

Remote-sensing of water stress in fynbos vegetation



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Introduction

There is considerable interest in the global scientific community on the influence climate change will have on current environmental patterns and processes. This has led to the development of a number of General Circulation Models (GCM) which attempt to predict long term changes in climate characteristics. Despite the lack of consensus regarding the accuracy of the predictions, for example temperature and precipitation changes (Schneider, 2001), there is a clear message from the GCMs; climate variability and the occurrence and magnitude of extreme events is expected to increase (IPCC, 2002; McCarty, 2001; Easterling *et al*, 2000). Fowler and Hennessey (1995), for example, propose a global intensification of the hydrological cycle and consequentially an increase in the occurrence and magnitude of heavy precipitation events. However, the implications of this are complex; modelling changes in precipitation are hindered by the intricate dynamics of atmospheric circulation and the hydrological cycle (Allen and Ingram, 2002).

Climate Change and Southern Africa

On a global scale, mean precipitation is expected to increase with rising temperatures (Allen and Ingram 2002), yet at a regional scale, there is less certainty and the change will most likely not be uniform. Precipitation is expected to increase at equatorial and mid-latitudes and decrease in sub-tropical regions (Weltzin *et al*, 2003), in effect, the change will exacerbate current conditions and increase the probability of prolonged droughts and flooding (Joubert *et al*, 1996). Despite the uncertainty surrounding precipitation changes, there is a general consensus that the winter-rainfall region in the Western Cape, South Africa, will experience a decrease in precipitation (Schulze and Perks, 2000; Fauchereau *et al*, 2003; Joubert *et al*, 1996).

Using the HadCM2 global circulation model, Schulze and Perks (2000) predict potential climatic conditions for South Africa in 2050, assuming no change in current atmospheric CO₂ trends. The predictions for the Cape Floristic Region (CFR) point towards widespread droughts, a 25% reduction in mean annual precipitation and a 0.5 - 1°C increase in mean annual temperature. Fauchereau *et al* (2003) and Joubert *et al* (1996) predict greater variability in

rainfall incidence and intensity and a higher probability of droughts. The Cape Floral Kingdom is one of the smallest and yet most species diverse Floral Kingdoms with approximately 9000 species, over 6000 of which are endemic (Mucina and Rutherford, 2006). Fynbos, the dominant vegetation of the CFR, is subject to hot, dry summers with the majority of the rainfall occurring in the winter months (Mucina and Rutherford, 2006). The vegetation shows characteristic drought adaptedness expected in a Mediterranean climate (Chaves *et al*, 2002). However, the predicted changes (Schulze and Perks, 2000; Fauchereau *et al*, 2003; Joubert *et al*, 1996) raise concern over how one of the worlds "biodiversity hotspots", (Myers *et al*, 2000), will respond to warmer, drier conditions with prolonged drought (Midgley *et al*, 2002).

Currently, bioclimatic envelope modelling is the most accurate and popular approach to predicting climate change impacts (Pearson and Dawson, 2003; Davis and Shaw, 2001). There is concern regarding the accuracy of these models which assume species within a biome will respond collectively to climate change (Pearson and Dawson, 2003; Willis *et al*, 2009; Walther *et al*, 2002). Midgley *et al* (2002) point out discrepancies in the biome scale approach of bioclimatic envelope modelling which, in comparison to a finer scale species approach, underestimates the potential impacts of climate change. "Detailed species-level data are therefore essential for revising and fine-tuning biome-level predictions and designing effective response strategies. These could include methods to detect the early signs of climate change." (Midgley *et al*, 2002). This project forms part of a larger field experiment where plots of fynbos were subjected to water stress to simulate prolonged drought. Remote sensing of species responses to climate change type drought has the potential to improve predictions and detect early signs of climate change.

Remote Sensing

Over the last half century, the launch of a vast assortment of airborne and satellite sensors to monitor the biosphere has increased the practicability of remote sensing in environmental sciences (Turner *et al*, 2004; Kerr and Ostrovsky, 2003; Cohen and Goward, 2004). The spatial scale at which environmental remote sensing can take place has the ability to improve the scaling of data from local to regional to global scales and hence improve climate change

et al. is an abbreviation of *et alia*; hence full stop after "l"

prediction (Ustin and Gamon, 2010; Gould, 2000). The notable range of variables (i.e. land cover classification, biophysical properties and change detection) and the precision with which they can be measured suggests remote sensing be incorporated into more environmental studies (Ustin and Gamon, 2010; Turner *et al.*, 2004; Kerr and Ostrovsky, 2003).

In contrast to traditional point field-data collection, remote sensing refers the collection of data by a device not in contact with the area or object of investigation (Gould, 2000; Jensen, 1983). The majority of remote sensors record electromagnetic radiation from the sun which is reflected off biosphere surfaces (Jensen, 1983). Changes in the properties of this electromagnetic radiation are analysed using ratios between wavelengths to present indices; such as the popular Normalised Vegetation Difference Index (NDVI) (Jensen, 1983; Kerr and Ostrovsky, 2003). These indices have been tested, corrected and calibrated to provide a remarkably accurate array of biophysical variables (Kerr and Ostrovsky, 2003). These indices are based on sound biological theory; NDVI for instance relies on plant responses to water stress to influence the spectral reflectance of Red and Near Infrared wavelengths (Cohen and Goward, 2004).

Remote sensing cannot, as of yet, replace point field-data in terms of detail and diversity (Kerr and Ostrovsky, 2003), however, it will largely provide a broad-scale perspective which will help in the understanding and scaling of processes from local to regional to global scales. The impacts of climate change are best detected if data are collected over a large spatial scale (Ustin and Gamon, 2010). This presents us with a problem; most environmental studies are highly specialized and focus on individual plants, species or small plots (Kerr and Ostrovsky, 2003). It is imperative that a link be established that will eliminate the tedious collection of plant specific ecophysiological data and allow for stress detection in a multitude of landscapes. This has been done in a variety of vegetation types including forests (Breshears *et al.*, 2005), agricultural crops (Baret *et al.*, 2007) and grasslands (Seaquist *et al.*, 2003), however little work has been done on the Fynbos of the Western Cape.

Dyring (1973), as well as Kerr and Ostrovsky (2003), emphasize the importance of ground truth data in the validation of remote sensing results, without which "even highly sophisticated

remote sensing methods are useless". In this case, the plant specific ecophysiological data collected as part of a larger study (West, *unpublished*) will act as the ground truthing to validate the remote sensing results. I aim to determine whether or not remote sensing, through multispectral satellite and digital photography, is a feasible and accurate method for determining drought stress in Fynbos vegetation. I hypothesize that (1) water stress in fynbos is detectable with the use of a remote sensing index, namely NDVI and (2) that the remotely sensed trends will correlate with ground truth measures of water stress.

Methods

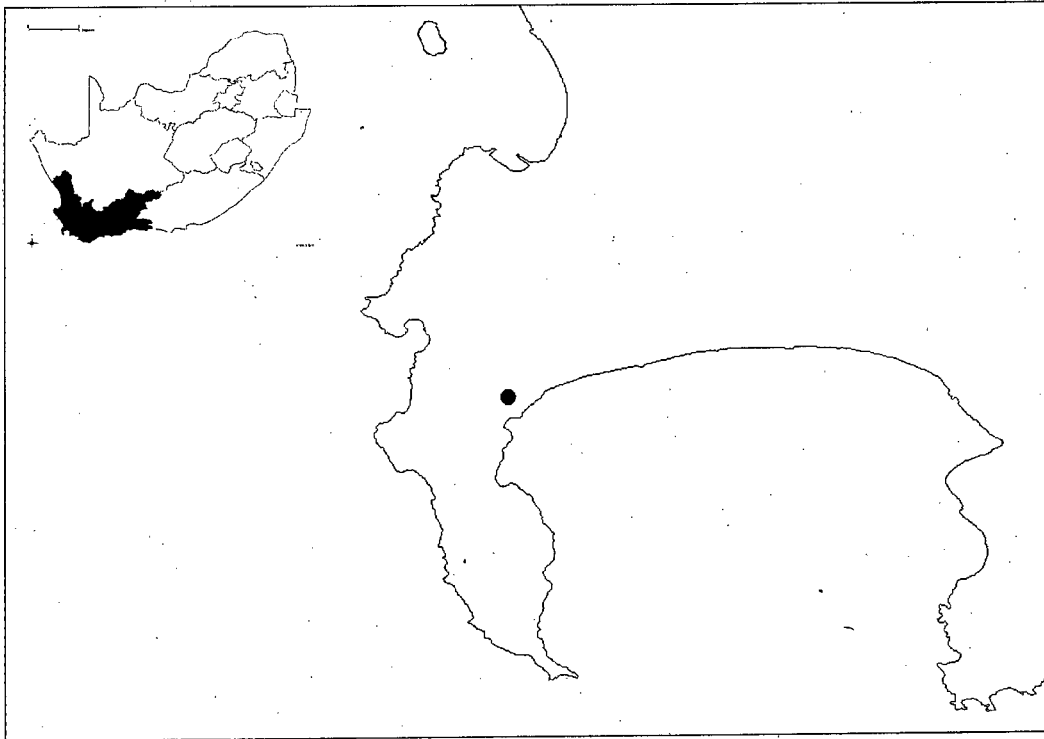


Figure 1: Location of both sites within the Table Mountain National Park at which the study was done. The two study sites occur within 1.2km of each other and so are represented with a single marker.

Study Site

Two study sites were selected within the Silvermine section of Table Mountain National Park, South Africa (Figure 1). The sites were chosen based on the maturity of the vegetation: a mature site (8 years post-fire) and a young site (2 years post-fire). The sites were located within 1.2 km of each other at a similar aspect and elevation (Mature site – 385[#]m ASL, Young site – 415[#]m ASL). Soils at both sites were white sand with a poorly developed organic horizon. Soil depth was uniformly greater than 1.5 meter^g at the young site but was more variable at the mature site, with fractured sandstone rock being encountered between 0.5 and 1.5 meter^g depth.

Mucina and Rutherford (2006) classify the vegetation at both sites as Mountain Sandstone Fynbos. Vegetation height was approximately 0.5^{#m} and 1.5 meter^g at the young and mature site

respectively. Species diversity at both sites was high as is characteristic of mountain fynbos stands. A plant survey recorded 37 and 68 species in 144 m² at the mature and young site respectively (West, *unpublished*). The dominant species at the mature and young sites are listed in Table 1.

Table 1: Dominant species found at the Mature and Young sites in the Silvermine section of the Table Mountain National Park.

	Mature Site	Young Site
Proteoid	<i>Leucadendron lauratum</i>	<i>L. lauratum</i> <i>Diastella divaricata</i>
Restioid	<i>Staberoha cernua</i>	<i>Hypodiscus aristatus</i> <i>Roella triflora</i>
Ericoid	<i>Erica subcapitata</i> <i>Erica ericoides</i>	<i>Erica pyxidiflora</i> <i>E. ericoides</i>

This project forms part of a larger field experiment where plots of fynbos were subjected to water stress to simulate prolonged drought (West, *unpublished*). The excerpts below (Experimental Design, Soil moisture profiles, Meteorological, Water Potential and Growth Measurements) provide a brief outline of the components of the larger study relevant to this thesis (West, *unpublished*).

Experimental design

Nine 4 x 4 meter experimental plots were selected at each site. Plots were selected so as to include sufficient individuals of the focus species for this study (Table 1). Focus species were chosen from the three classic functional types in the fynbos – proteoids, ericoids and restioids. Over each of the experimental plots, a rain exclusion structure was constructed. The rain exclusion structures were constructed from a steel framework with six overlapping, clear polycarbonate roof panels. The roof panels could be tilted flat or at a 30° angle. When the panels were flat, rain falling on the surface would run off into the gutter and be piped off site, resulting in 100% rain exclusion. When the panels were at 30°, rain falling on the panels would

run straight on to the plot, resulting in 0% rain exclusion while still casting the same shade as for the flat configuration. In this manner, the shading effect of the roofs was controlled for. The roofs of the treatment plots were tilted flat from November 2007 to May 2008 and again from November 2008 to May 2009. The roofs were positioned slightly above the height of the tallest vegetation at the site. The roofs were raised during measurement periods, permitting access to plants and instruments under them.

Soil moisture profiles

Soil moisture was measured every 10cm for 1m fortnightly using a Frequency Domain Reflectometry (FDR) soil water profile sensor (Diviner 2000, Sentek Sensor Technologies, Stepney, Australia). In addition to the Diviner profiles, a continuously logging FDR soil moisture profile (EnviroSMART SOLO, Sentek Sensor Technologies, Stepney, Australia) was established at each site. Data was logged every 30 minutes at depths of 0.1, 0.2, 0.4, 0.6, 1.0 m (Young site) and 0.1, 0.2, 0.4, 0.6, 0.7 m (Mature site).

Meteorological measurements

Rainfall was measured at both sites using tipping bucket rain gauges connected to HOBO data loggers (spec). Temperature and relative humidity were measured at the young site with an HMP-45C sensor connected to a CR10x data logger. Additional temperature and relative humidity measurements were made with Easylog sensors (EL-USB-2, Lascar Electronics).

Water potential measurements

Predawn water potential measurements (Ψ_{PD}) were made 2 hours before dawn using a Scholander Pressure Chamber (PMS Instruments, Corvallis, Oregon). Care was taken to select measurement times only when weather conditions were predicted to be consistent for several days and there was no rainfall expected. This was successfully achieved for all the measurement campaigns. All plants within a site were measured on the same day in order to eliminate the effects of variable weather. The healthiest, sunlight foliage on the north side of each plant was selected for the measurements.

Growth measurements

Monthly measurements of growth were made on 6 individuals per species, per treatment, per site. Monthly shoot growth (mm day^{-1}) was measured on 4 shoots per individual that were tagged with coloured wire. The total length of all shoots above this tag were measured and divided by the number of days since last measurement. Following this the tag was repositioned on another healthy shoot on the plant. In this manner, measurements were biased towards healthy parts of the plant and any reduction in growth represents the minimum for a given plant. For the Restionaceae (*S. cernua* and *H. aristatus*), from Dec 2007 to June 2008, total culm length was recorded on healthy mature culms. However, this data failed to capture the ability of the plant to generate new growth. Thus, in July 2008 we shifted to recording the presence of new culms (under 5cm long) and measuring the elongation of newly emerged culms > 5 cm long.

Plot Photography

Over the course of the study, six plot photography campaigns were completed at both sites (November 2007; March and September 2008; February, May and December 2009). The photographs were taken using twin Sigma SD-10 cameras; one to capture visible wavelength reflectance and the other to capture infrared wavelength reflectance. The infrared filter in the visible wavelength camera excluded infrared wavelengths while recording the red wavelength at approximately 620-750nm. Conversely, for the infrared wavelength camera, the infrared filter was removed and a B+W 82 093 IR filter was fitted (www.schneideroptics.com). This filter blocks the entire visible spectrum, therefore the wavelengths captured fall between 800 and 900nm, the near-infrared spectrum.

The photos were taken on clear sky days between 10 am and 3pm to reduce the amount of shadow in the plot. The plot roofs were removed to allow for photographs to be taken from above. A white card was placed adjacent to the plot and captured in the photo as a reference for complete visible wavelength reflection. The cameras were mounted on a boom and suspended approximately 7m above the centre of the plot. Both cameras were set to the highest resolution and the focal stop was set at f/7.1. The visible and infrared photos were

taken simultaneously at the highest possible shutter speed to reduce blur from camera shake. Where the shutter speed was below 1/200s, the focal stop was adjusted to decrease the exposure time.

Image Processing

There are a number of issues with digital photography as a platform for remote sensing. The photographic procedure allowed for variation in the angle at which photos were taken i.e. the cameras were not always perpendicular to the ground. The boom on which the cameras were suspended allowed for variation in the location of the cameras i.e. the images were not taken from directly above the centre of the plots. These changes cause distortion in the photographs which warrants corrections for these changes before they can be used for vegetation analysis. These 'corrections' can be done in the widely used remote sensing software ENVI.

The best visible image was selected for each plot and time period based on three selection criteria; firstly, the four corner targets on the rain exclusion structure were visible, secondly, the white card showed full reflectance for the Red, Green and Blue bands, and thirdly, the image was not blurred. The corresponding infrared image was checked for similarity; where shutter speed differed, the exposure was adjusted manually.

The image pairs were imported into ENVI remote sensing software for processing. The image pairs of each plot over all time periods were georeferenced using an arbitrary coordinate system based on distance measurements between the four corner targets on the rain exclusion structure. Next, the images from each plot for all time periods were aligned using image-to-image registration based on an RST Warp Parameter. The plots were generally flat with little variation in ground surface height. For this reason a simple warp parameter was chosen in favour of a more complex polynomial or Delaunay triangulation parameter which allow for multidimensional transformation. The RST (rotation, scaling and translation) parameter acts as a rigid body transformation minimising distortion and shearing of the images. The limited number of ground control points used to georeferenced the images restricted the availability of warp parameters.

A Bilinear Resampling method was chosen for resampling the warped images. This method performs a linear interpolation using four pixels from the original image which surround the approximate location of the pixel in the warped image to determine the new digital number. The Bilinear Resampling method was chosen in favour of the more popular Cubic Convolution method. The Cubic Convolution method performs a linear interpolation with sixteen pixels which effectively smoothes images and reduces the diversity in an image. This is undesirable in a high resolution image with sharp contrasts such as those between individual Restionaceae culms and the underlying soil.

The plot specific image pairs from each time period were layer stacked, using bilinear resampling, to produce a multiband image of chronologically stacked visible and infrared images. A 3 x 3 meter region of interest (ROI) was defined in the centre of each plot to account for and remove edge effects. The average digital number of the ROI of each plot at each time period was calculated in the visible and infrared image which provided an average Red and Infrared value respectively. These values were then used to calculate a plot specific NDVI for each time period using the following equation:

$$NDVI = \frac{Infrared - Red}{Infrared + Red}$$

Four focus species were identified in two control and three treatment plots from the mature fynbos site. A ROI was defined around the largest possible section of a plant which remained within the ROI in all time periods. A species specific NDVI was calculated following the same process as the plot specific NDVI above.

NDVI values from the Moderate Resolution Imaging Spectroradiometer (MODIS) aboard the Terra satellite were extracted for a 500 x 500 meter plot surrounding the rain exclusion structures at both the young and mature sites (data courtesy of Adam Wilson). The values were calculated as a 16 day average to reduce the effects of clouds. The NDVI was calculated using MODIS Bands 1 and 2 which record the wavelengths 620-670nm and 841-876nm respectively at a 250 meter resolution (Carroll *et al*, 2004).

Data Analysis

The data were analyzed using Statistica 9 and Microsoft Excel. The MODIS NDVI values were compared to their respective site meteorological measurements, soil moisture profiles and the combined absolute growth rate ($\text{mm}\cdot\text{day}^{-1}$) of all species at each site. The average growth rates of all the focus species within control plots were combined for a measure of absolute vegetation growth rate at a 4x4 meter plot scale. This was assumed to indicate the average absolute growth rate of the 500x500 meter plots observed by MODIS. A least-squares regression was used to fit a curve to the relationship between the MODIS NDVI values and monthly rainfall, average monthly temperatures, soil moisture profiles and the combined absolute growth rate of all species at each site.

The nature of the study did not allow for many statistical analyses, the following analyses are qualitative. The MODIS NDVI was compared to the average plot NDVI of the control plots. Both sets of NDVI values were normalized to display relative changes from the initial value. The absolute values of the plot specific NDVIs were not within the usual range and so the relative changes were of more use. The average control and treatment plot NDVIs were visually analysed for differences during drought periods.

The average control and treatment species specific normalized NDVIs for four species (*Leucadendron laureolum*, *Staberoha cernua*, *Erica subcapitata* and *Erica ericoides*) at the mature site were qualitatively compared to predawn water potential and relative growth rate ($\text{mm}\cdot\text{mm}^{-1}\cdot\text{day}^{-1}$) data. The absolute growth rate ($\text{mm}\cdot\text{day}^{-1}$) of *Leucadendron laureolum* was used due to a difference in growth patterns.

Results

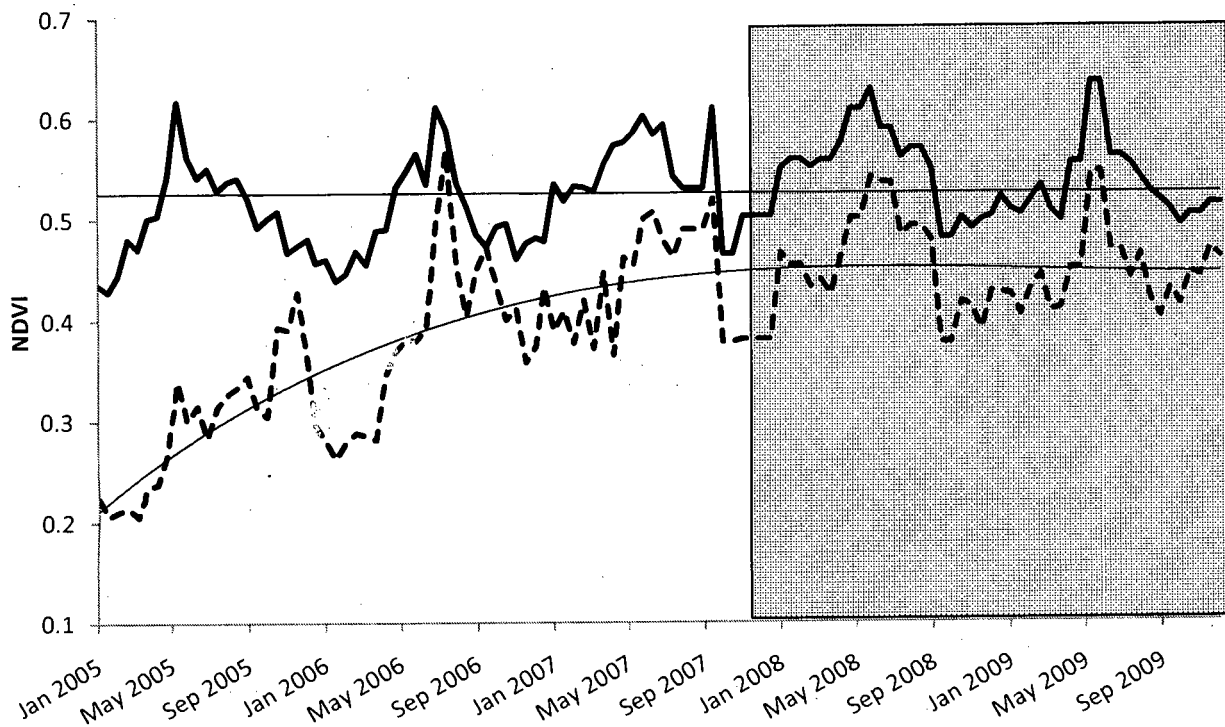


Figure 2: 16-Day composite MODIS NDVI values from two 2500m² plots covering the mature and young sites. The solid line represents the mature site and the dashed line represents the young site. The shaded rectangle indicates the time period of this study. The trendlines indicate a general trend expected from such data.

There is a general increasing trend in the MODIS NDVI of the young site from a post-burn environment in early 2005 until late 2007; thereafter the trend reaches a plateau similar to that of the mature site (Figure 2). All the while, both plots show a seasonally fluctuating NDVI which peaks annually approximately between May and September and then shows an abrupt decrease and trough during the summer months. Initially, this trend is distorted in the young site where the post-fire recovery may have influenced the pattern. The post-fire recovery of the young site is not as evident during the study period. Of the potential factors influencing the fluctuation (Figure 3), the MODIS NDVI fluctuations seem to be in synchrony with the rainfall and soil moisture measures. This is not true, however, for the absolute growth rates and average monthly temperatures (Figure 3a and 3b). These relationships can be analysed statistically and are done so in Figure 4.

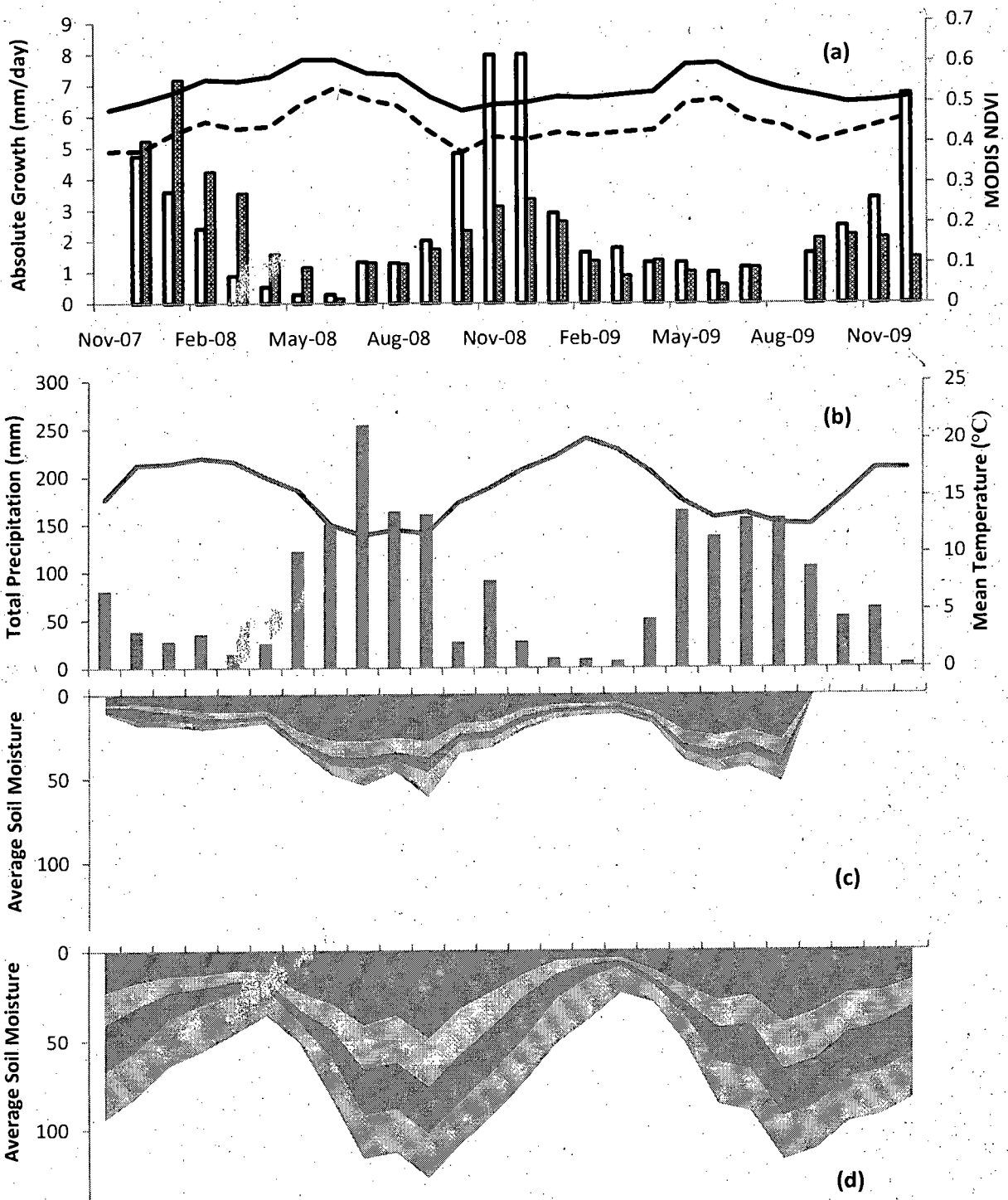


Figure 3: (a) MODIS NDVI values of the mature (solid line) and young (dashed line) sites plotted over the combined species absolute growth rate of the mature (solid bars) and young (empty bars) site. (b) Average monthly temperature (line) plotted over total monthly rainfall (bars) for both sites. (c) Average monthly soil moisture content at the mature site. Layers are stacked according to depth. The data gap from August 2008 onwards is due to instrument failure (d) Average monthly soil moisture content at the young site. Layers are stacked according to depth.

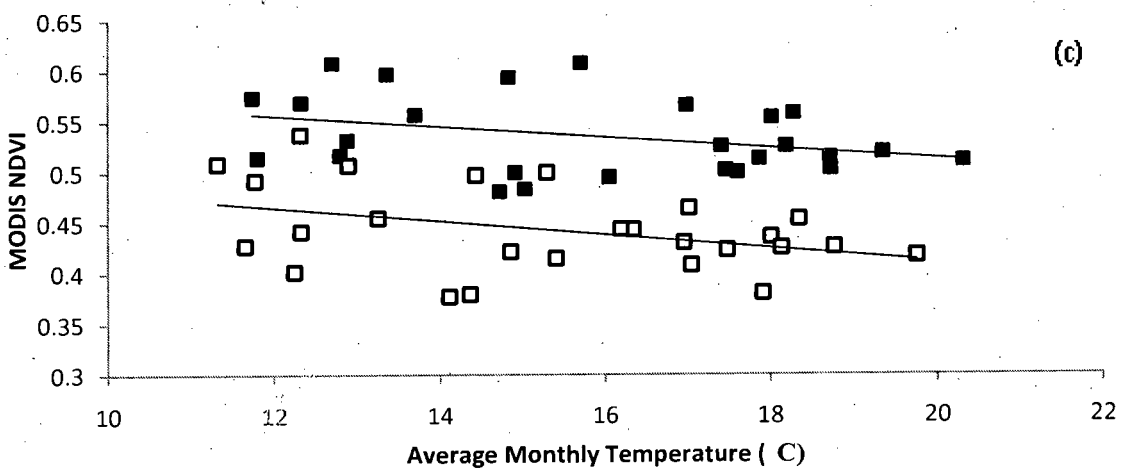
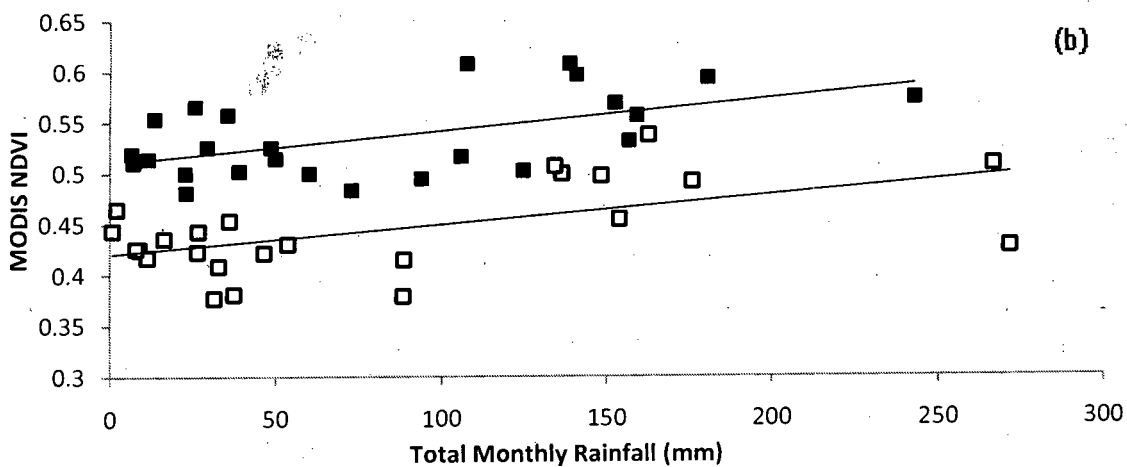
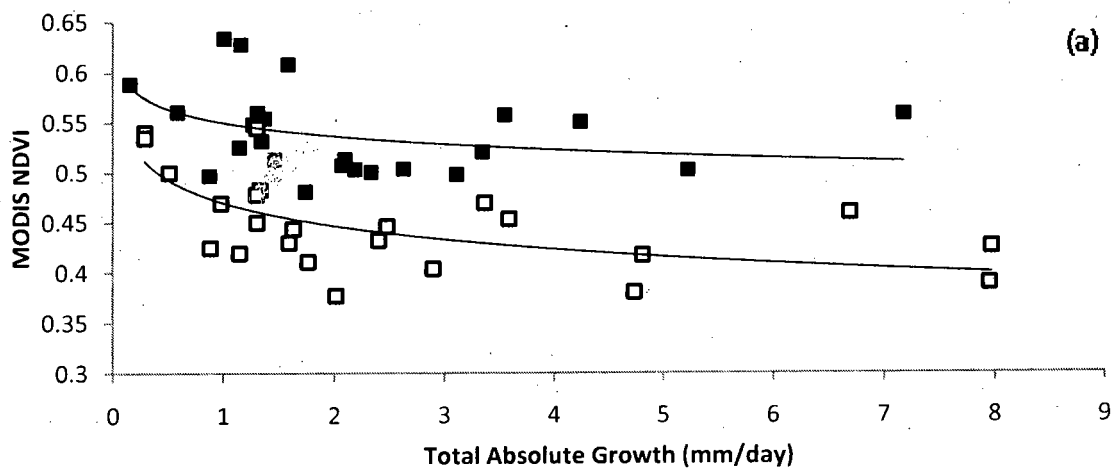


Figure 4: Relationship between MODIS NDVI and (a) the combined total absolute growth rate of all species, (b) the total monthly rainfall and (c) the average monthly temperature, in the mature (solid squares) and young (empty squares) sites. Statistics are listed in Appendix A and B.

NDVI has a weak logarithmic relationship with the combined absolute growth rate for the mature site (Figure 4a, Appendix A). The young site shows a slightly stronger relationship ($y = -0.034\ln(x) + 0.47$, $R^2 = 0.23$, $p < 0.05$, $n = 24$). The peak NDVI values are found during periods of lowest growth for both sites. These low growth periods occur, for the most part, during the winter periods (Figure 3a). In the both sites, the range of change in NDVI is less than 0.2 which does not indicate significant change in vegetation health. This is constant in Figure 4 and is to be expected from the vegetation. The rainfall values (Figure 3b) are typical of the region, therefore the vegetation are not under high levels of water stress. The two sites have analogous relationships with NDVI and rainfall (Appendix A). The NDVI and rainfall data show, as expected, a positive linear relationship. The rainfall values are clumped in the lower range with very few high rainfall months ($>200\text{mm}$) to improve the significance of this relationship. The weak relationship between temperature and NDVI shows a linear decrease in NDVI as temperatures increase. The relationship between NDVI and soil moisture profiles (Appendix B) differs considerably between the young and mature sites. For shallow soil depths (10 – 40 cm) at the mature site, an increase in soil moisture leads to increasing NDVI (Appendix B). This relationship disappears at greater depths. The young site shows very weak relationships between NDVI and soil moisture at all depths (Appendix B). The soil moisture values at the young site are considerably higher than the mature site year round (Figure 3c and 3d) and so slight fluctuations in the moisture content do not have as much of an effect in the young site in comparison to the mature site.

The relative changes and general patterns of the average normalized NDVI from the control plots correlates well with their respective MODIS NDVI (Figure 5). Therefore the pattern observed at a satellite level is observable at a plot scale. The lower temporal resolution of the plot NDVI means the peak seen in the MODIS data are not completely captured in the plot NDVIs. The mature site shows a similar fluctuation of NDVI despite this lower temporal resolution, the young site on the other hand, does not show the fluctuation. The young site does however show a similar increase in NDVI over the time period of the study.

When comparing the NDVI of the control and treatment plots (Figure 6) a similar trend is seen in the mature site. Both treatment and control fluctuate seasonally, however the treatment NDVI is consistently lower than the control (Figure 6a). The treatment plot of the young site shows a similar lack of seasonal fluctuation as the control (Figure 6b). The control and treatment plots do not, however, show any separation.

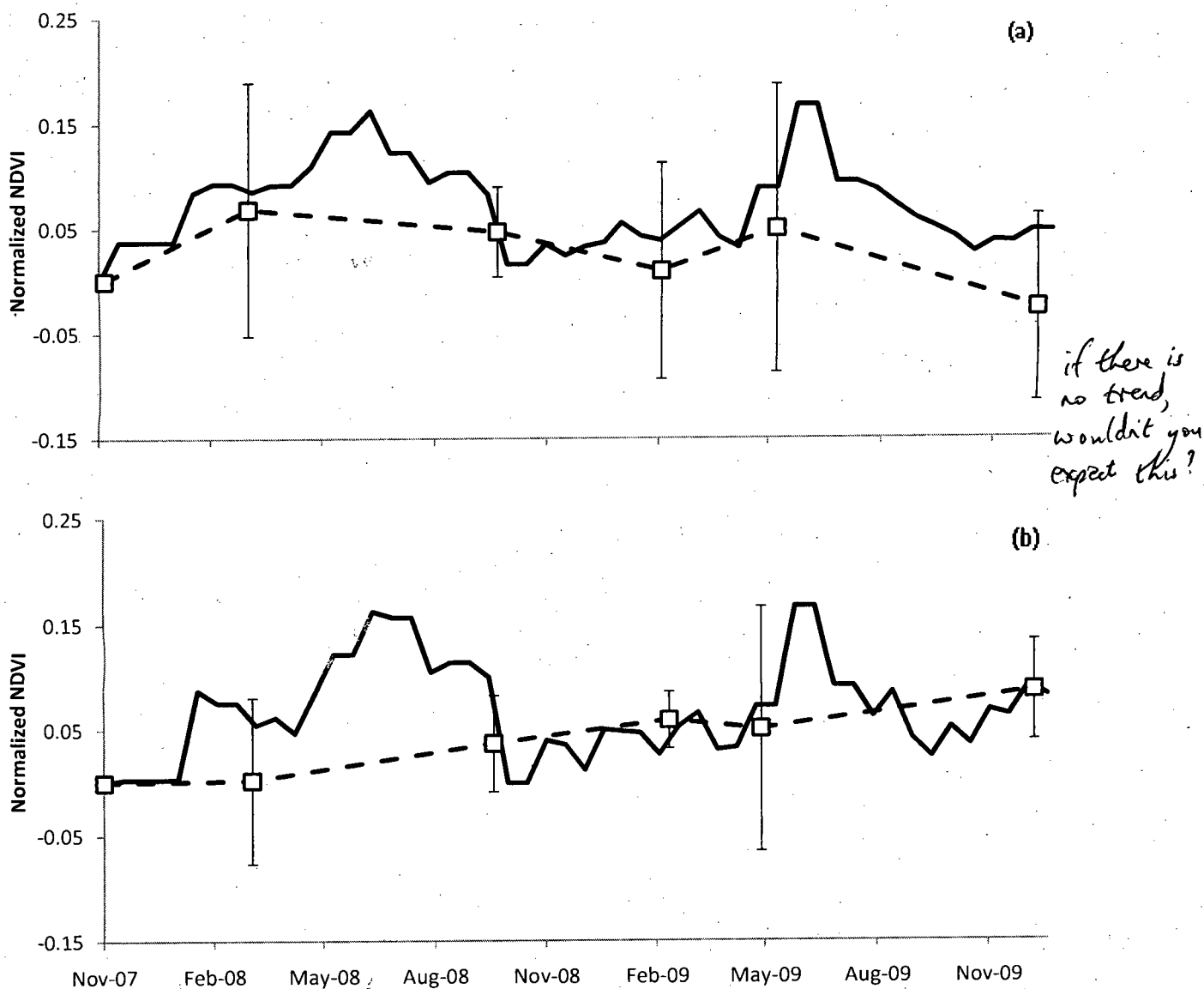


Figure 5: Similarity between the average control plot normalized NDVI (dashed line) and MODIS NDVI values (solid line) for (a) the mature site and (b) the young site. Error bars indicate the standard deviation.

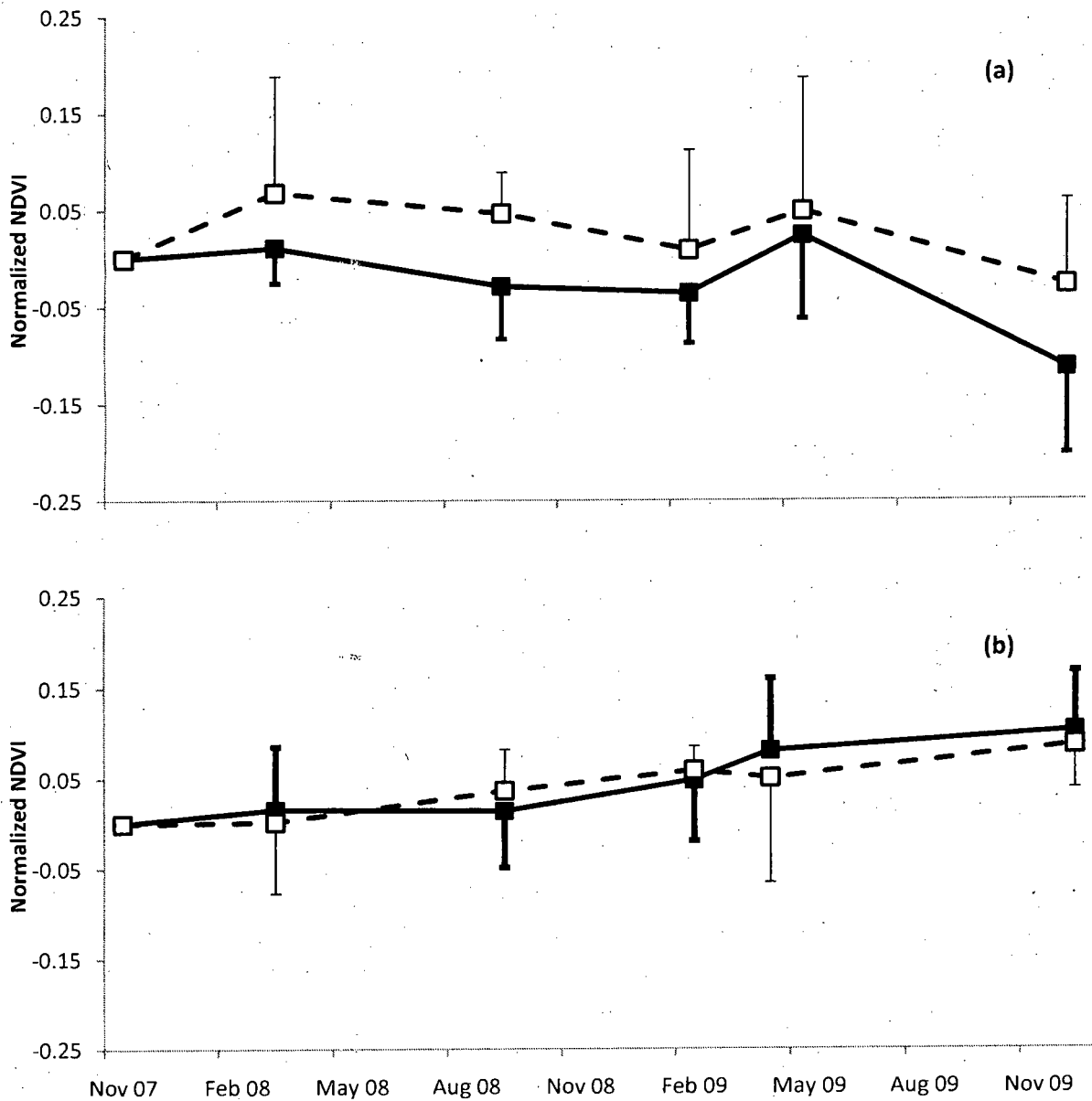


Figure 6: Difference between the average control (dashed line) and treatment (solid line) plot normalized NDVI values for (a) the mature site and (b) the young site. The thick and thin error bars indicate the standard deviation of the treatment and control plot respectively.

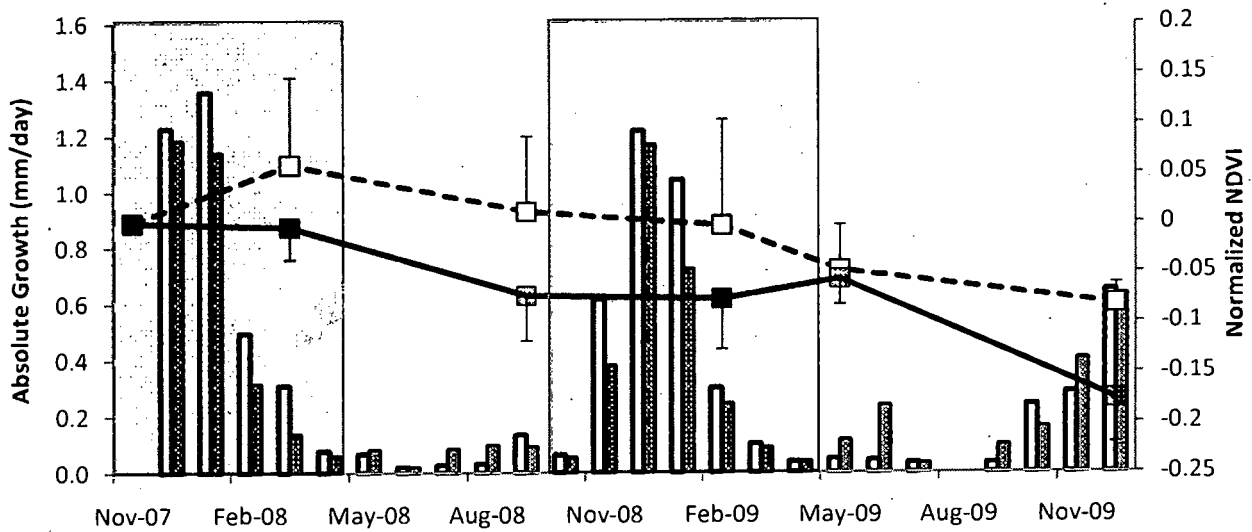


Figure 7: Average control (dashed line) and treatment (solid line) NDVI plotted over the control (empty bars) and treatment (solid bars) absolute growth rate of *Leucadendron laureolum*. Error bars indicate the standard deviation. Periods of 100% rain exclusion are indicated by the shaded rectangles. which?

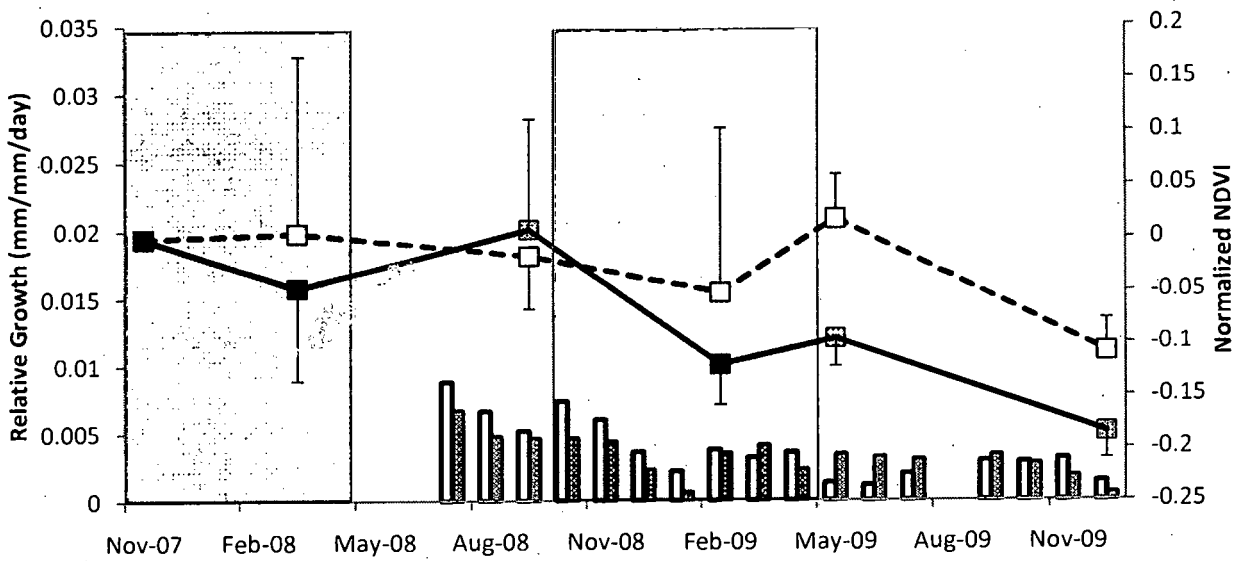


Figure 8: Average control (dashed line) and treatment (solid line) NDVI plotted over the control (empty bars) and treatment (solid bars) relative growth rate of *Staberoha cernua*. Error bars indicate the standard deviation. Periods of 100% rain exclusion are indicated by the shaded rectangles. Due to changes in the methods, there are no data prior to July 2008.

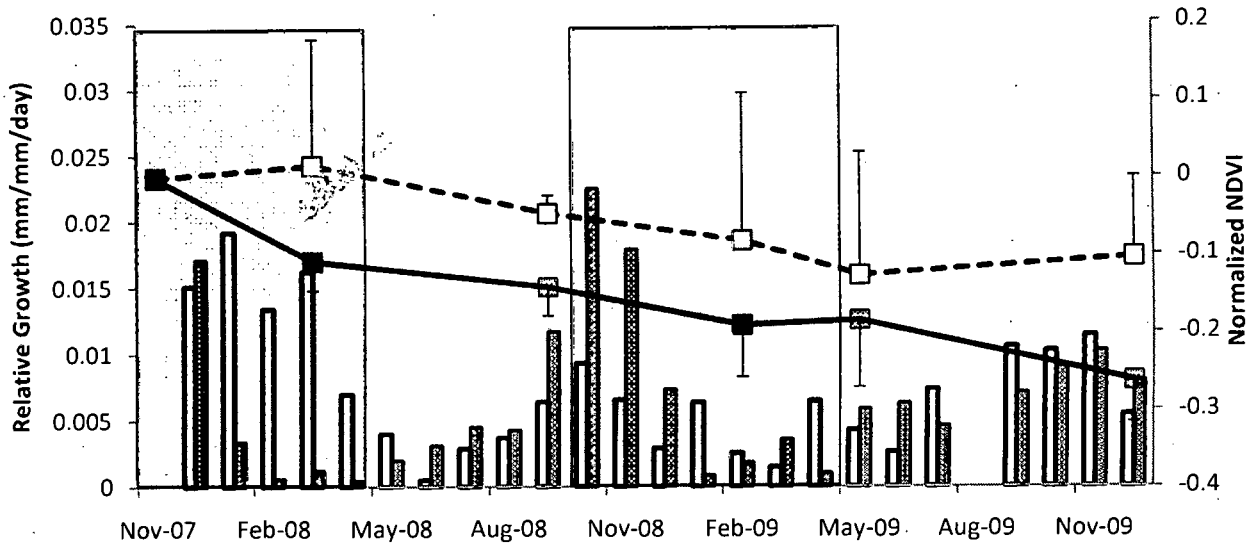


Figure 9: Average control (dashed line) and treatment (solid line) NDVI plotted over the control (empty bars) and treatment (solid bars) relative growth rate of *Erica subcapitata*. Error bars indicate standard deviation. Periods of 100% rain exclusion are indicated by the shaded rectangles.

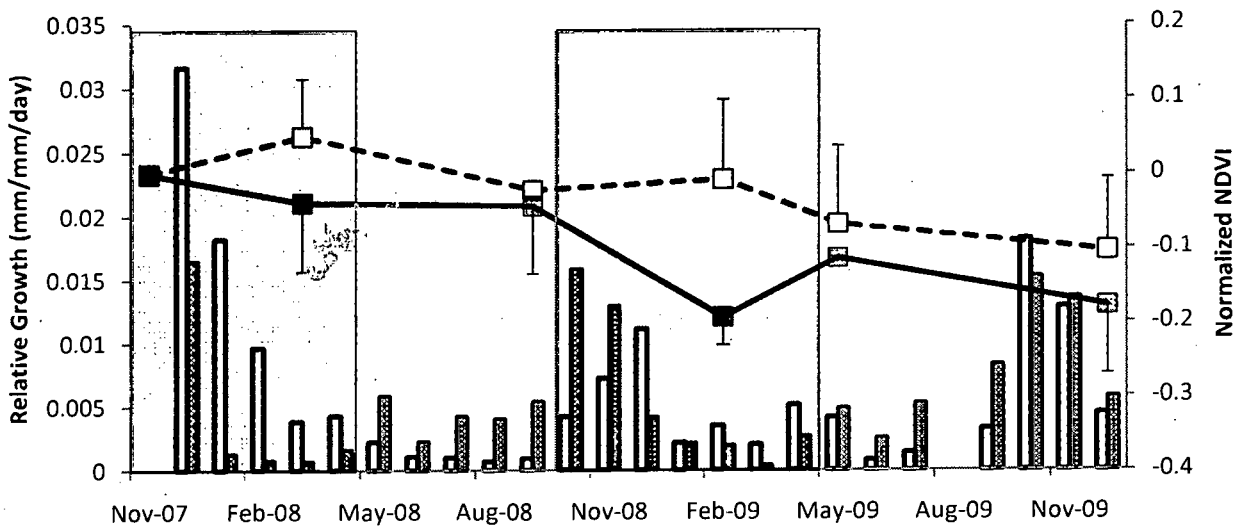


Figure 10: Average control (dashed line) and treatment (solid line) NDVI plotted over the control (empty bars) and treatment (solid bars) relative growth rate of *Erica ericoides*. Error bars indicate standard deviation. Periods of 100% rain exclusion are indicated by the shaded rectangles.

At a species level, *Leucadendron laeolium* shows differences in NDVI between the control and treatment species with the treatment NDVI remaining consistently lower (Figure 7). There is however, no trend in the changes of the treatment plot; the NDVI values do not decrease explicitly during the drought periods. The absolute growth rate is, mostly, higher in the control plot with the exception of May and June, 2009 (Figure 7). The NDVI values do not follow the same pattern as the growth rates; however the relative difference between the control and treatment plots may be explained by the growth rates. The smallest difference in NDVIs occurs during the growth rate anomaly in May/June 2009 (Figure 7).

Staberoha cernua does not show a consistent difference in NDVI values between the control and treatment plots (Figure 8). There is however a trend in the treatment plot which shows decreasing NDVI during periods of drought and subsequent recovery. The growth rate anomaly seen in May/June 2009 does not have the same effect as for the *Leucadendron laeolium*.

The NDVI of the treatment plots for both *Erica subcapitata* and *Erica ericoides* show a consistent decrease during the drought periods which is not evident in the control plots (Figure 9 and Figure 10). The extent to which this change is controlled by growth rate is uncertain. The decrease in growth rate of the treatment *Erica subcapitata* is reflected in the NDVI, however the increase in growth rate observed from May to November 2008 does not increase the NDVI (Figure 9). A similar pattern is observed from November 2007 to November 2008 for *Erica ericoides* (Figure 10). Due to the low temporal resolution of the plot photography, the NDVI is not captured during the period of highest growth rates.

Leucadendron laeolium and *Staberoha cernua* show very little change in predawn water potential for both the control and treatment plots over the period of the study (Figure 11). Despite this, there are changes in the NDVI of these species (Figure 11). The *Ericoides* in the treatment plots show large fluctuations in predawn water potential in response to drought; these fluctuations are not seen in the control species (Figure 11). The drought induced decrease in predawn water potential is accompanied by a decrease in NDVI for both *Erica subcapitata* and *Erica ericoides* for both drought periods. The subsequent recovery of predawn water potential does not show a standard response (Figure 11). The water potential measurements

were shoot specific where as the NDVI measures covered the majority of the plants. The different responses could be the result of plant die back which would influence the NDVI measure but not the water potential measurement.

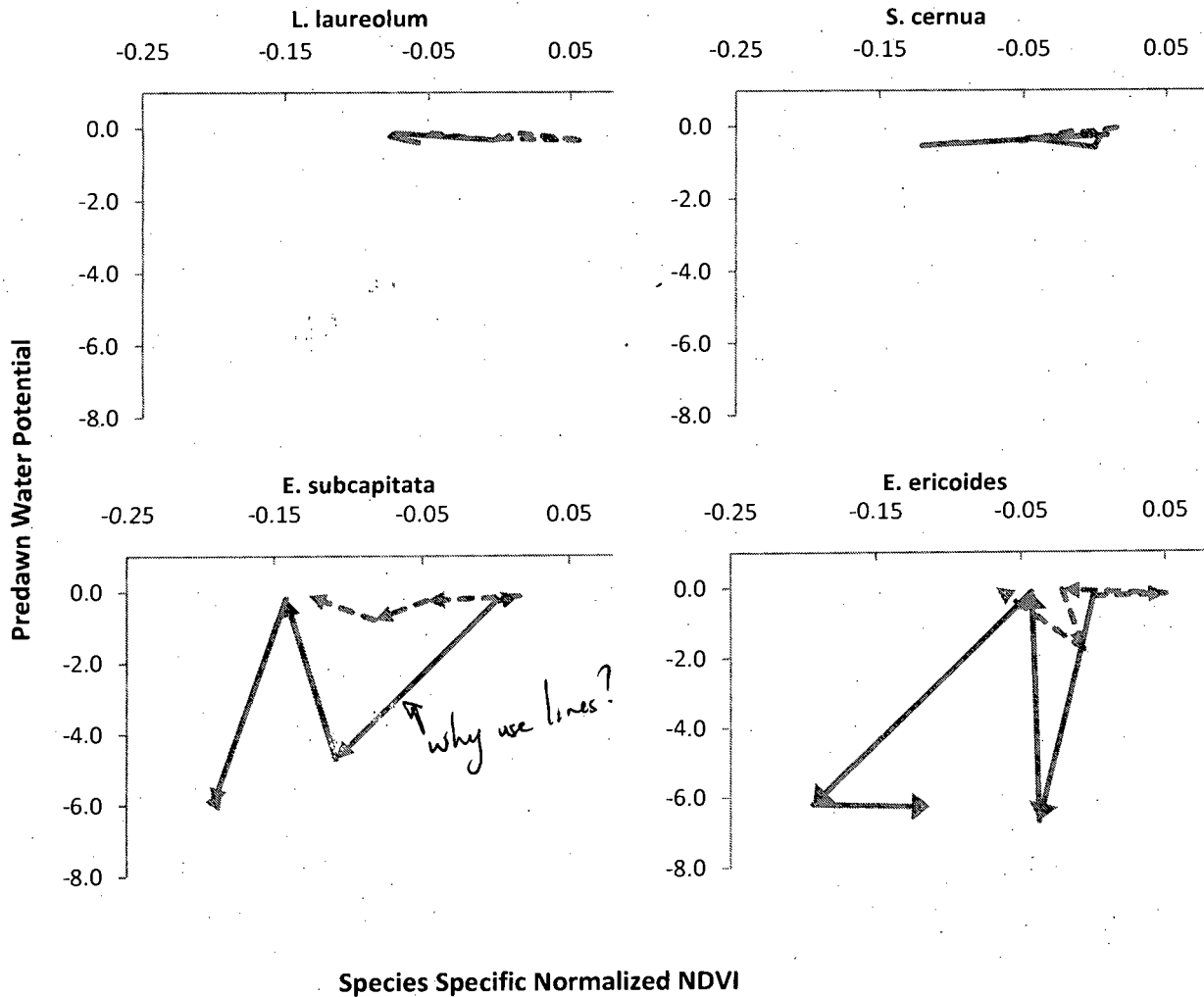


Figure 11: Relationship between Normalized NDVI and Predawn Water Potential for each species. See Table 1 for species names. Dashed line indicates control plots and the solid line indicates treatments plots. Arrows have been added to *Erica subcapitata* and *E. Ericoides* for clarification.

Discussion

MODIS Observations

At a landscape scale, NDVI values from MODIS appear to be a good indicator of vegetation cover. This is evident in the post-fire recovery of the young site (Figure 2) where the NDVI values recover and plateau, as is expected in a post-fire environment (Hope *et al*, 2010). However there is uncertainty regarding the seasonal fluctuations in NDVI, seen in both sites, which is not expected for evergreen vegetation. These fluctuations peak annually approximately between May and September and then show an abrupt decrease and trough during the summer months. Four potential drivers of this pattern were investigated, namely monthly precipitation, average monthly temperature, soil moisture content and vegetation growth rate.

The MODIS NDVI values are in synchrony, accounting for a slight time lag, with rainfall data (Figure 3 and 4b) and soil moisture profiles (Figure 3), essentially, plant health is highest during the wetter periods. This suggests NDVI is a reliable indicator of water stress in fynbos vegetation. However, the answer is not that simple; the asynchrony of rainfall and temperature, and hence NDVI, complicate this matter. Fynbos vegetation faces a unique set of challenges presented by the Mediterranean climate. During winter, when there is abundant moisture, plant growth is restricted by low temperatures (Oliveira and Penuelas, 2002). When the temperatures increase, growth rates increase (Figure 3) however the Mediterranean summer drought limits growth (Chaves *et al*. 2002).

The peaks of the fluctuations seen in Figure 2 and Figure 3 therefore do not correlate with the maximum growth rates. Theoretically, NDVI values increase as the amount of photosynthetically active surface area increases or the amount of photosynthetic activity increases (Ustin and Gamon, 2010). In fact the opposite is true (Figure 4a), the highest NDVI values correspond to the lower growth rates. The MODIS NDVI values correlate with the surface soil moisture values for the mature site (Appendix B). This correlation may be due to a more direct effect of soil moisture on NDVI than on the indirect effect it has on vegetation

through plant water stress (Jeyaseelan, 1999). This observation does not hold for the young site, perhaps due to greater vegetation cover.

MODIS NDVI is able to detect changes in vegetation cover and seasonal fluctuations which correlate to water availability. This does not, however, answer the question of whether or not remote sensing can be used to detect drought. This was investigated at two scales: a plot and species level scale.

Plot Level Observations

The plot photography NDVI of the control plots, for both the young and mature sites, nest well in the MODIS data, so I have assumed that the trends seen are not due to errors in photography, image processing ^{write out what these are} (etc) (Figure 5). The lower temporal resolution of the plot NDVI means the peak seen in the MODIS data are not completely captured in the plot NDVIs.

The effects of drought seen in the mature site are reassuring for the use of NDVI as an indicator of water stress. There is a clear and consistent difference in the control and treatment plots at the mature site where the treatment plot shows lower NDVI than the control (Figure 6). This pattern is not observed at the young site (Figure 4); this however can be attributed to the difficulty to stress the treatment plots due to a high water table (Figure 3). The general increase in NDVI of the young plot over the time period of the study can be attributed to increasing vegetation cover as post-fire recovery (Figure 2).

The variability in the plots, shown by the standard deviation error bars, highlights how diverse the plot responses were to water stress. This may be due to the species composition of the plots, for example some plots were centred over a large ^{l.c.} Proteoid (*Leucadendron laeolium*) which is less likely to experience water stress than an ^{l.c.} Ericoid (*Erica subcapitata*) due to differences in rooting depths (Jacobsen *et al*, 2007). Midgley *et al.* (2002) calls for greater focus [?] on species level responses to climate change as opposed to the popular biome level approach. The drought responses of species vary from the MODIS and plot NDVI responses; this can be seen in the NDVI values for the four selected species.

Species Level Observations

The focus species show individualistic responses to drought in NDVI, growth rates and predawn water potential values. As in the plot level NDVIs, there is variability within a species. This may be due to the low number of plants sampled, alternatively, individuals within a species might respond differently to water stress due to plant age, micro site conditions, and external disturbances.

Leucadendron laureolum and *Staberoha cernua* do not show significant differences between treatment and control species in predawn water potential during the drought periods (Figure 11). This may indicate that the changes in NDVI, seen in Figure 7 and Figure 8, are not in response to water stress. The *Leucadendron laureolum* chosen for analysis were all male and so it is possible that NDVI values were influenced by periods of flowering. The low temporal resolution of the photographs make assumptions difficult, however I speculate that growth rate has minor effect on the NDVI of *Leucadendron laureolum* as can be seen in May/June 2009 (Figure 7). *Staberoha cernua* shows a decrease in NDVI during drought periods, which as stated above, is not related to plant water stress or growth rates.

The two Ericoides, *Erica subcapitata* and *Erica ericoides*, show a large change in predawn water potential of the treatment species during the drought periods which indicates that the spectral response of these species may be indicative of plant water stress. Both species show a decrease in treatment NDVI during the drought periods which indicates that water stress may be detectable through remote sensing for these species. The water potential change during the first drought is accompanied by a decrease in NDVI; the subsequent recovery of water potential does not see an analogous recovery of plant NDVI. This could be due to a 'water potential fatigue', where the stress from the drought has reduced the plants ability to recover to its initial state, which may cause the eventual death of these plants (personal observation). The growth rate of these species potentially explains the differences between control and treatment NDVIs however higher temporal resolution is needed to test this.

Conclusion

Collecting data over the large spatial scales necessary to develop accurate climate change predictions is an arduous task and in many instances is not possible (Ustin and Gamon, 2003; Midgley *et al.*, 2002). Remote sensing provides a possible tool with which these data can be collected at a remarkably high resolution, both temporally and spatially (Turner *et al.*, 2004; Kerr and Ostrovsky, 2003). The remote sensing of water stress in Fynbos vegetation is complicated by the effects of the Mediterranean climate. This is evident in the MODIS data where the NDVI values relate to meteorological measures rather than vegetation growth. At a plot level, drought stress is detectable in the treatment plots however the high resolution of the imagery and the diversity of species compositions led to variable responses. At a species level, remote sensing can be used to detect water stress in *Erica subcapitata* and *Erica ericoides*. The spectral responses of *Leucadendron lauroolum* and *Staberoha cernua* are most likely not in response to water stress. There are obviously a range of responses to climate change type drought which is evident in the differences in species spectral responses.

Pearson and Dawson (2003) warn of the implications of such a finding which makes "predictions from bioclimate envelope models erroneous." However as Midgley *et al.*, (2002) highlight, a detailed understanding of species responses will improve the accuracy of climate change predictions. Remote sensing of water stress in ^{l.c.} Fynbos is a promising field which deserves attention due to the diversity of species and functional types.

Appendix A

Table 2. Least Squares Regression statistics of the relationship between MODIS NDVI and rainfall, temperature and absolute growth rate for the mature and young sites.

	Regression Equation		R ²		n		P		df	
	Mature Site	Young Site	Mature Site	Young Site	Mature Site	Young Site	Mature Site	Young Site	Mature Site	Young Site
Rainfall	$y = 0.0003x + 0.51$	$y = 0.0003x + 0.4207$	0.27	0.27	26	24	0.0038	0.0056	1.24	1.22
Temperature	$y = -0.0053x + 0.6179$	$y = -0.0067x + 0.5451$	0.090	0.12	26	26	0.075	0.044	1.24	1.24
Growth	$y = -0.02\ln(x) + 0.5501$	$y = -0.034\ln(x) + 0.47$	0.05	0.23	24	24	0.30	0.018	1.22	1.22

Appendix B

Table 3. Least Squares Regression statistics of the relationship between MODIS NDVI and soil moisture at different depths for the mature and young sites.

Soil Moisture Depth (cm)	Regression Equation		R ²		n		P		df	
	Mature Site	Young Site	Mature Site	Young Site	Mature Site	Young Site	Mature Site	Young Site	Mature Site	Young Site
10	$y = 0.0052x + 0.4989$	$y = 0.002x + 0.4207$	0.28	0.040	22	26	0.0065	0.17	1.20	1.24
20	$y = 0.0051x + 0.502$	$y = 0.0015x + 0.4267$	0.30	0.005	22	26	0.0053	0.30	1.20	1.24
40	$y = 0.0067x + 0.5037$	$y = -0.0001x + 0.4451$	0.23	0.001	22	26	0.15	0.90	1.20	1.24
60	$y = 0.0004x + 0.5387$	$y = -0.0009x + 0.4588$	0.001	0.001	22	26	0.93	0.40	1.20	1.24
100 (70 for the Mature Site)	$y = 0.0014x + 0.5334$	$y = -0.0023x + 0.4954$	0.001	0.032	22	26	0.63	0.19	1.20	1.24
Total	$y = 0.0011x + 0.5065$	$y = -1E-05x + 0.4439$	0.15	0.001	22	26	0.041	0.97	1.20	1.24

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Inconsistent formatting

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