 Catchment-scale assessment of plantation expansion on the water resources of the Stray Creek sub-catchment

While we acknowledge that there is considerable uncertainty in the parameterisation derived from the plot scale modelling, we have applied these parameter sets using the spatial version of the 3-PG2 growth model to assess the potential impacts of a progressive expansion of the plantation estate within the broader Daly River catchment using the Stray Creek sub-catchment as a case study. In the model scenarios used here we found that the impact of this planned expansion on the water resources of the sub catchment were small. The major reasons underlying this were that the total area of plantation estate at the end of the model scenario was still only approximately 30% of the catchment and that we were predominantly replacing savanna forests with plantation forests. Annual ET in these two systems was reasonable similar (Table 9). We ran model scenarios for 20 years into the future and at the end of this period detected only small differences in cumulative ET and drainage, it might be potentially interesting to examine this response over longer time periods (up to 50 years) to start to explore the impacts of 2nd rotation forestry on the water balance. We also recognise the need for a more detailed understanding of the potential impacts of the higher dry season tree transpiration rates on soil water availability and drainage under these plantations. These dynamics have not been well explored in this study. Polglase and Benyon (2009) specifically identify the interaction of plantations with groundwater as being a critical knowledge gap, and this may be particularly important in the Daly River region because groundwater resources supply a significant component of the dry season base flows. To some extent the impacts of this on groundwater systems can be managed *a priori*. African mahogany was planted in the Kununurra region to specifically address the issue of rising groundwater levels and resulted in localised drops in the water table of up to 7 m (Carter *et al.*, 2010). In the Daly River region however the aim would be to minimise direct access to groundwater resources and this could potentially be achieved by ensuring that plantations are not positioned at shallow water table sites, e.g. water table depths < 10 m (O'Grady *et al.*, 2010).

It is important to note that we deliberately concentrated the expansion of the plantation estate within one catchment for two reasons;

- The Stray Creek sub-catchment has a high proportion of the favoured Blain soil types
- And a more concentrated estate reduces the cost associated with managing the estate for the companies.

However, this scenario may not be a realistic representation of future plantation expansion. Only a few of the sites for which we collected growth data during July 2011 visits were actually within the Stray Creek sub-catchment boundaries although plots were all located on Blains soil types and were representative of these extensive soil types supporting a plantation. An outcome of this observation is that future expansion of the mahogany plantations within the Daly River region may be more spatially distributed and this would further reduce the overall impact of these plantations on the basin (i.e. 50, 000 ha planted over a much larger region and over more sub-catchments). We also acknowledge that we do not explicitly address many of the other natural and cultural values that may be impacted by an expansion of a plantation industry within the catchment, and that a full assessment of these impacts goes beyond an assessment of the water resources alone (Jackson *et al.*, 2005).

The 3-PG2S is predominantly a growth model and while the water balance components of the model have been improved in recent years (Almeida *et al.*, 2010). However, the model cannot differentiate many of the below processes that may impact of eventual recharge to local and regional aquifers or discharge and runoff into rivers. Frameworks currently exist that would improve this situation. For example, (Gilfedder *et al.*, 2010) have recently developed an integrated modelling framework that incorporates 3-PG with the pasture model PERFECT and the groundwater model 2CSalt. This framework provides a much more complex framework for assessing the impacts of plantation on water resources; however, this increased complexity is associated within increased parameterisation and in the current scenario would only add to uncertainty around model predictions.

4.15 Conclusions

In this study we conducted a preliminary parameterisation of the 3-PG2 growth model and have used this to assess the likely impacts of expansion of mahogany plantations on water resources in the Daly River region of the Northern Territory.

The model does a reasonable job predicting the growth and water use of African mahogany although tends to over predict growth in younger plantations. A thorough model validation and testing was limited due to limited availability of comprehensive validation data. However, this outcome provides some confidence that the model would reasonably predict ET from these plantations although we acknowledge that there is not enough growth or water balance data available for this species to perform a detailed evaluation of model performance.

The model predicts reasonably well evapotranspiration from pasture and savanna compared with previous ecohydrological modelling efforts by TRaCK in this catchment by Creswell *et al.* (2011). These outcomes were calibrated against 3 years of eddy covariance ET data and some confidence can be placed in this result. Modelled estimates of 3PG-2 were within the range of estimates predicted and observed in complimentary studies. Based on these two sets of observations we believe that estimates of ET and drainage derived from the model for mahogany plantations are reasonable. Annual ET from mahogany plantations is similar to that from the savannas system, although the partitioning and seasonal dynamics of ET is markedly different between the two forest types. The impacts of these changes in seasonality of transpiration on drainage and subsequent stream flow need further investigation

Modelling suggests that the impacts of the projected expansion of the plantation estate on the water resources of the Daly River catchment will be low. Industry projects that up to 50, 000 ha of plantations is desirable for a sustainable industry, and this development is small compared to the total catchment area. Furthermore, much of this expansion will result in replacement of savannas with similar annual ET to that predicted in this preliminary modelling scenario, and this would act to further reduce the impacts of plantation expansion on water resources.

In this assessment, only the potential impacts of plantation expansion on water resources explicitly address - there is a degree of uncertainty within the current model parameterisation due to the lack of available parameter sets and data for model validation. In addition, for this assessment, potential impacts of plantation expansion on other natural and cultural values within the catchment are not addressed.

5 Managing the impacts of non-irrigated plantation forestry on the NT's water resources

5.1 Introduction

Given the potential size of the plantation forestry industry, some examination of impacts informing a policy framework is required. In the mid-2000s the Northern Territory experienced an unprecedented surge in demand for land in the Douglas Daly region from Managed Investment Scheme (MIS) investors seeking to establish African mahogany plantations. This resulted in the establishment of a forestry estate which now covers an area of 10,000 to 12,000 ha and is expected to expand to 30,000-40, 000 ha as described above. These plantations were established on previously cleared freehold land and hence did not require formal assessment under the *Planning Act* or *Environmental Assessment Act*. As these operations are not irrigated, they also did not require licencing under the Northern Territory's *Water Act*. The Daly basin encompasses highly valued and significant economic and environmental assets including rivers and streams whose dry season baseflows are sustained by groundwater.

In 2004, the Northern Territory Government signed an Intergovernmental Agreement on the National Water Initiative (NWI). The NWI identified large-scale plantation forestry as an activity which may be undertaken without a water access entitlement (WAE) and has the potential to intercept significant volumes of surface and/or groundwater. Under the agreement, the NT Government is required to assess the significance of these plantation forestry activities and apply appropriate planning, management and/or regulatory measures. While significant studies have been undertaken into the water use characteristics of Top End native savannas, no similar research has been undertaken on African mahogany, either within Australia or overseas.

This section addresses **Aim 4** by proposing a policy that imbeds research results from Chapters 2 and 4 into a water planning framework, and in so doing, addresses elements of the Territory's NWI obligations (Section 5.6). Background to this policy formulation is provided through a brief outline of the forestry industry's history in the NT, as well as the legislation, policy and industry standards relating to the industry. Approaches to water allocation planning for plantation forestry in Western and Southern Australia are covered (Section 5.4). A brief outline of a study conducted in the Ord River area is included as it provides insights into African mahogany water use under a vastly different land use scenario.

It is important to note that this recently work has been undertaken within significant constraints and that further work is required to reduce uncertainties associated with its outcomes and to inform an ongoing policy review process. Specifically, these constraints include a the lack of mature stands of African mahogany in the Top End; the short (8 month) time period over which data could be collected for this study; and the seasonal context in which data were collected, including record 2010/11 wet season rainfall, and high average annual rainfalls experienced over the last 20 years in the Top End.

5.2 Background

5.2.1 Forestry developments in the NT

The early forestry history of the Northern Territory has been poorly documented; although it is known that native timbers were harvested in the 1860s. Forestry was initially licenced by the Commonwealth Lands Branch, with registration required to harvest timber or remove timber from

Crown lands, including those under pastoral leases. In 1959, the *Forestry Ordinance (1959)* was implemented and a separate Forestry and Timber Bureau was established as a branch of the NT Administration. This provided a dedicated system for regulating the harvesting of forest products (Armstrong *et al.* 2004).

Beginning in the 1960s, the Commonwealth Government encouraged forestry as an industry to support economic development of aboriginal communities. The newly formed Forestry and Timber Bureau worked with the CSIRO conducting forestry trials on the Coburg and Gove peninsulas. Armstrong *et al.* (2004) report that early trials focused on *Callitris intratropica* (Cypress pine), however this species was found to have poor growth rates and high susceptibility to fire disturbance (a characteristic thought to be responsible for current reduction of natural populations) and the trials were abandoned. An industrial scale plantation of *Pinus carribea* var. *hondurensis* (Caribbean pine) was established, but was not managed through to harvest.

From 1969 to 1979 the CSIRO established four test plantations at sites receiving greater than 1,600 mm annual rainfall including Humpty Doo, Howard Springs, Gunn Point and Melville Island. The sites were used to test over 190 high value exotic tree species. The growing plots were not thinned, limiting the application of the results to managed forestry situations. The management of the sites after 1979 was erratic, but assessment of the plantings in 1983 and 2002 provided some information on survival and performance of key species (Bristow 2004). Social and political factors including the recovery from Cyclone Tracey and NT self-government lead to a massive reduction in funding and staffing for forestry, severely impacting research throughout the 1980s and 90s (personal communication Don Reilly, DoR, 12/12/11).

The Top End Regional Tropical Hardwood Forestry Project (TERTHFP), a collaboration between Greening Australia Northern Territory (GANT), the then Northern Territory Department of Primary Industries and Fishing (now DoR) and the Northern Territory Forestry and Timber Products Network (NTFTPN), conducted forestry trials from 1998 until 2003 with funding from the Natural Heritage Trust. The trials incorporated 12 species tested in 24 x one to two ha sites across the four sub-regions of the Top End. Most species included in the trials performed poorly, growing slowly or sustaining damage from wind, fire or termites (Reilly *et al.* 2004).

The Natural Heritage Trust then funded the Top End Farm Forestry Development project which addressed forestry practices on the four best candidates from the TERTHFP trials –African mahogany, *Tectona grandis* (teak), *Eucalyptus pellita* (red mahogany) and *Eucalyptus camaldulensis* (river red gum). These trials used five hectare plots to examine the impacts of silvicultural management regimes on quality timber production.

5.2.1.1 Tiwi Islands

Acacia mangium plantations have been established on Melville Island and were significantly expanded in 2001. Hundreds of thousands of *A. mangium* seedlings were provided by GANT to SylvaTech Pty Ltd. to develop the plantation targeting woodchip and pulp export markets and employment of local Indigenous works from Melville Island. Ownership of the plantation was transferred to Great Southern Limited, and after investigation of environmental breaches in 2007 and a senate enquiry into the Tiwi Islands mining and forestry industries, a formal application to wind up the business was submitted in late 2009. The plantation is currently managed by the Tiwi Land Council and Plantation Management Partners who manage a total of 35,000 ha of forests across Queensland and the NT. The initial harvest of *Acacia mangium* is expected in 2012 (personal communication Kate Hadden, Tiwi Land Council, 8/12/11).

5.2.1.2 Current and projected development

The development of African mahogany plantations in the Douglas Daly in the mid-2000s was driven by an influx of Managed Investment Scheme (MIS) investments, including Willmott Forests, Great Southern Limited, Timbercorp and Northern Tropical Timber. The catchment was viewed as a desirable with available land resources and outside of cyclone prone areas, but as close to the Darwin transport corridor as possible. Up to 20% of the 100,000 ha of freehold land in the region was purchased by the MIS industry (Angus Grigg, 19/5/09, *The Financial Review*), although not all of this land area has been put under plantation to date. NT Government budget papers reflect the impact of the GFC on expectations of NT forest industry productivity. The 2009 budget estimated that a further 40,000 ha of forestry plantations would be established in the Douglas Daly; while the 2010 paper indicated that the industry's future was uncertain. It is expected that anticipated changes to the *Pastoral Lands Act*, allowing the conduct of non-pastoral uses on pastoral leases, will open the way for further development of plantation forestry (personal communication Ian Lancaster, NRETAS, 7/3/12). The current estate is estimated to be 13, 000 ha, with a 2000 ha planting per annum a target. Cattle agistment prior to plantation establishment is being investigated as a land use option on future acquisitions. Planned management includes two rounds of thinning at approximately seven and 14 years although these are subject to ongoing assessment of tree performance. Further industry development will also see application for seek ISO and Forest Stewardship Council (FSC) or similar certification in the future.

5.3 Legislation, policy and industry standards

A variety of Commonwealth and Northern Territory Government legislation, policies and strategies apply to the establishment and operation of forestry plantations in the NT. Those of most relevance to this discussion paper are outlined below. National industry standards for forest management are also discussed.

5.3.1 Commonwealth Government

5.3.1.1 National Water Initiative (NWI)

In 2004 the Northern Territory Government signed an Intergovernmental Agreement on a National Water Initiative (NWI). The Agreement identified large-scale plantation forestry as an activity which may be undertaken without a water access entitlement and has the potential to intercept significant volumes of surface and/or groundwater. It stipulates that all parties should:

'…assess the significance of such activities on catchments and aquifers, based on an understanding of the total water cycle, the economic and environmental costs and benefits of the activities of concern, and to apply appropriate planning, management and/or regulatory measures where necessary to protect the integrity of the water access entitlements system and the achievement of environmental objectives.' (Clause 57)

Sections 55 to 57 of the agreement stipulate requirements for dealing with surface and groundwater interception depending on the allocation status of water systems. These actions are summarised in Table 13 and are shown in full in Appendix A.

The Forest and Forest Products Committee (FFPC 2008:1) surmises that large-scale plantation forestry is the only crop or land-use specified in the interception clauses of the NWI because 'plantations have a higher water use than other dry land crops'. It is noted that other crops such as lucerne and intensive pasture also have relatively high water use and may be a significant contributor within some regions or catchments.

Table 13 A summary of NWI requirements relating to interception for water systems of varying allocation status.

Allocation status	NWI requirement
Fully allocated Over allocated Approaching full allocation	• Significant interception activities should be recorded (eg. through licencing) • Proposals for new activities above an agreed threshold require a WAE • Compliance monitoring should be implemented
Not fully allocated Not approaching full allocation	• Water interception estimates for each significant activity should be identified. • Appropriate thresholds of water interception should be calculated, under which significant interception activities should not require a WAE. • Once the threshold (or full allocation) is approached, new proposals should require a WAE • Monitoring should be implemented.

5.3.2 Key terms and concepts

The FFPC scoping paper pointed out that there was no guidance on how the actions proposed by the NWI may be implemented in a nationally consistent manner. The paper highlighted a lack of clarity regarding key terms and concepts referred to in the agreement such as 'large-scale plantation forestry', 'significance' of impact on water resources (particularly in areas with little data such as the NT), and the translation of spatially and temporally limited water use data to catchments and full plantation life-cycles.

The NWI also adopted a different definition of 'interception' than the hydrological definition, which is the amount of rainfall intercepted and subsequently evaporated back to the atmosphere. In translating the NWI's use of the term and how it may be incorporated in the legislative framework, the NT Government has interpreted interception as:

'*…the measurable diminution of flow or likely flow of water in or into a waterway and/or aquifer at any time within the duration of a water plan or proposed water plans*' (personal communication Ian Smith, NRETAS, 7/3/12).

These are two distinct concept and in terms of a policy framework, the NWI defined term and as interpreted by the NT Government will be used here.

5.3.3 Forestry export regulations and codes of practice

Each State and Territory is required under the *Export Controls (Unprocessed Wood) Regulations 1996* to operate plantation forestry under a code of practice. The codes cover the establishment, management and harvesting of plantations. The CSIRO is currently undertaking a scientific assessment of these codes, which was due to be complete by July 2011. The codes of practice 'incorporate scientific knowledge, regulatory and legislative requirements, and take into account the range of plantation types, conditions and situations that apply due to natural variations in regions' (http://www.daff.gov.au/about/media-centre/dept-releases/2011/australian-government-bolster-plantation-forest-codes-practice, accessed 16 January 2012).

The NT Code of Practice (Appendix B) is due to be reviewed and refers broadly to the NT Government's legislative controls on clearing under the *Planning Act* and *Pastoral Lands Act*, development of plans of management in accordance with the code, and stipulates broad requirements relating to biodiversity, soil conservation, habitat protection, control of chemicals and hazardous substances, heritage and cultural protection, weed, pest and disease prevention. Under paragraph seven, the Code requires that 'water quality, stream stability and habitat values will be maintained in the forest environment including the development area and adjoining lands', however, there is currently no direct regulatory or compliance regime in place in the Northern Territory to either measure, monitor or enforce this requirement, unless the area to be developed has been subject to assessment under a clearing proposal. At this point in time, forestry development in the Douglas-Daly catchment has been undertaken on land already cleared for other purposes.

5.3.4 Environment Protection and Biodiversity Conservation Act

The Commonwealth *Environment Protection and Biodiversity Conservation Act 1999* (the EPBC Act) regulates actions expected to have significant impacts on matters of national environmental significance including flora, fauna, ecological communities and heritage places. Any project expected to have such impacts must apply for approval under this Act, in addition to any state or local government approval required. Projects are assessed by the Australian Government's Department of Sustainability, Environment, Water, Population and Communities, based on information provided by the proponent and comments from the public. The Federal environment minister then decides whether the project should proceed, and if so, if any specific conditions that should be applied.

The *A. mangium* plantations on the Tiwi Islands was approved under the EPBC Act in 2001 and holds AS/NZS ISO 14001:2004 accreditation. The EPBC referral was based on potential impacts on the habitat of four listed threatened species (the red goshawk, masked owl, partridge pigeon and *Carpentarian dunnart*) and two migratory species (the rainbow bee-eater and oriental cuckoo). The EPBC approval was issued with 11 special conditions covering clearing rate limitations, buffer zones, and requirements for species management and impact monitoring plans, appointment of an Environmental Officer and periodic independent audits.

5.3.5 Northern Territory Government

5.3.5.1 Legislative controls

Control over the environmental management of land in the NT is provided by various pieces of legislation (Table 14). The development of existing forestry plantations in the Douglas Daly did not invoke the *Planning Act* or the *Environmental Assessment Act* because these operations are non-irrigated and undertaken on previously cleared freehold land. The clearing of native vegetation is currently controlled by the *Planning Act*. Where an area greater than 200 ha is to be cleared, the application is referred to NRETAS as a Notice of Intent under the *Environmental Assessment Act*. The Commonwealth *Environment Protection and Biodiversity Conservation Act* is only triggered where there are considered to be potential impacts on matters of national environmental significance. A bilateral agreement is in place for proposals that require formal assessment under both Northern Territory and Australian Government legislation. Under the bilateral agreement, the assessment undertaken by the Northern Territory is taken to fulfill the requirements of the EPBC Act.

Table 14 NT Government legislation relating to environmental management of forestry plantations.

NT environmental legislation	**Purpose relevant to plantation forestry**
Northern Territory Aboriginal Sacred Sites Act	Established the Aboriginal Areas Protection Authority which is responsible for overseeing the protection of sacred sites across the whole of the NT.
Bushfires Act	Includes the legal framework and responsibilities for bushfire management. The fundamental principle established by the Act is that the responsibility for bushfire management rests with the landholder.
Environmental Assessment Act	Applications for clearing of native vegetation in areas greater than 200 ha are referred to NRETAS as a Notice of Intent under this legislation. If environmentally significant a Public Environmental Report or Environmental Impact Statement is required, depending on the significance and extent of potential impacts.
Territory Parks and Wildlife Commission Act	Provides for the establishment of parks and reserves and the study, protection, conservation and sustainable utilisation of wildlife. Under this act development proposals are assessed in terms of flora and fauna harvest and utilisation, the import and use of non-native wildlife, and the impact of development on the environment and threatened species.
Northern Territory Heritage Conservation Act 1991	The principle object of this Act is to provide a system for the identification, assessment, recording, conservation and protection of heritage places and objects.
Native Vegetation Management Bill 2011	When enacted will regulate clearing on any land outside of town planning boundaries.
Pastoral Land Act	Controls the clearing of native vegetation on pastoral land. Changes to this act will enable the conduct of non-pastoral uses on pastoral leases, which may trigger further expansion of the forestry estate.
Planning Act	This Act provides for the planning and control of the use and development of land across the Territory, establishes the NT Planning Scheme and provides for a development approval process. This Act controls the clearing of native vegetation. Clearing outside of town boundaries will be controlled by the *Native Vegetation Management Act* when enacted.

Plant Health Act 2008	The objects of this Act are to ensure appropriate actions can be taken for the control of pests; and to facilitate the production and trading of plants and plant products that are free from pests.
Soil Conservation and Land Utilisation Act	An Act to make provision for the prevention of soil erosion and for the conservation and reclamation of soil.
Waste Management and Pollution Control Act	Regulatory Act to provide for effective waste management and pollution control.
Water Act	The *Water Act* provides for investigation, allocation, use, control, protection, management and administration of water resources, including waste discharge licenses.
Weeds Management Act 2001	If a proponent wishes to grow a plant declared under the Northern Territory Weeds Management Act as a crop, then a 'Permit to Use a Declared Weed' is required.

5.3.5.2 Policy development responsibilities

NRETAS has responsibility for development of the Territory's water resource policy and planning framework, while DoR has responsibility for supporting the growth of the Territory's forestry industry. The Department of Resources has made some progress towards development of an overall NTG forestry policy and any water management policies associated with plantation forestry will be developed in collaboration with that department.

5.3.5.3 NWI compliance

NRETAS has considered how the *Water Act* may be amended to enable NWI compliance (personal communication Ian Smith NRETAS, 28/2/12). Through this process the department more rigorously defined terms referred to by the NWI including the definition of interception outlined above. Given this broad definition of interception, it was determined that in the development of a water plan the consumptive pool should be considered to include both metered and non-metered interception activities and that all of these activities (including Native Title rights in water) should be identified and described in terms of the diminution of flow of water into each water system. It was also determined that known and/or potential impacts associated with these activities should be described and priorities assigned for reducing these impacts and that limitations in knowledge, information and data and priorities for addressing these, should be also identified and described.

5.3.5.4 Water allocation planning

Water allocation planning in the Northern Territory is legislated through the *Water Act*, which is also used to define water control districts and the beneficial uses for which such planning will be undertaken. The purpose of allocation planning is to define the longer term management outcomes for a particular resource and assign appropriate levels of usage for all consumptive and non-consumptive users (NRETAS 2009). For groundwater not within a water control district, or where there are insufficient data to support decision making, a contingent rule applies whereby at least 80% of annual recharge must be retained for environmental and other public benefit.

5.3.5.5 Oolloo aquifer draft water allocation plan

The *Draft Water Allocation Plan for the Oolloo Aquifer* (which underlies all existing areas of plantation development in the Douglas Daly) was recently released for public comment (NRETAS 2012). The draft plan covers an area of 5,200 km^2 stretching from southwest of Katherine to just north of the confluence of the Daly and Douglas Rivers (Figure 2) and divides the area into a Northern and Southern Water Management Zones. Pastoral properties comprise the majority of land use (80%), but the majority of demand for groundwater comes from agricultural uses on freehold land which comprise 19% of the plan area (NRETAS 2012).

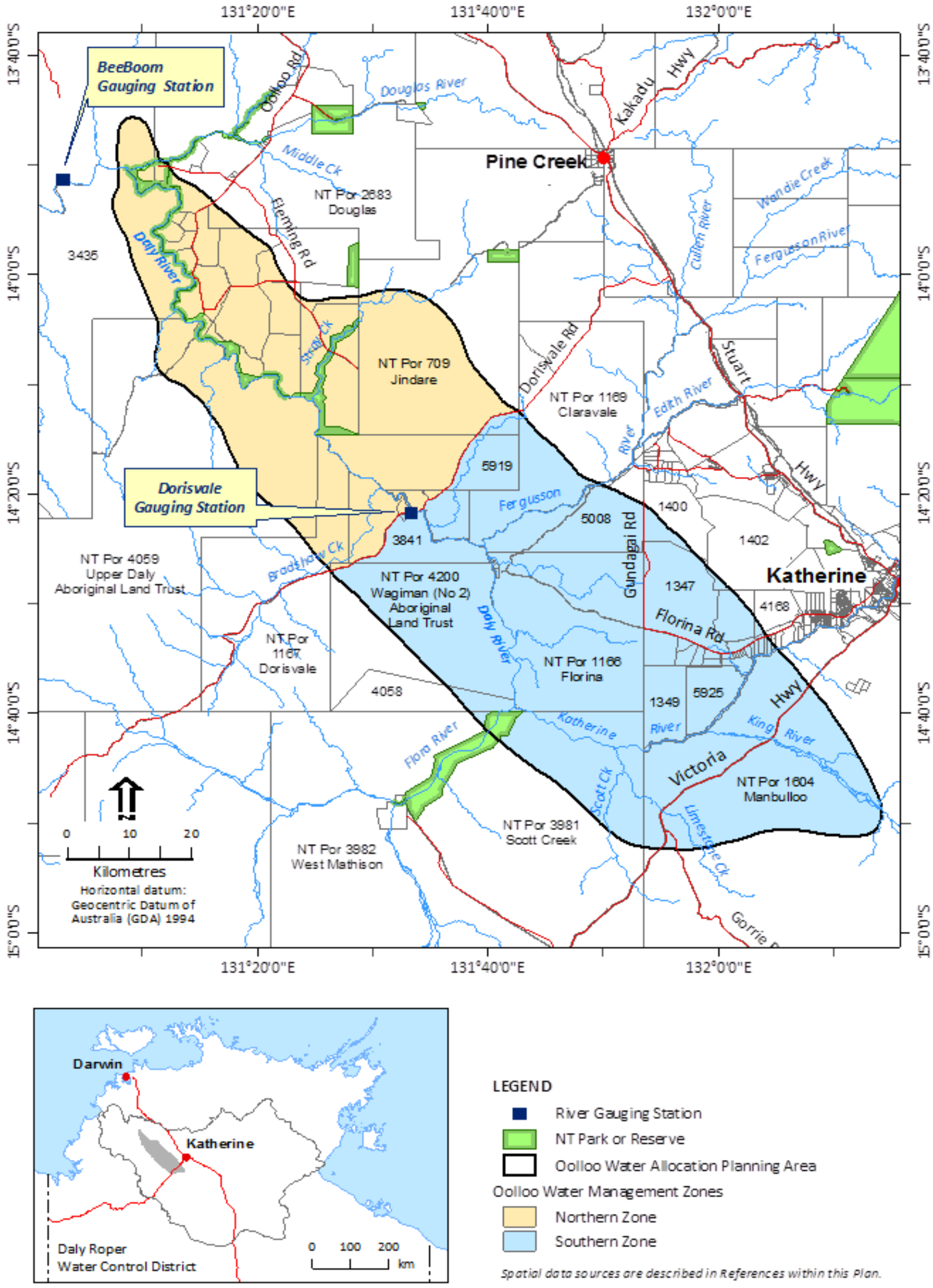

Figure 31 Planning area for the Draft Water Allocation Plan for the Oolloo Aquifer (NRETAS 2012).

Approximately 40,000 ML/yr have been allocated for licenced use in the Northern Management Zone where the most common crops are melon and hay. While African mahogany plantations are referred to, the background document to the plan states ‘at the time of writing the Plan the Department had no policy for licencing their water use from the groundwater’ (NRETAS 2012:16). Licenced water use in the Southern Management Zone has been assigned at approximately 20,000 ML/yr. Extraction limits for both zones have been determined based on hydrological modelling and will be adjusted annually to meet environmental flow requirements determined by Erskine et al (2004). It should be noted that mahogany plantations is a non-irrigated land use.

5.3.6 Industry standards

The Forest Stewardship Council (FSC) is an international, non-profit organisation promoting the responsible forestry management according to 10 principles and criteria. The principles of particular relevance to this policy discussion include Principles 6, 7, 8 and 10 relating to environmental impacts, management planning, monitoring and assessment and plantations.

In Australia, various Interim FSC standards are in use while an accredited national standard is developed. The *SmartWood Interim Standards for Assessing Forest Management in Australia* (Rainforest Alliance 2007) refers to the establishment of riparian buffers and the reduction or elimination of impacts on local hydrology. The 2008 *FSC Australia National Standard DRAFT 00,* however, specifically refers to interception under Criteria 10.6:

‘C10.6 Measures shall be taken to maintain or improve soil structure, fertility, and biological activity. The techniques and rate of harvesting, road and trail construction and maintenance, and the choice of species shall not result in long term soil degradation or adverse impacts on water quality, quantity or substantial deviation from stream course drainage patterns.’ (FSC Australia 2008: 50)

Specific indicators are proposed for medium (M) and large-scale (L) plantations:

> ***‘Indicator 10.6.1MLP***
>
> *A comprehensive water impact assessment has been completed which includes, at a minimum:*
>
> - *estimates or measures of water flows and quality (including maximum, minimum and seasonal variations) within the FMU* (Forestry Management Unit) *and downstream from the FMU prior to plantation establishment;*
> - *comparable measures or predictions of water flow and quality within the FMU and downstream from the FMU subsequent to plantation establishment, and covering at least one rotation period.*
> - *an evaluation of the ecological and social impacts of any changes in water flow and/or quality resulting from the plantation establishment.*
>
> ***Indicator 10.6.2MLP***
>
> *The results of the water impact assessment are publicly available.*
>
> ***Indicator 10.6.3MLP***
>
> *EITHER The enterprise can demonstrate that there are no significant social or ecological impacts outside the FMU resulting from changes in* **water interception***, transpiration, quality due to the plantation's establishment.*

OR The enterprise has documented and is implementing a comprehensive plan to reduce its impacts on water to levels comparable to that for the naturally occurring vegetation expected for the site prior to major anthropogenic disturbance.' (FSC Australia 2008: 50)

No plantations in the Northern Territory are currently accredited under the FSC.

5.4 Australian approaches to water allocation planning for plantation forestry

Research needs and the progress of water allocation policies specific to plantation forestry and water interception across Australia were reviewed by Polglase and Benyon (2009). This review and additional information acquired from Western Australian and South Australian government water agencies have been used to inform this discussion paper. These jurisdictions have undertaken considerable policy development in this area and are summarised below.

5.4.1 Western Australia

Western Australia has approximately 370,000 ha of commercial forestry plantations concentrated in the state's south-west and south coast regions (Department of Water 2009). Existing legislation (the *Rights in Water and Irrigation Act 1914*) does not enable the WA Department of Water (DoW) to licence plantation forestry. The Act 'accounts for the 'taking' of water by a person or persons', rather than the prevention of water entering the resource by a plantation. Legislation also only allows for fixed term licences requiring legal access to the land upon which development is to occur, rather than the perpetual water access entitlements (WAEs) required by the NWI, which are independent of the land and can be traded without legal access.

5.4.1.1 2009 Strategic policy

Considerable background policy work has been undertaken in WA with regard to NWI obligations, leading to the development of *Strategic policy 2.08 – Managing water interception by plantation forestry in Western Australia (under the Water Resource Management Bill)* (Department of Water 2009), and a companion guide comprised of a series of questions and answers on how the interception policy may be implemented (Kalaitzis 2010). While the latter was current to 2010, the formulation of new legislation is currently on hold (personal communication, Phillip Kalaitzis, WA Department of Water, 10/01/12).

The purpose of the strategic policy was to guide the management and regulation of interception by large-scale plantations across the state. The policy foreshadowed that the proposed regulatory regime would: define interception as a separate clause; 'authorise the regulation of water interception by land use activities in specified areas'; define plantation forestry as a 'water affecting activity'; and would separately consider the interception of rainfall and accessing of shallow groundwater by plantations (DoW 2009:2). The approach was that plantations existing prior to enactment of new legislation would not require regulation, but that new large scale plantations in areas of water competition would be treated like other water users and be required to hold a WAE above a certain threshold.

The strategic policy is based on 16 guiding principles that relate to specific issues of concern within the state. These include: recognition of plantation forestry as a non-irrigated agricultural land use that is part of a range of uses that can lead to water interception; consideration of water quality; the use of sound, repeatable and reliable science and clarity regarding the magnitude of likely impacts including seasonal variability and error estimations; consideration of potential ecological, social, cultural and economic impacts; stakeholder engagement; use of the precautionary principle; and monitoring, compliance, public reporting and accounting arrangements.

WA's four broad policy objectives include: continued investment in plantation forestry; reasonable certainty for all water users; sustainable water resource management; and positive environmental outcomes. These are to be achieved by:

- regulating new large scale plantation forestry where they:
  a. are located in water management units subject to water allocation plans or where allocation plans are contemplated;

  b. are located in water management units subject to consumptive pools;

  c. may present a risk to the future integrity of water access entitlements or licences and/or the achievement of environmental objectives;

  d. may cause a detrimental impact on water quality such as in areas of potential acid sulphate soils;

  and:

- allowing unregulated plantation development in areas not subject to water allocation planning or where they provide environmental benefit;
- encouraging existing large scale plantation forestry, located in management units subject to water allocation plans and consumptive pools and/or licensing to apply for a water allocation for their current water interception' (DoW 2009:7).

The strategic policy also refers to 'operational policies' for smaller areas relating to catchments and

WA KEY ATTRIBUTES

- ***Scale of industry***
  Commercial plantations cover approximately 370,000 ha in the Perth, south-west and south coast regions.
- ***Industry attitudes to water allocation planning***
  The industry has indicated that they 'do not have any major issues with being regulated from a perspective of water availability in areas that are actively managed or proposed to be actively managed' (DoW 2009:3).
- ***Rainfall***
  Plantations are grown across a range of average annual rainfall zones from 400 to 1100 mm/year
- ***Plantation species***
  Blue gums, pine and native species for environmental benefit
- ***Environmental benefits of forestry in salt affected areas***
  In areas of WA where saline groundwater occurs, plantation forestry can be used to improve water quality and reduce land and water salinisation through interception of runoff and groundwater recharge and the lowering of water tables.
- ***Plantation approvals***
  Local government has responsibility for final approval of forestry plantations.

aquifers which 'will assess the significance of … activities… based on an understanding of the total water cycle, the economic and environmental costs and benefits of the activities of concern, and apply appropriate planning, management and/or regulatory measures where necessary' (DoW 2009:3).

Polglase and Benyon (2009: 31) state that 'because the predominant issue is groundwater, WA is generally following the Lower Limestone Coast policy of SA to inform policy development'. However, WA may propose to licence plantations with a maximum, rather than average, amount of water used throughout the rotation period. WA has developed and used the LUCICAT model which can ‘predict water use by native forests, pasture and plantations on water use and follows the pathways of water loss through run-off and drainage into base flow and streams’.

5.4.2 South Australia

Polglase and Benyon (2009) found that South Australia has the most advanced policy framework for dealing with water use by plantation forestry, particularly with respect to groundwater impacts. Since that time, the state has introduced the Natural Resource Management (Commercial Forests) Amendment Bill, paving the way for the development of water allocation plans which can prescribe licenced water allocations to plantation forestry.

5.4.2.1 Lower Limestone Coast

The Lower Limestone Coast in the south-east of South Australia encompasses the majority of the state’s plantation forests, including 146,000 ha of hardwood (Tasmanian blue gum – *Eucalyptus globulus*) and softwood (*Pinus radiata*) plantations (Harvey 2009).

Forestry occurs in areas receiving an average of 700 mm/year annual rainfall and which overlie two main aquifers. A shallow unconfined Tertiary limestone aquifer lies between two to sixty metres below the surface, provides about 95% of the region’s water resources and is recharged by diffuse local sources. This shallow aquifer overlies a deeper confined sand aquifer. At some locations, the water table is shallow enough to be accessible to deep-rooted vegetation and groundwater dependent ecosystems are present in the area (Polglase and Benyon 2009).

The groundwater resources of the Lower Limestone Coast are prescribed under the *Natural Resources Management Act (2004)* and approximately 600,000 ML has been licenced for extraction from 46 groundwater management areas (Harvey 2009). Metered flow recording is mandatory for these extractions. In terms of the NWI, the south-east coast area is considered to be at, or approaching, full allocation.

Research conducted as early as the 1960s indicated that plantations were ‘intercepting most or all of the groundwater recharge’ (Polglase and Benyon 2009:19). Later studies indicated that plantations were in some cases a net user of groundwater. Since that time, groundwater recharge rates for the unconfined aquifer have been refined for each management area mainly using the water table fluctuation methodology, as well as some isotope analysis. Land use for each management area is classified as homogenous (Harvey 2009)

5.4.2.2 Forestry as a ‘water affecting’ activity

Prior to the 2011 legislative amendments, South Australia’s only mechanism for managing water resource impacts associated with forestry was by ascribing the activity as a ‘water affecting activity’. In June 2004, new plantation forests in the State’s south-east were assessed as such and the impacts on recharge had to be accounted and offset with a licensed water allocation for the life of the forest and while the land was defined as commercial forest under the *Planning Act*. The licence was only required where the plantation area exceeded a threshold area which accounted for existing forest impacts and an allowance for expansion[1]. In 2007 this provision extended to the extraction of groundwater from shallow groundwater tables (less than six metres median depth to water).

[1] This expansion potential was distributed over a number of management areas and was possible because it had previously been assumed that no recharge occurred under plantation forest. It was later determined that this was only the case under a closed canopy forest and that a recharge credit was due for the period of plantation development.

5.4.2.3 Water allocation planning

In 2012, the South East Natural Resources Management Board will commence community consultation on the development of a water allocation plan for the Lower Limestone Coast; the first to be developed under the new legislative amendments. 'The two main issues will be the conversion of area-based irrigation allocations to volumes and the inclusion of plantation forest impacts into the water budget (both recharge and extraction) (personal communication, Darryl Harvey, Department for Water 12/01/12). It is considered likely that existing plantations will be granted allocations to reflect existing use and in line with their 'deemed impacts'; this is in accordance with the approach used for existing irrigation at the time the groundwater resources were prescribed.

5.4.2.4 Deemed recharge impact values

Deemed recharge impact values for hardwood and softwood plantations have been developed over a number of years and are determined relative to the agricultural landscape which it has replaced or been substituted for:

- Hardwood plantations are deemed to reduce groundwater recharge by 78% of that of the agricultural landscape.
- Softwood plantations are deemed to reduce groundwater recharge by 83% of that of the agricultural landscape (Harvey 2009:20).

These values are considered to be a practical way to account for variability in seasonal conditions, plantation age and silvicultural practices and are thought to 'reflect a reasonable characterisation of biophysical reality in plantation forests of the same type in the same groundwater management area'. (Harvey 2009: 15). Annualised values have been adopted which '... smooths hydrological impacts over the full forest rotation period and expresses impacts as an annualised value for the full rotation of all plantations of the same species in the same groundwater management area' (page 19). This is considered to be an appropriate approach for a mature plantation area in which activities of planting, thinning and felling are occurring, and for an area which is considered to be serviced by a 'robust' groundwater resource. Harvey (2009) notes that this may not be an appropriate management approach for surface water or 'fragile' aquifer systems.

5.4.2.5 Groundwater extraction impacts

In 2004, the CSIRO reported on a study of plantation water use in the south-east coast area (Benyon and Doody 2004 in Harvey 2009). This has formed the basis of extraction models which indicated that where the median height of the water table was less than six metres:

- hardwood plantations extract 1.82 ML/ha/year; and
- softwood plantations extract 1.66 ML/ha/year.

Recent data and water table depth information derived from a LIDAR survey and digital elevation modelling shows that approximately 60,000 ha of plantation forest is extracting about 106,000 ML/year from the region's groundwater. It is estimated that the impact of plantation forestry is about 32 % of the total water budget.

SA KEY ATTRIBUTES

- ***Scale of industry***
  The Lower Limestone Coast in the south-east of South Australia encompasses the majority of the state's plantation forests, including 146,000 ha of hardwood and softwood plantations.
- ***Industry attitudes to water allocation planning***
  The South Australian forest industry originally opposed the legislative changes, but 'now appear to want the security of a property right that is transferable' (personal communication, Darryl Harvey, SA Department for Water, 12/01/12).
- ***Rainfall***
  The Lower Limestone Coast receives an average annual rainfall of 700 mm/yr.
- ***Plantation species***
  Tasmanian blue gum (Eucalyptus globulus) and pine (Pinus radiata)
- ***Plantation approvals***
  Change of land use requires a development application to be submitted through the local council. Development applications are also assessed by the relevant planning authority.

5.5 Water interception by plantation forestry in the NT

This section summarises the findings of scientific modelling conducted in Section 4 and describes a range of relevant national studies and investigations specific to the Top End of the Northern Territory. An outline of an Ord River water balance assessment is also included to provide insight into the behaviour of African mahogany plantations under these vastly different land use conditions.

5.5.1 Modelling results – plantations in Douglas-Daly

In order to assess the impacts of African mahogany plantation expansion on the water resources of the Douglas Daly region, preliminary growth modelling was undertaken for plantations of varying ages Modelled water balance was compared to native savanna and improved pasture, the two dominant land types within the catchment. Annual evapotranspiration (ET) from mahogany plantations was similar to that observed in the surrounding savannas, although there were marked differences in the partitioning of total ET and its seasonal dynamics.

Savanna vegetation features a mixture of a woody overstory and a tropical grass dominated understorey. For well-developed stands on Blains soils within the Stray Creek catchment, annual water use from the overstory eucalypt and semi-deciduous woody species is approximately 400 mm/yr with tropical grasses at approximately 300 mm/yr. At canopy closure on mahogany plantations, this grassy understory layer, and associated water use, is absent due to shading and plantation management. Understory evaporation from a plantation system is therefore dominated by soil evaporation alone, also likely to be reduced under a plantation canopy compared to the more open savanna canopy. As a result, moisture that would have been used by the understory layer is retained within the soil profile and is available to support mahogany tree growth and transpiration, estimated to be 2.3 times that of native savanna eucalypt stands. This higher tree transpiration is maintained throughout the dry season and may result in significant depletion of soil water stores during this period and possibly, reduced drainage from the root zone. A larger volume of water is therefore required during the following wet season to replenish soil water resources.

The impact of this dynamic could not be fully explored within the current modelling framework due to model uncertainties and limited data available for validation, but this may be an important dynamic in this system as dry season baseflow in the rivers of the catchment is derived from groundwater discharge. However, spatial scenario modelling of a plantation estate with a projected planting of 2,000 ha y^{-1} suggested little impact on the water resources at a catchment scale over time. This is due to the similarity in annual ET from the estate (approximately 30% of the Stray Creek catchment in this scenario) when compared to savanna vegetation.

5.6 Policy recommendations

The following policy outline has been developed in light of the results summarised in Section 5.5.1, and is presented in a stand-alone format consistent with NRETAS' policy framework.

Title

Water resource policy for African mahogany plantations in the Douglas Daly basin

Overview

Under the National Water Initiative, the NT Government is required to consider water interception by large-scale plantation forestry in the water planning framework. Recently completed research suggests that there is currently a low risk of impact on the water resources of the Douglas Daly basin due to interception by non-irrigated African mahogany plantations. As such, it is recommended that this land use does not require a water allocation licence. Further work is required, however, to reduce the significant uncertainties associated with the outcomes of this research and to inform the policy review process.

Background

The purpose of this policy is to embed the results of recently completed research relating to water interception in large-scale African mahogany plantations in the Daly basin to the water planning framework and in so doing, to address elements of the NT's National Water Initiative (NWI) obligations.

In 2004, the Northern Territory Government signed an Intergovernmental Agreement on the NWI. The NWI identified large-scale plantation forestry as an activity which may be undertaken without a water access entitlement (WAE) and has the potential to intercept significant volumes of surface and/or groundwater. Under the agreement, the NT Government is required to assess the significance of these activities and apply appropriate planning, management and/or regulatory measures.

In the mid-2000s an influx of Managed Investment Scheme (MIS) promoters resulted in the development of large-scale plantations of African mahogany (*Khaya senegalensis*) in the Douglas Daly basin. These non-irrigated plantations were developed predominantly on freehold land previously cleared for improved pastures. Due to the nature of this land use change—specifically the land tenure and lack of clearing and irrigation—formal development assessment was not triggered. While many of the companies initially involved in plantation establishment have since been liquidated, there remains an estate of approximately 10,000 to 12,000 ha owned and managed by African Mahoganies (Australia) (AMA) and Northern Tropical Timbers. No information has previously been available regarding the water use characteristics of this species and how the development of such plantations may affect the overall water balance of the Daly basin.

Research results

In 2010, Charles Darwin University (CDU) and the department of Natural Resources, Environment and The Arts (NRETAS) sought funding from the National Water Commission (NWC) to undertake a project to quantify interception associated with large-scale plantation forestry in the Douglas Daly. This research has since been undertaken in tandem with a complementary project funded by the Australian Research Council (ARC) encompassing other investigations relating to greenhouse gas emissions and carbon.

A preliminary growth model has been developed for mahogany plantations of varying ages and a modelled water balance was compared to native savanna and improved pasture, the two dominant land types within the catchment. Specifically, the modelling examined the difference in the total amount of water lost through evaporation from the soil and transpiration from the plants (evapotranspiration or ET) under these different land uses.

The research found that:

1. Total annual evapotranspiration from mahogany plantations was similar to that observed in surrounding savannas.
2. Transpiration from a mahogany stand is estimated to be 2.3 times that of native eucalypt savanna stand—a level that is maintained throughout the dry season. This compares with a eucalypt stand which has a significantly reduced transpiration rate during the dry season.
3. There were marked differences in the source of evapotranspiration (i.e. the canopy and soil under a closed canopy mahogany stand, rather than the canopy, understory and soil in a savanna). The loss of high water using understorey layer at plantation sites largely off-set increased water use from plantation trees and annual ET was similar.
4. There were marked changes in the amount of evapotranspiration occurring at different times of the year.

Savanna vegetation features a mixture of a woody overstory and a tropical grass understorey. For well-developed stands on Blain soils within the Stray Creek catchment, annual water use from the woody overstory was found to be approximately 400 mm/yr, while tropical grasses used approximately 300 mm/yr. On a mahogany plantation with a closed canopy, however, the grass is mostly absent due to both shade and management practice. Consequently, evaporation from the understory of a plantation is dominated by soil evaporation alone, which is also likely to be reduced given the greater canopy cover of a plantation compared to savanna woodland. As a result, moisture that would have been used by the understory layer would be retained within the profile and be available to support both the growth and higher rate of transpiration of mahoganies throughout the dry. This may result in significant depletion of soil water stores during this period and possibly, reduced drainage from the root zone into the groundwater. A larger volume of water is therefore required during the following wet season to replenish soil water resources.

The impact of this change could not be fully explored due to limited data and model uncertainties, but could be important given that dry season baseflow in the rivers of the catchment is derived from groundwater discharge. However, spatial scenario modelling of a plantation estate with a projected planting of 2,000 ha/yr suggested little impact on the water resources at a catchment scale over time. This is due to the similarity in annual evapotranspiration from the estate (approximately 30% of the Stray Creek catchment in this scenario) when compared to savanna vegetation.

This assessment has been made with the best available data at this time. There is, however, considerable uncertainty given the limited amount of data available. Future investigations and data collection should focus on improving the capacity to refine and validate the model.

FSC accreditation

While no forestry plantations in the NT are currently accredited under the Forestry Stewardship Council (FSC), currently available interim standards do refer to elimination of impacts on local hydrology. A public information draft or ‘Straw Dog’ of an Australian National Standard (FSC 2008) specifically refers to interception. Such standards provide an optional alternative framework under which the Territory Government could address interception in forestry plantations.

Policy recommendation

Recently completed research suggests that there is currently a low risk of impact on the water resources of the Douglas Daly Basin due to interception by non-irrigated African mahogany plantations. It is therefore recommended that this land use does not require a water allocation licence under the *Water Act*. Further work is required, however, to reduce the significant uncertainties associated with the outcomes of this research and to inform the policy review process.

Scope/application

This policy applies to non-irrigated African mahogany plantations grown in the Daly Basin. Application of the policy to other species requires research and modelling specific to that species. This approach, however, provides a useful and appropriate template for future research and policy development.

While consideration of interception and large-scale plantation forestry is currently being dealt with as a policy matter, potential amendments to the *Water Act* have been considered to encompass all of the Territory's NWI obligations. Work specifically relating to the interception clauses of the NWI (55-57), and associated definitions, has informed development of this policy. This work highlights that the NWI's interpretation of 'interception' is more broadly defined than the commonly accepted hydrological term, and relates to any non-licenced use which takes water from the consumptive pool and leads to a 'measurable diminution of flow, or likely flow of water, in or into a waterway and/or aquifer'.

Given this broad definition, it was determined that in the development of a water plan the consumptive pool should be considered to include both metered and non-metered interception activities and that all of these activities (including Native Title rights in water) should be identified and described in terms of the diminution of flow of water into each water system. It was also determined that known and/or potential impacts associated with these activities should be described and priorities assigned for reducing these impacts and that limitations in knowledge, information and data and priorities for addressing these, should be also identified and described.

Definitions

Evapotranspiration	A combined term for water lost as vapour from the soil's surface (evaporation), rainfall intercepted by a plant canopy and subsequently evaporated to the atmosphere plus water lost from the surface of a plant (transpiration).
Interception	The measurable diminution of flow or likely flow of water in or into a waterway and/or aquifer at any time within the duration of a water plan or proposed water plans. Note this definition is consistent with the meaning implied by the NWI. This is distinct from the use of the term 'interception' as used in ecohydrology and hydrology as a component of evapotranspiration (see above).

Procedures

Not applicable

Related policies

The NT Implementation Plan for the NWI (NRETAS 2006) set in place the '80/20 rule' for areas in which there is a paucity of relevant scientific data to inform water planning. This rule allows for the allocation of 80% of the total water yield to the environment and other in-stream public benefit, while the remaining 20% is allocated to consumptive use.

Relevant legislation

Water Act

Date of next review

It is recommended that this policy be reviewed in March 2014 and/or on the receipt of information which further refines the modelling on which this policy has been based.

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7 Appendix A Intergovernmental Agreement On A National Water Initiative (2004)

(Between the Commonwealth of Australia and the Governments of the New South Wales, Victoria, Queensland, South Australia, the Australian Capital Territory and the Northern Territory)

Interception

The Parties recognise that a number of land use change activities have potential to intercept significant volumes of surface and/or ground water now and in the future. Examples of such activities that are of concern, many of which are currently undertaken without a water access entitlement, include:

i) farm dams and bores;

ii) intercepting and storing of overland flows; and

iii) large-scale plantation forestry.

The Parties also recognise that if these activities are not subject to some form of planning and regulation, they present a risk to the future integrity of water access entitlements and the achievement of environmental objectives for water systems. The intention is therefore to assess the significance of such activities on catchments and aquifers, based on an understanding of the total water cycle, the economic and environmental costs and benefits of the activities of concern, and to apply appropriate planning, management and/or regulatory measures where necessary to protect the integrity of the water access entitlements system and the achievement of environmental objectives.

Accordingly, the Parties agree to implement the following measures in relation to water interception on a priority basis in accordance with the timetable contained in their implementation plans, and no later than 2011:

iv) in water systems that are fully allocated, *overallocated*, or approaching full allocation:-

a) interception activities that are assessed as being significant should be recorded (for example, through a licensing system);

b) any proposals for additional interception activities above an agreed threshold size, will require a *water access entitlement*:

– the threshold size will be determined for the entire water system covered by a *water plan*, having regard to regional circumstances and taking account of both the positive and negative impacts of water interception on regional (including cross-border) natural resource management outcomes (for example, the control of rising water tables by plantations); and

– the threshold may not apply to activities for restricted purposes, such as contaminated water from intensive livestock operations;

c) a robust compliance monitoring regime will be implemented; and

v) in water systems that are not yet fully allocated, or approaching full allocation:

a) significant interception activities should be identified and estimates made of the amount of water likely to be intercepted by those activities over the life of the relevant water plan;

b) an appropriate threshold level will be calculated of water interception by the significant interception activities that is allowable without a *water access entitlement* across the entire water system covered by the plan:

   – this threshold level should be determined as per paragraph 0(iv)b) above; and

c) progress of the catchment or aquifer towards either full allocation or the threshold level of interception should be regularly monitored and publicly reported:

   – once the threshold level of interception is reached, or the system is approaching full allocation, all additional proposals for significant interception activities will require a *water access entitlement* unless for activities for restricted purposes, such as contaminated water from intensive livestock operations.

8 Appendix B Northern Territory Codes Of Practice For Forestry Plantations

1. All clearing of vegetation in the NT, irrespective of land tenure, is now subject to approval under legislation. For all freehold and crown land this approval is provided under the Planning Act initially through an Interim Development Control Order and eventually through amendments to the NT Planning Scheme. For the remaining 47% of land which exists as Pastoral estate, the approval is provided under provisions of the Pastoral Land Act. All vegetation clearing applications are assessed according to statutory processes and for plantation forestry proposals both the NT Clearing Guidelines and the NT Code of Practice for Forestry Operations would be used in the assessment process.

2. Clearing proposals are assessed by a range of government agencies including the Office of Environment and Heritage. The referral of a plantation forestry proposal to this Office of Environment and Heritage would trigger the environmental assessment of the proposal under the NT *Environmental Assessment Act* and relevant Commonwealth legislation. The referral of a plantation forestry proposal is a requirement of the *Environmental Assessment Act* and would be made by the agency responsible for approving clearing either under the Planning Act or the Pastoral Land Act.

3. A plan of management will be prepared by the developer setting out work prescriptions that address the requirements of this Code of Practice. Any plan would need to take into account recommendations as specified under an approval granted under the *Planning Act* and would be subject to the approval of the Minister for the Environment.

4. The plan of management will detail procedures for monitoring compliance with work prescriptions that address the requirements of this Code of Practice. A committee comprising representatives of Departments of Business, Industry and Resource Development, and Infrastructure, Planning and Environment, together with a representative of the proponent will review and oversight compliance.

5. There will be no net loss of biodiversity values associated with new plantation development. Losses caused by development activities essential for the viability of the plantation enterprise will be compensated by expanded conservation activity in other areas. The plan of management will detail mechanisms to protect endangered or threatened species.

6. Soil quality will be protected by preventing erosion and mitigating processes which could lead to chemical and structural change. The risk of water pollution caused by soil erosion will be minimised.

7. Water quality, stream stability and habitat values will be maintained in the forest environment including the development area and adjoining lands.

8. A high standard of operational planning, clear work instructions, and adequately trained workforce will ensure effective and reliable implementation of complying management operations. Inspection of operations, keeping of adequate records, and periodic auditing of the system's performance will ensure the maintenance of standards and their continuous improvement.

9. The threat to water quality will be minimised by controlling the extent of road construction, and the number of stream crossings to that required for efficient plantation operations. Roads

will be located and designed to minimise run-off and to facilitate effective construction and maintenance.

10. Permanent watercourse crossings will be located, designed, constructed and maintained so as to minimise disturbance during construction and to ensure stability in the long-term in order to minimise risks of degrading water quality and aquatic habitat. Temporary crossings will be sited, prepared and used so as to avoid exposure of dispersible soils and minimise the disturbance of banks. Temporary crossings will be rehabilitated to the satisfaction of the Commissioner for Soil Conservation.

11. Roads will be constructed to provide long-term stable traffic surfaces. Control measures will be implemented during the construction phase to protect against soil erosion and water quality degradation. Culverts and crossings will be installed to ensure long-term effective performance and to meet the needs of aquatic fauna.

12. Roads and their associated drainage systems will be maintained in effective functioning order to minimise risk of degradation of water quality.

13. Adverse impacts on soil, such as compaction, soil erosion and fertility loss, and degradation of water quality will be minimised during site preparation.

14. Forestry and associated operations will be conducted in such a fashion that they caused minimal disturbance of soil in buffers, in order to allow their effective and continuing functioning in filtering water pollution and preventing damage to aquatic habitat.

15. Chemical selection, rates and method of applications will assure healthy plantations, minimise risk to human health, and minimise adverse impacts on the environment.

16. Handling and storage of hazardous substances will be conducted to minimise risks to human health, site contamination, and off-site pollution, including adverse impact on flora and fauna.

17. Oils, fertiliser bags, empty chemical containers, unused chemicals, and other plantation and machinery waste will be removed off-site and disposed of by authorised disposal methods only in order to minimise risks to human health, site contamination, and adverse impacts on the environment.

18. Risks to life, property and the environment from wildfire will be minimised through adequate precautionary measures.

19. Sites with heritage and archaeological significance will be protected from disturbance by plantation activities.

20. Harmful pest outbreaks will be minimised by monitoring of plantation health and by timely implementation of control measures. Adjacent lands and forests will be prevented from degradation caused by the spread of weeds, pests and diseases.

21. Environmental disturbance associated with harvesting will be minimised by ensuring that operations are adequately planned, that clear work instructions are provided, and that supervision is effective.

22. The risk of water pollution caused by run-off from areas disturbed by harvesting machinery traffic, will be minimised during and after operations.

    The extent of adverse impacts on soils such as compaction caused by machinery traffic during wet weather will be minimised.

23. Turbid run-off from roads causing water pollution will be minimised.

24. Areas reserved for the protection of soil, water quality and maintenance of biodiversity will be protected and managed so that these environmental attributes remain functional in perpetuity.

25. Adverse impacts on neighbours and members of the public caused by employees, dust or safety hazards will be minimised.

26. The plan of management will provide for periodic reporting of compliance against the requirements of the plan and this Code and for ongoing monitoring. Breaches may result in action being taken under relevant legislation including the *Water Act*, the *Weeds Act,* the *Bushfires Act*, the *Soil Conservation and Land Utilisation Act*, the *Parks and Wildlife Conservation Act* and the *Work Health Act*.