Using pre-dawn leaf water potential and MODIS LAI to explore seasonal trends in the phenology of Australian and southern African woodlands and savannas.

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Abstract

Trends in global soil moisture are needed to inform models of soil-plant-atmosphere interactions. Pre-dawn leaf water potential (Ψ_{pd}), a surrogate for soil moisture and an index of plant water stress. Ψ_{pd} has been routinely collected in Australian forests, woodlands and savannas, but the associated leaf area index (LAI) has seldom been available to enable the preparation of a Ψ_{pd} on LAI relationship. Following an analysis of Ψ_{pd} and MODIS LAI data from Australian forests, woodlands and savannas, we identified patterns in Ψ_{pd} which provide an understanding of the role of soil moisture status in controlling LAI. In the savanna of Northern Australia, the MODIS LAI product had a basal value of 0.96 during the dry season as compared with a mean value of 2.5 for the wet season. The dry season value is equivalent to the LAI of the tree component and corresponds with ground-truthed LAI. Ψ_{pd} is lowest (more negative) during the height of the dry season (late October) at -2.5 MPa, and highest (-0.1 MPa) during the wet season (early March). We present two models which predict Ψ_{pd} from the MODIS LAI product. These may be useful surrogates for studying trends in soil moisture in highly seasonal climates and may contribute to climate change research.

Keywords

Evergreen woodland, savanna, leaf area index, soil water potential

Introduction

Soil moisture is a crucial component of the hydrological cycle and is important to agriculture and forest production throughout the world. In water balance equations, quantifying soil moisture is essential for accurately predicting the rate of vegetation and surface evapotranspiration, soil water storage, groundwater recharge and runoff. Furthermore, soil moisture, together with other land surface conditions, determines the partitioning of energy between sensible heat and latent heat (Li *et al.* 2007). Measuring global soil moisture has not been done with consistency, and the numbers of data sets which provide continuous measurements are limited (Robock *et al.* 2000). With the paucity of global *in situ* observations, model-simulated soil moisture (mainly Land Surface Simulation Models) has been used as a substitute for observations in climate change studies. However, these depend on the critical values of ‘forcings’ used (radiation, precipitation, wind velocity and other weather variables), and are not sufficiently reliable to determine trends (Li *et al.* 2007, Trenberth *et al.* 2007). Using data from studies in Australia and South Africa, we have explored an approach to assess soil moisture using pre-dawn leaf water potential (Ψ_{pd}) as an approximately equivalent value of soil water potential (Ψ_s), estimated from MODIS in evergreen woodland, and we provide an alternative, fully independent source of trends in soil moisture in these ecosystems.

The standard MODIS LAI product from Terra and Aqua MODIS sensors is generated as an 8-day composite at 1-km spatial resolution. The approach uses passive remote sensing data at optical and infrared (NIR and SWIR bands) wavelengths to generate the normalized difference vegetation index (NDVI), a ratio of the NIR and SWIR bands. The procedure applies strict requirements on atmospheric correction, compositing to minimize the atmospheric impact, as well as cloud and snow screening. The retrievals are performed with the radiative transfer algorithm which generates LAI values given sun and view directions, a bidirectional reflectance factor (BRF) for each MODIS band, band uncertainties, and an 8-biome land cover class. The technique compares observed and modeled BRFs for a suite of canopy structures and soil patterns that represent an expected range of typical conditions for a given biome type (Knyazikhin *et al.* 2002)

Vegetation is important in transferring moisture from the soil to the atmosphere and *vice versa* (Smith *et al.* 1999). In response to elevated [CO_2], many plant species reduce stomatal conductance to reduce water loss through transpiration (Eamus and Jarvis 1989). This potentially leads to an increase in soil water storage and streamflow. Measuring trends in soil moisture associated with changing atmospheric [CO_2] is therefore essential for understanding the anthropogenic effects on the hydrological cycle (Henderson-Sellers *et al*. 1995).

If soil moisture content is generally increasing with the reduction in stomatal conductance that has occurred over the past 200 y, then the detection of trends in increasing soil moisture becomes even more crucial to explain and understand trends in atmospheric moisture. Robock *et al*. (2005) analysed over 40 y of gravimetrically-measured soil moisture data for grasslands and forests at 55 weather stations in Ukraine and Russia and showed no summer desiccation. Rather, they show an upward trend in summer soil moisture and it has been suggested that solar dimming may be responsible (Robock *et al.* 2005). Pan evaporation can be thought of as a direct measurement of the atmospheric evaporative demand. The trend of increasing summer soil moisture is consistent with the decreasing pan evaporation from Russia and the Ukraine, a trend which has also been described in Australia (Roderick and Farquhar 2004), southern Africa (Eamus and Palmer 2007) and New Zealand (Roderick and Farquhar 2005). If soil moisture is indeed increasing as atmospheric [CO_2] increases then new methods for determining this increase become a necessity.

Soil water potential (Ψ_s) within the rooting zone is often estimated by measuring Ψ_{pd}. It has been argued that equilibration of leaf water potential and soil water potential will occur overnight and that predawn leaf water potential reflects the soil water potential in the zone of water uptake (Hinckley *et al.* 1978, Katerji and Hallaire 1984, O'Grady *et al.* 2006). There is evidence for significant nocturnal leaf conductance and transpiration in widely differing ecosystems (Caird *et al*., 2007, Dawson *et al*., 2007, Howard and Donovan 2007), and the assumption that all transpiration stops at nighttime may not hold under all circumstances. In these cases, a correction factor may be necessary to adjust Ψ_{pd} to compensate for noctural transpiration. The role for nocturnal leaf conductance and transpiration in correcting Ψ_{pd} is, however, very small relative to the inter-seasonal variation in Ψ_{pd} (e.g. 0 to -4.6 MPa in this study). We propose that Ψ_{pd} is a suitable index of Ψ_s, and when collected throughout a year, identifies the season of maximum water stress, and will provide the driest point in the seasonal process of soil desiccation.

The focus for many savanna ecologists has been on available water as one of the primary drivers for savanna structure (Walter 1971, Walker *et al*. 1981, Sankaran *et al*. 2005, February *et al*. 2007, Hempson *et al.* 2007). In attempting to understand the role of water availability in determining savanna structure and dynamics, models make some determination of seasonal soil moisture (Walker *et al*. 1981, Walker and Noy-Meier 1982, van Langevelde *et al.* 2003, Liedloff and Cook 2007). Problems with these models include difficulties in determining the seasonal discontinuity in soil moisture as soils dry out (Walker *et al*. 1981). A confounding factor in these models is that the moisture release curve varies for different soil types (Walker and Langridge 1996) making it very difficult to parameterize these models for different environmental conditions. An understanding of the relationship between length of the growing season and available water is therefore critical for developing an understanding of savanna structure (Scholes and Archer 1997). Here we evaluate the potential for using MODIS LAI to determine the extent of the growing season in Australian tropical savanna woodlands and southern African semi-arid savanna. We do this using MODIS LAI data as a surrogate for Ψ_{pd} in the dry season.

Methods

MODIS LAI product (Collection 5)

We acquired 8 years of the MODIS 8-day 1 km Collection 5 (MOD15A2) composite LAI/FPAR product (Knyazikhin *et al.* 2002) for the period 26 February 2000 to 31 December 2007 from the NASA Distributed Active Archive Centre. The data were extracted from the archive using the MODIS re-projection tool (HegTool) and imported into IDRISI (Version I32.11, Clark Labs) image processing package to create an 8-year data stack. The geo-codes for each study site (Table 1) were entered into the GIS and 8-day LAI values for each site were extracted. Where the MODIS LAI showed dramatic variation from the obvious season patterns (e.g. x10), data points were smoothed using the mean of the adjacent values. The study summarises data from a range of study sites located in evergreen forests, evergreen woodlands, woody savannas and savannas across Australia, representing a gradient in mean annual precipitation from 316 – 1534 mm and one site in South Africa (746 mm). At six sites (1, 2, 10, 11, 12 and 18) (Table 1), canopy LAI was measured using digital photographs following the methodology proposed by Macfarlane *et al.* (2007). A Nikon® Coolpix 995 (3,145,728 pixels in total) mounted on a tripod with a bubble level to obtain images at the zenith angle was used to acquire digital, upward viewing images from the nine sites. Images were collected at 1.5 m from the ground in FINE JPEG mode. The camera was set to automatic exposure using the F2 lens, which gives a zoom angle of approximately 35^{o} across the diagonal, or about 0-15^{o} zenith angle range. At each site, 25 images was captured (1 image every 10 m along five 50 m transects located 10 m apart). This procedure was repeated twice per site, giving a total of 50 images per site. LAI_{canopy} was computed using GAP analysis (Macfarlane *et al.* 2007). Canopy LAI and wet season understory LAI values for the remaining sites were extracted from published accounts.

The relationship between MODIS LAI and pre-dawn water potential

During this part of the study we collected new Ψ_{pd} data in different seasons and different years at three sites (two in New South Wales, Australia, in the period 2004-2007, and one in South Africa during 2004). Pre-dawn leaf water potential was measured using a Scholander-type pressure chamber (Plant Water Status Console, Soil Mositure Equipment Corporation, Sanata Barbara, CA, USA) on three replicate leaves of three individuals of the dominant tree species at each site. Mature leaves were sampled in the outer canopy between 2 and 8 metres height at pre-dawn. In addition, we surveyed the literature for Ψ_{pd} reported from other studies in Australia since 26 February 2000 and identified a further fifteen sites which had recorded Ψ_{pd} (Hutley *et al.* 2001, Cernusak *et al.* 2003, Zencich 2003, Macinnis-Ng *et al.* 2004, McClenahan *et al.* 2004, O'Grady *et al.* 2006, Zeppel 2006) and provided recording date. In all cases, we extracted the MODIS LAI and the data quality flag from the distributed archive that were recorded on or near the date of the lowest Ψ_{pd} measurement for that site. The LAI value that had been provided by the main algorithm we termed the MODIS LAI_{min} and we believe it represents the most water stressed condition recorded for the site. A regression analysis was applied to these data to determine the relationship between MODIS LAI_{min} and Ψ_{pd}.

In the savanna of the Northern Territory of Australia, we collated Ψ_{pd} data collected prior to the inception of MODIS (26 February 2000), including Thomas & Eamus (2002) and Prior *et al.* (1997) (1993-1995). After examining the MODIS LAI product for the eight years in the Northern Territory, a regular pattern of high LAI during the wet season and low LAI during the dry season (Figure 1) was evident. Although we only had historical Ψ_{pd} data (before 26 February 2000) for this region, we felt it valid to use these data as they represent a seasonal Ψ_{pd} series. We model a typical year from the MODIS LAI for Darwin, Northern Territory, Australia using a maximum value compositing routine. This model is referred to as MODIS LAI_{comp}. Regression analysis was used to prepare a relationship between MODIS LAI_{comp} and the historical Ψ_{pd}.

Results

The linear regression, MODIS LAI = 0.9591 LAI_{canopy} – 0.2371 (r^2 = 0.89) describes the relationship between LAI_{canopy} and MODIS LAI for the woodland and forests sites where LAI_{canopy} had been collected (Fuentes *et al*. In press). Although MODIS LAI tended to slightly overestimate LAI_{canopy}, this could be explained by the absence of understorey in the LAI_{canopy} technique. The result justifies the use of MODIS LAI as a surrogate for LAI_{canopy} and to proceed with further exploration of the MODIS LAI and Ψ_{pd} relationship.

The relationship between Ψ_{pd} and MODIS LAI_{min} for evergreen woodlands, shrublands and savannas at sites throughout Australia (Figure 2) can best be described by the equation:

$$\Psi_{pd} = -25.09 * Exp(-6.624 * \text{MODIS } LAI_{min}) + (-2.137 * Exp(-1.206 * \text{MODIS } LAI_{min})). \quad \text{Equation 1}$$

Model fit constrained to y=0.

Adjusted r^2=0.7109.

This relationship provides the ability to predict Ψ_{pd} from the MODIS LAI product. As a proof of concept, we used a MODIS LAI image for the first week of 2006 to calculate a new image using equation 1. This is a prediction of the Ψ_{pd} for woodlands and shrublands during the dry season in Western Australia (Figure 3).

In Northern Australia, the relationship between 8-day maximum MODIS LAI (2000-2004) and historical trends in Ψ_{pd} (Figure 4) is:

Ψ_{pd} =-5.326*Exp(-1.13* MODIS LAI_{comp}) Equation 2

Model fit constrained to y=0.

Adjusted r^2=0.612.

The MODIS LAI has mean value of 1.2 (Day of year (DOY) 169 through to DOY 49) during the dry season as compared with a mean value of 2.6 for the wet season (DOY 57-161). The former is the LAI of the tree component only, and the latter represents both the tree and the understory LAI. The dry season value corresponds well with ground-truthed LAI from sites in the region (Hutley *et al.* 2001). Ψ_{pd} are lowest (more negative) at the end of the dry season (late October) at -2.5 MPa, and highest (very close to 0) during the wet season (early March). In mid-July (DOY 185) there is a critical value of -1 MPa when the MODIS LAI declines from the wet season highs to the basal value of ~1.

Discussion

In the woody savanna of the Northern Territory of Australia, the tree layer of the vegetation comprises four phenological leaf types: evergreen, brevideciduous, semideciduous and fully deciduous (Williams *et al.* 1997), and a grass/shrub understory. The MODIS LAI value during the wet season (LAI~4) is a combination of all four components of the vegetative cover, and it is not possible to separate the contribution of any one component to the MODIS product. From field measurements, Hutley *et a*l. (2001) show that at Howard Springs the tree layer contributes 42% and the herbaceous understory layer contributes 58% to the LAI during the wet season. As the wet season ends and soil dries out, the maximum value composite (MODIS LAI_{comp}) shows a rapid decline, suggesting that the three types of deciduous trees and the grass/shrub understory respond rapidly to a decline in Ψ_s. This rapid response to the change in Ψ_s has been described previously (Williams *et al.* 1997) and is mirrored in the data from the southern African savanna. The latter is also a deciduous savanna with a large shrub/grass component contributing to the high LAI during the wet season. There is a strong argument that phenology of the woody savanna of the Northern Territory of Australian with its dominant evergreen component that survives the dry season drought, plus a complex wet season cover of evergreen trees, deciduous trees as well as a grass/shrubs understory, is driven strongly by the rapid decline in soil water potential at the onset of the dry season. The Ψ_{pd} time series presented here using the data of Prior *et al.* (1997) and Thomas and Eamus (2002) compares favourably to the threshold-delay (T-D) savanna ecosystem model (Olge and Reynolds 2004). It appears that the rapid decline in soil moisture at the end of the wet season, when evaporative demand is very high (high VPD in April-May), forces the grasses and deciduous trees to decouple from the system. Evergreen species in the Northern Territory have lower CO_2 assimilation and growth rates than deciduous species (Prior *et al.* 2004), and it is suggested that this enables them to respond rapidly to the onset of the wet season. In addition, we suggest that the ability of the evergreen trees to cope with this rapid onset of dry season physiological stress (desiccation) also gives them an advantage.

In the savanna of the Northern Territory of Australia, the Ψ_{pd} continues to decline for a long period after MODIS LAI_{min} has been reached (from DOY 170 to 320). The MODIS LAI_{min} , which is the LAI of the evergreen tree component, maintains an LAI ~1 throughout the dry season even though soil moisture content continues to decline. Maintaining this LAI cannot be attributed to the evergreen trees having greater access to groundwater, as they have been shown to use soil water rather than groundwater during the dry season (Cook *et al.* 1998). It will be interesting to test the impact of exceptional events (a long dry season followed by a below average wet season) on evergreen trees (90% of biomass). A better understanding of how evergreen trees survive these exceptional events will enhance our capacity to predict the impact of global climate change on woody savannas.

As we sampled the dry season MODIS LAI_{min} in untransformed examples of six IGBP land cover categories (Belward *et al*. 1999) which occur in Australia (evergreen broadleafed forest, evergreen broadleafed woodland, mixed forest, open shrubland, woody savanna and savanna), the relationship that we have developed (Figures 2 and 3) should only be applied in these land cover classes. According to the MODIS Land Cover map, these cover classes currently occupy 90% of the surface area of Australia. The model cannot be applied to the areas of cleared woodland that are cultivated or planted to perennial pasture, which represents much of the highly productive agricultural land of Queensland, New South Wales, Victoria and Western Australia. Alternative methods for measuring Ψ_{pd} will need to be developed for these land condition classes.

The similarity of the patterns from the Australian and southern African savannas suggest that there may be an opportunity to use MODIS LAI to further explore the role of soil water potential as a driving factor in the tree-grass dynamic.

Conclusions

We have successfully related the MODIS LAI_{min} to Ψ_{pd} and show the potential for using MODIS LAI to define Ψ_{pd} for the evergreen woodland in Australia and the savanna of Australia and South Africa. Efforts at monitoring soil moisture patterns, which are fundamental inputs into many models, may benefit from this insight. In rangeland production modeling, the identification of the end of the grass growing season is crucial to setting the limits to annual forage production. The MODIS LAI product has the potential to identify this point in the arid and semi-arid savannas.

Acknowledgements

We wish to acknowledge the assistance of Tony O'Grady and Craig Macfarlane for providing some of the original LAI and Ψpd data for Western Australia and the Northern Territory. Funding for the research in South Africa was made available from a grant by the Mellon Foundation of New York.

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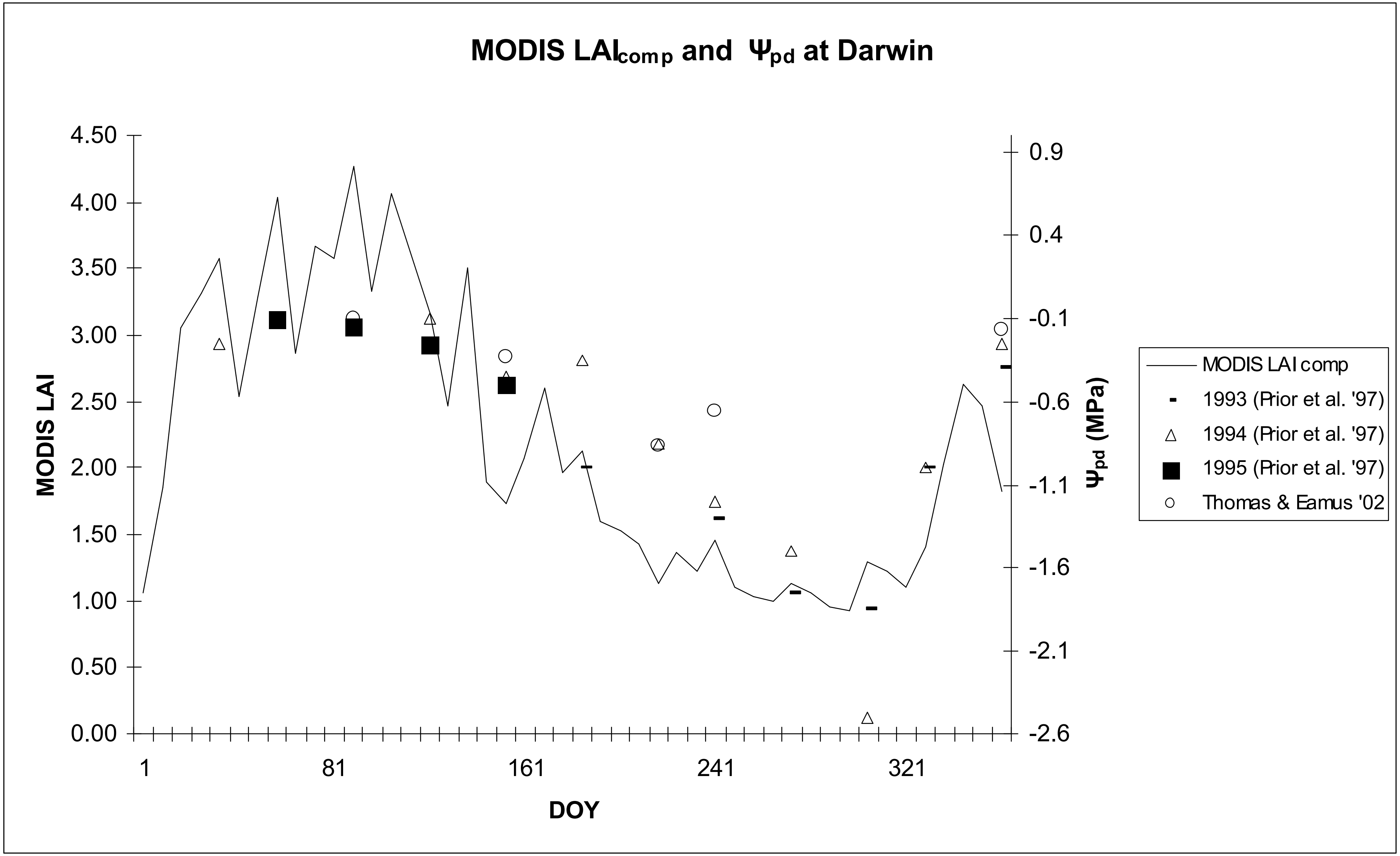
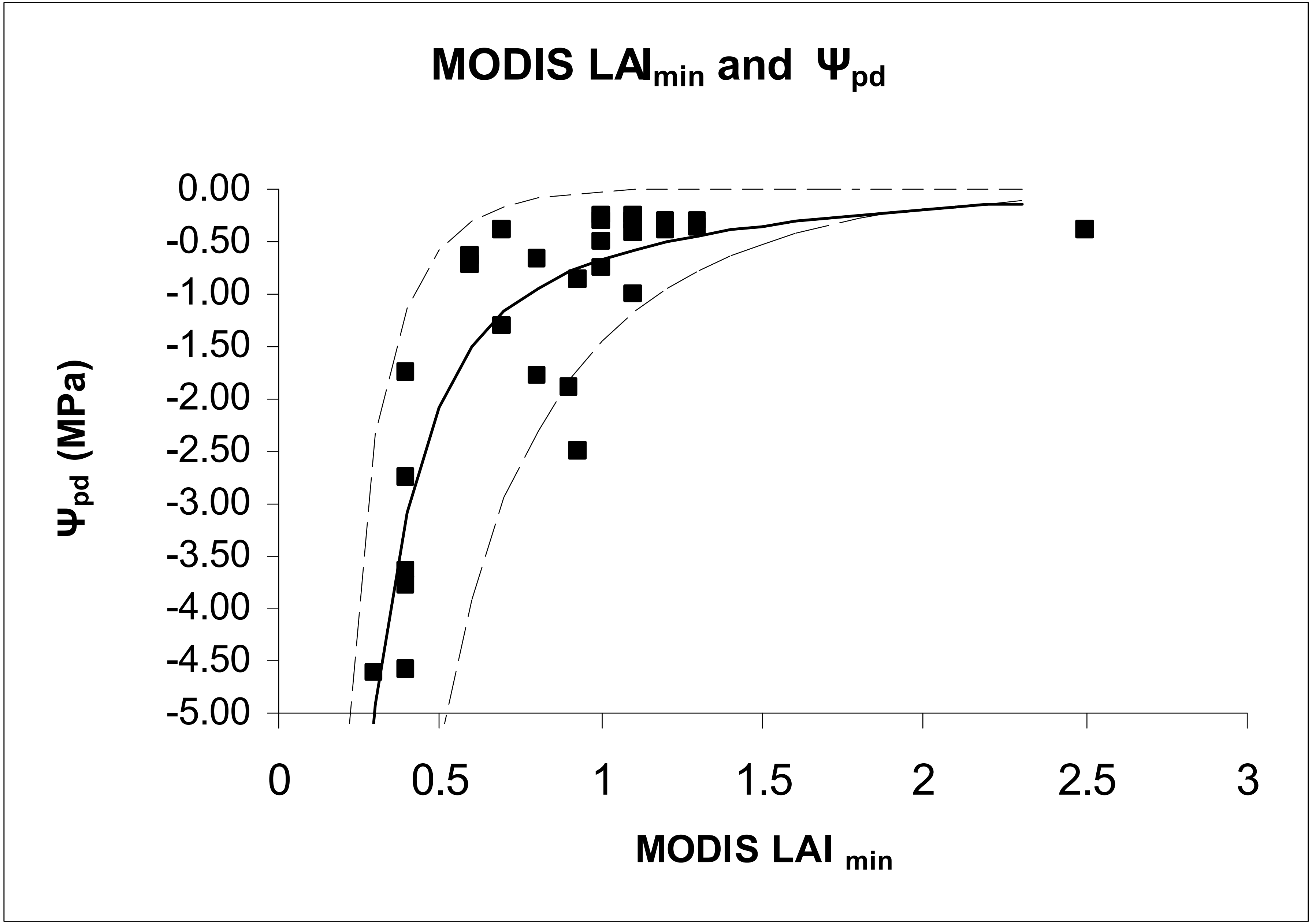
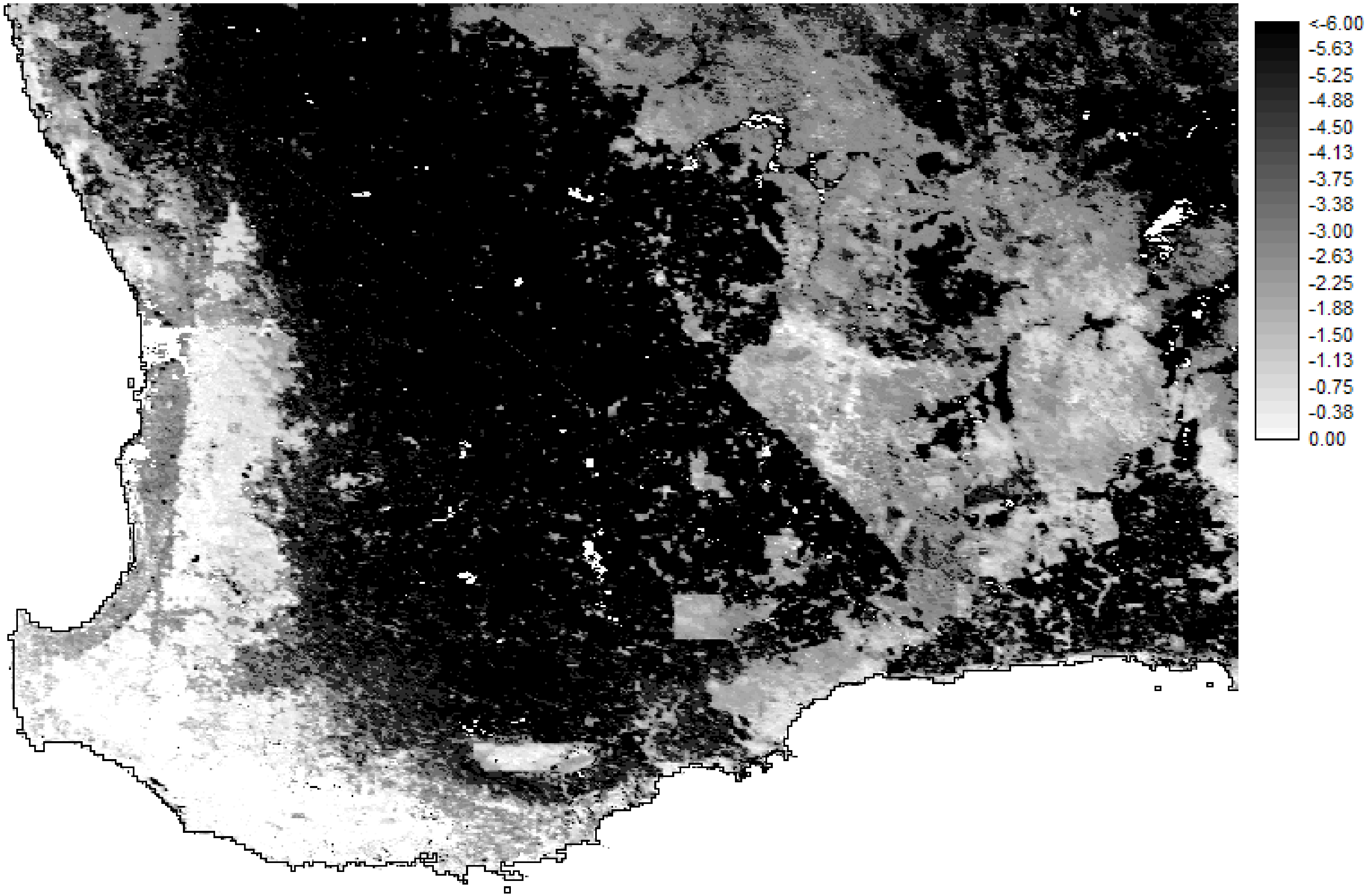
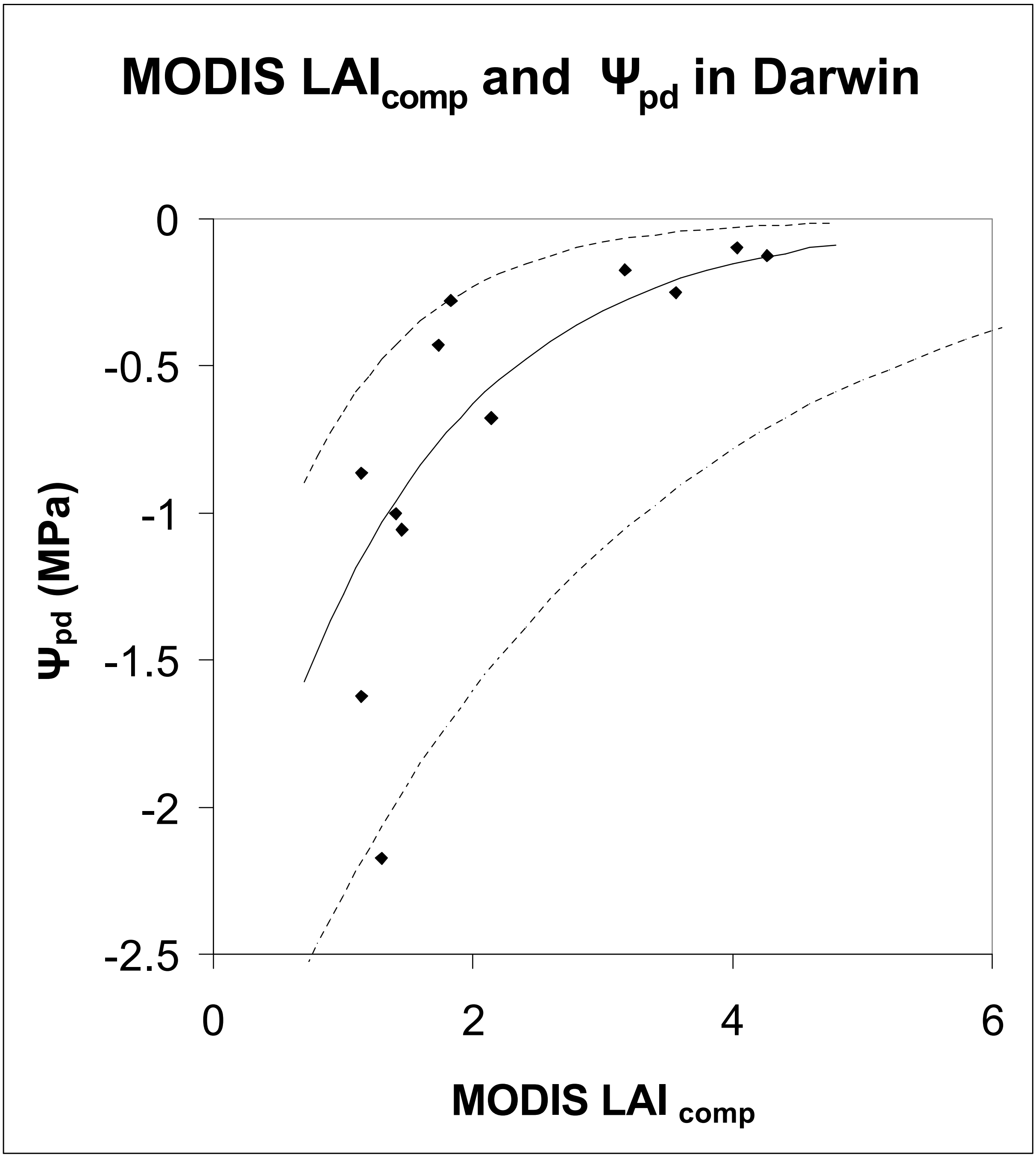
Table 1. Location of sites used in the survey of the relationship between MODIS LAI $_{min}$ and Ψ_{pd}. Land Cover Classes: 1=evergreen broadleaf forest, 2=evergreen broadleaf woodland, 3=mixed forest, 4=open shrubland, 5=woody savanna, 6=savanna. Precipitation data are provided by the nearest Bureau of Meteorology weather station.

Site number	**Site Name**	**Latitude**	**Longitude**	**Mean annual rainfall (mm)**	**Location**	**Land Cover**
1	Castlereagh	33.67S	150.79E	800	NSW, Australia	2
2	Hornsby	33.64S	151.11E	1135	NSW, Australia	1
3	Pretoriuskop	31.28S	25.19E	746	Mpumalanga, South Africa	6
4	Palmerston	12.45S	131.04E	1534	NT, Australia	5
5	Berrimah	12.40S	130.93E	1534	NT, Australia	5
6	Mount Barker	34.22S	116.08E	736	WA, Australia	3
7	Swan Coastal Plain	31.42S	115.6E	740	WA, Australia	4
8	Howard Springs	12.46S	131.05E	1713	NT, Australia	5
9	Catherine	14.7S	131.03E	1099	NT, Australia	5
10	Quairading	32.0S	117.3E	330	WA, Australia	4
11	Wandoo NP	32.07S	116.23E	595	WA, Australia	2
12	Pemberton	34.22S	116.08E	1200	WA, Australia	5
13	Ti Basin	22.13S	133.43E	316	NT, Australia	4
14	Dorisvale	14.36S	131.54E	1179	NT, Australia	5
15	Oolloo	14.0S	131.24E	1179	NT, Australia	5
16	Douglas/Daly	13.87S	131.22E	1179	NT, Australia	5
17	Many Peaks Range	19.18S	145.75E	1041	Queensland, Australia	1
18	East of Dwellingup	32.58S	116.2E	542	WA, Australia	2


MODIS LAIcomp and Ψpd at Darwin
MODIS LAI
4.50
4.00
3.50
3.00
2.50
2.00
1.50
1.00
0.50
0.00
1
81
161
241
321
DOY
Ψpd (MPa)
0.9
0.4
-0.1
-0.6
-1.1
-1.6
-2.1
-2.6
MODIS LAI comp
1993 (Prior et al. '97)
1994 (Prior et al. '97)
1995 (Prior et al. '97)
Thomas & Eamus '02


MODIS LAImin and Ψpd
0.00
-0.50
-1.00
-1.50
-2.00
-2.50
-3.00
-3.50
-4.00
-4.50
-5.00
Ψpd (MPa)
0
0.5
1
1.5
2
2.5
3
MODIS LAI min


<-6.00
-5.63
-5.25
-4.88
-4.50
-4.13
-3.75
-3.38
-3.00
-2.63
-2.25
-1.88
-1.50
-1.13
-0.75
-0.38
0.00


MODIS LAIcomp and Ψpd in Darwin
0
-0.5
-1
-1.5
-2
-2.5
Ψpd (MPa)
0
2
4
6
MODIS LAI comp

List of Figures