

Journal of  
**Applied Remote Sensing**

**Satellite normalized difference  
vegetation index data used in managing  
Australian plague locusts**

Edward D. Deveson

# Satellite normalized difference vegetation index data used in managing Australian plague locusts

Edward D. Deveson<sup>a,b</sup>

<sup>a</sup>Australian Plague Locust Commission, Australian Government Department of Agriculture, Fisheries and Forestry, GPO Box 858, Canberra, ACT 2601, Australia

[Ted.deveson@daff.gov.au](mailto:Ted.deveson@daff.gov.au)

<sup>b</sup>Australian National University, Fenner School of Environment and Society, College of Medicine, Biology and Environment, Canberra, ACT 0200, Australia

**Abstract.** The Australian Plague Locust Commission (APLC) has a mandated role in monitoring, forecasting, and managing populations of key locust species across four Australian states. Satellite normalized difference vegetation index (NDVI) imagery is used to monitor vegetation condition in locust habitat and is integrated with mapping software to support forecasting and operations within the strategic framework of APLC activities. The usefulness of NDVI data for monitoring locust habitats is tested using historical control and survey records for the Australian plague locust, *Chortoicetes terminifera* (Walker). In arid habitat areas, control of high-density nymphal populations was consistently associated with high and increased relative NDVI during summer and autumn, providing important information for locating possible infestations. Regression models of NDVI data and regional biogeographic factors were fitted to summer survey records of *C. terminifera* presence and abundance. Models identified increased vegetation greenness, measured by a one-month positive change in NDVI, as having a significant positive relationship with nymph distributions, while NDVI was significant in adult distributions. Seasonal rainfall regions and a binary habitat stratification were significant explanatory factors in all models. © The Authors. Published by SPIE under a Creative Commons Attribution 3.0 Unported License. Distribution or reproduction of this work in whole or in part requires full attribution of the original publication, including its DOI. [DOI: [10.1117/1.JRS.7.075096](https://doi.org/10.1117/1.JRS.7.075096)]

**Keywords:** National Oceanic and Atmospheric Administration normalized difference vegetation index; remote sensing; locusts; Australian plague locust; *Chortoicetes terminifera*; generalized linear models.

Paper 13099SS received Mar. 31, 2013; revised manuscript received May 24, 2013; accepted for publication May 30, 2013; published online Jul. 10, 2013.

## 1 Introduction

The Australian Plague Locust Commission (APLC) is responsible for the monitoring of locust populations across 2 million km<sup>2</sup>, covering the inland areas of four states in eastern Australia, and for strategic management of those that could pose an interstate migration threat to agriculture. The management of the three locust species under the APLC charter<sup>1</sup>—the Australian plague locust, *Chortoicetes terminifera* (Walker), the spur-throated locust, *Austracris guttulosa* (Walker), and the migratory locust, *Locusta migratoria* (L.)—relies on strategic population intervention through the detection and the aerial insecticide treatment of nymphal bands or adult swarms early in breeding sequences that potentially lead to plagues.<sup>2</sup>

*C. terminifera* is the most common and widespread locust pest of agriculture in the eastern states of Australia and regional infestations are frequent. Major infestations or plagues, affecting numerous regions across several states, occur irregularly and usually last 1 or 2 years.<sup>3</sup> Plagues result from several consecutive generations of successful breeding and rapid population increase, often linked by long-distance migrations to different regions. Impacts on agricultural crops usually occur in autumn or spring, coinciding with winter grain crop establishment and maturation, and can result in significant economic losses.<sup>4,5</sup> Swarm outbreaks of *A. guttulosa* and *L. migratoria* are less common and agricultural impacts have been largely restricted to Queensland and northern New South Wales (NSW).

Managing locust populations within APLC member states relies on ground surveillance monitoring of population distribution and age structures across a large area of inland Queensland, NSW, South Australia, and Victoria. This provides continuous field data for producing forecasts of likely population developments, based upon the species phenology, behavior and measurable environmental correlates of population outcomes. It also gives direct identification of high-density populations that pose an immediate or potential subsequent threat to interstate agriculture, therefore warranting control intervention.

The principal known environmental factor associated with *C. terminifera* and *A. guttulosa* population increase is the distribution, amount and sequence of rainfall in areas of locust habitat,<sup>6-8</sup> which can produce soil and vegetation conditions that favor egg maturation, oviposition and nymphal survival.<sup>9,10</sup> Monitoring of inland rainfall and the direct measurement of vegetation response through satellite normalized difference vegetation index (NDVI) images are therefore logical primary environmental data requirements for identifying the location and likely timing of possible breeding events. For these species, long-distance migrations also play an important role in population dynamics, often producing major redistributions over wide areas.<sup>11-14</sup> Remote sensing data from insect monitoring radar<sup>15-17</sup> observations are used to analyze migrations and, along with atmospheric circulation model data, are used to simulate migration displacements.

This paper deals with the use of satellite remote sensing applied to the monitoring and management of *C. terminifera*. Section 2 provides background biological information and a review of global and APLC uses of satellite remote sensing (RS) data, principally NDVI images, as a means of improving the detection of areas where high-density locust breeding is likely to have occurred. Section 3 presents research addressing the value of NDVI image data, in particular a relative index of NDVI for identifying potential locations of higher density *C. terminifera* activity leading to infestations. The relationship of locust distribution with NDVI, both for the probability of occurrence and as an indicator of habitat conditions suitable for high density population development, is tested using historical data on locust control and surveillance.

## 2 Australian Locusts and Satellite Remote Sensing

### 2.1 Australian Plague Locust

The APLC has been responsible for managing *C. terminifera* since its inception in 1975, whereas *L. migratoria* and *A. guttulosa* were included under its charter in 1987.<sup>18</sup> The monotypic *C. terminifera* is endemic and widely distributed on the Australian mainland. Together with the related genus *Austroicetes*, it forms a distinct phylogenetic clade within the acridid subfamily, Oedipodinae.<sup>19</sup> *C. terminifera* is a “model” locust in exhibiting behavioral phase polyphenism at both nymph and adult stages,<sup>20</sup> which, because of its consequences for abundance and behavior, has contributed to its status as a serious agricultural pest.

*C. terminifera* population dynamics are irruptive and are understood to be driven by habitat productivity during periods of rapid population increase. This is primarily determined by rainfall which, in inland environments with highly variable rainfall, produces a short-lived flush of ground vegetation, although this pattern varies with season, region, vegetation composition, and rainfall amount. The primary habitat of *C. terminifera* is open tussock grassland and grassy open woodland; vegetation formations that cover ~1 million km<sup>2</sup> in eastern Australia and a similar area in the western half of the country. Most of the habitat is climatically arid and semi-arid although it extends into natural and Euro-anthropogenic grasslands in the southern and eastern parts of the species range.

*C. terminifera* generally completes three generations annually in areas north of 32°S and two in the southern part of the distribution area. Infestations can develop from sparse initial populations in a single year, following two to three generations of high recruitment.<sup>21</sup> A feature of *C. terminifera* ecology is frequent nocturnal, high altitude, wind-assisted adult migrations with overnight displacements of several hundred kilometers.<sup>11-14,22</sup> Interseasonal or interannual prediction of population outbreak location is therefore complicated by rapid population fluxes

resulting from migrations. It also displays a dormancy syndrome of facultative egg and nymph diapause during winter and egg quiescence in dry soils.<sup>23,24</sup> Development rate of nondormant life stages is a function of temperature although nymphs and adults behaviorally regulate body temperature by basking or seeking shade. Lifecycle turnover during summer can be as short as 60 days and nymphal stages can be completed in <30 days.<sup>25</sup>

Plague cycles have historically been associated with widespread summer rainfall in inland regions and, therefore, often with La Niña phases of the El Niño Southern Oscillation cycle of surface water temperature variation in the tropical Pacific Ocean.<sup>26</sup> The most recent plague in 2010 was established by successful breeding over two generations, first in NSW then in western Queensland, following heavy inland rainfall during November 2009 to February 2010. The development of an intense La Niña by March 2010, producing further widespread rainfall, enhanced the development of a third, extensive nymphal generation and resulted in southward autumn swarm migrations into agricultural areas of NSW, South Australia, and Victoria. The development of plagues often involves an intergenerational exchange migration between the summer and the winter rainfall zones.<sup>27,28</sup>

## 2.2 Satellite Remote Sensing and Locusts

The regular synoptic views of land surface conditions from Earth observation satellites (EOS) led to the early adoption of Landsat imagery for landscape and surficial geology mapping.<sup>29</sup> The development of multispectral indices for discrimination of the photosynthetic components of land cover enabled the monitoring of vegetation greenness,<sup>30</sup> and the use of NDVI imagery from the U.S. National Oceanic and Atmospheric Administration (NOAA) satellites' advanced very high resolution radiometers (AVHRR)<sup>31</sup> gave considerable advantages in terms of coverage, frequency, and processing overheads over selected imagery from higher resolution instruments. The use of AVHRR and Landsat imagery for long-term monitoring of vegetation condition<sup>32</sup> and the enhancement of information content by combining RS data with geographic information systems (GIS) was piloted in Australia by the Commonwealth Scientific and Industrial Research Organisation.<sup>33,34</sup> The continuous global coverage and archives of satellite NDVI data, along with worldwide research collaboration, have today given rise to numerous regional and global vegetation monitoring projects.<sup>35,36,37</sup>

The possibility of using satellite imagery to detect locust breeding sites was first proposed for *Schistocerca gregaria* (Forskål) in Africa in the early 1970s during the initial evaluation of the NASA ERTS-1 satellite.<sup>38</sup> Most of the satellite RS applications for locust management have involved detecting vegetation changes in locust habitat areas. For arid zone locust species, such as *S. gregaria*, vegetation response to rainfall in known habitats is used as an indicator of potential gregarization.<sup>39</sup> For species in other continents with primary habitats in river floodplains and endogenous lake basins, such as *L. migratoria* and *Nomadacris septemfasciata* (Serville), the detection of areas exposed as floodwaters retreat and detailed discrimination of subsequent mosaics of reeds and grasses have been used to identify habitats, stratify surveys, and estimate the risk of population increase.<sup>40</sup> In a few cases, the detection of vegetation damage by dense locusts has been attempted.<sup>41</sup>

## 2.3 History of APLC Use of EOS Image Data

The association of *C. terminifera* population increases with rainfall and green vegetation was the basis for establishing regular habitat monitoring using NDVI imagery. Significant rainfall events in arid and semiarid areas, particularly during summer, often synchronize the timing and location of gregarious adult egg laying. This produces large gregarious nymphal populations, the survival of which is related to the persistence of green vegetation produced in response to the initial and any further rainfall.<sup>42,43</sup>

The need to stratify inland Australian landscapes to identify those that provide suitable locust habitat was investigated at the APLC in 1980, using Landsat false-color photographic image products.<sup>44</sup> APLC research in the 1980s focused on monitoring the arid zone for rainfall and vegetation response.<sup>45,46</sup> In the late 1980s, the APLC installed a satellite receiver and processing system based on the regular low resolution transmissions from weather and

environmental monitoring satellites.<sup>47,48</sup> Processed images were used to estimate rainfall from cloud-top temperatures and directly monitor vegetation condition.<sup>49</sup> Even in the early 1990s, there was a lag of several weeks in obtaining rainfall records and the reporting network in the Australian arid zone remains sparse today. Image analysis was also investigated for discriminating possible oviposition sites using Landsat multispectral data.<sup>50,51</sup> During the 1990s, the increased availability of a range of weather data (daily rainfall and temperature observations) and vegetation monitoring products (AVHRR NDVI) through the internet superseded the information content of the APLC satellite system.

In 1998, regular, calibrated NOAA AVHRR imagery, processed at Australian ground stations, was made available to the APLC by the Australian Department of Environment and Heritage.<sup>52</sup> Images were composited on a 14-day series, with cloud masking based on large NDVI differences between successive images. NDVI data were delivered as a rescaled index designed to discriminate variation in ground layer vegetation, with current pixel NDVI value above the previous dry season minimum (taken to represent the woody evergreen component typical of Australian vegetation), calculated as a percentage of its historic range.<sup>53</sup> From 2002 to 2009, APLC obtained AVHRR NDVI imagery directly from the Western Australian Department of Land Administration (DOLA), making data available within 2 weeks at the end of the compositing period. A simplified relative index of NDVI values was adopted, recalculating current pixel value as a percentage of its historical range (r-NDVI), allowing direct comparison between all years.

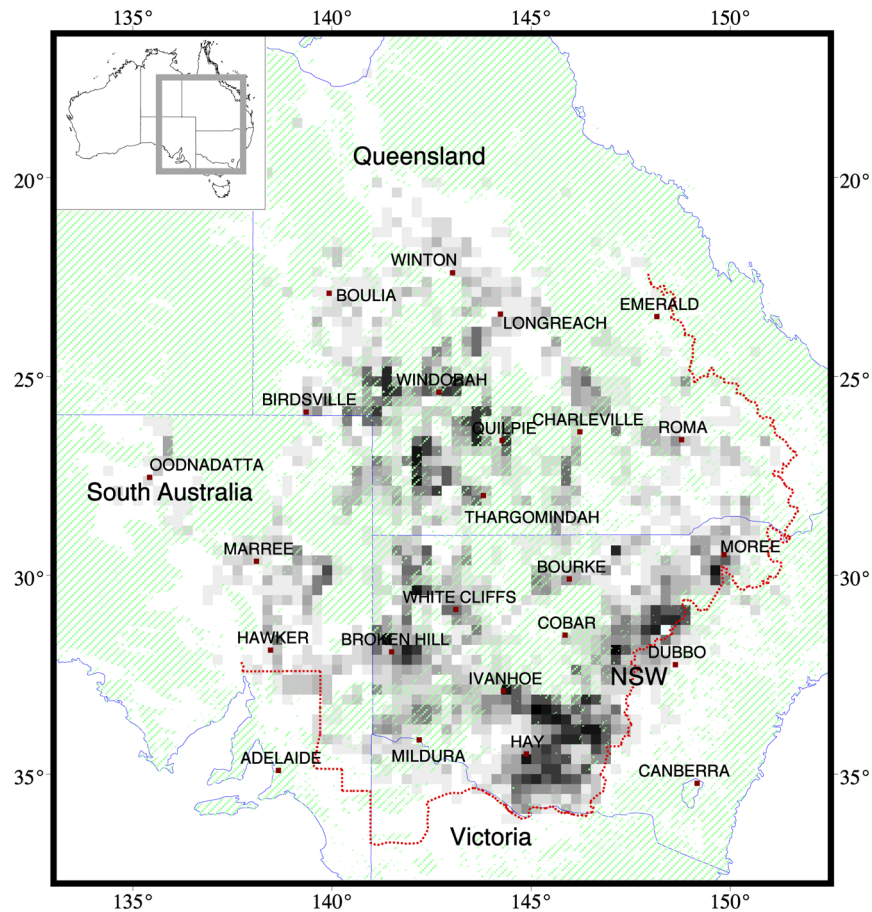
#### **2.4 Current APLC Application of Satellite NDVI Data**

Image composite mosaics of 14-day Moderate Resolution Imaging Spectroradiometer (MODIS) NDVI data from NASA Terra/Aqua satellites are supplied by Landgate (Western Australian Land Information Authority) as scaled 8-bit files of positive integer pixel values. The NDVI is sensitive to actively photosynthesizing vegetation amount, but small variations in values in low vegetation cover environments (where range in NDVI is small and historical maxima area <0.35) are often difficult to detect. The relative index of NDVI (r-NDVI) highlights vegetation greenness and small changes between consecutive images in the sparsely vegetated areas where many locust outbreaks occur. Initial studies showed that the relative NDVI reliably detects ground vegetation response to rainfall events over a range of arid and semiarid locust habitats and in locations where rainfall data are often unavailable.<sup>54,55</sup> It is used operationally as a visual tool in conjunction with a map of locust habitats to assess vegetation condition in locust habitat areas. Image files are converted to ArcInfo grids (ESRI, USA) and displayed with color ramping from dry to green (1 to 100% of r-NDVI) as a raster background to locust distribution and habitat information. Change images between sequential 14-day periods are generated after significant rainfall.

A preliminary map of potential locust habitats is used to stratify inland landscapes that often support successful breeding from those where locusts are rarely found. It is used to aid the interpretation of NDVI imagery by masking largely unsuitable habitats. NDVI values in these vegetation types (e.g., forest, scrub) usually exceed those in arid grassland formations. The habitat classification was based on an association of locust occurrence with tussock grasslands on clay, loam, calcareous, and stone-mantled desert soils. It was generated using a combination of available continental spatial datasets for soil type and tree cover.<sup>56</sup> The historical frequency of infestations over 30 years conforms to the general pattern of the habitat map (Fig. 1).

### **3 Testing NDVI for Australian Plague Locust Management**

A correlation between vegetation in green condition and the occurrence of *C. terminifera* has not previously been demonstrated using NDVI. Although there is a rapid growth response of grasses to significant rainfall (>40 mm) during summer, the peak NDVI response in ground vegetation occurs 3 to 5 weeks later.<sup>55,56</sup> Given that high-density egg laying often occurs within a week of rainfall,<sup>55</sup> and the subsequent time to mid-instar stages during summer of 4 to 5 weeks, peak



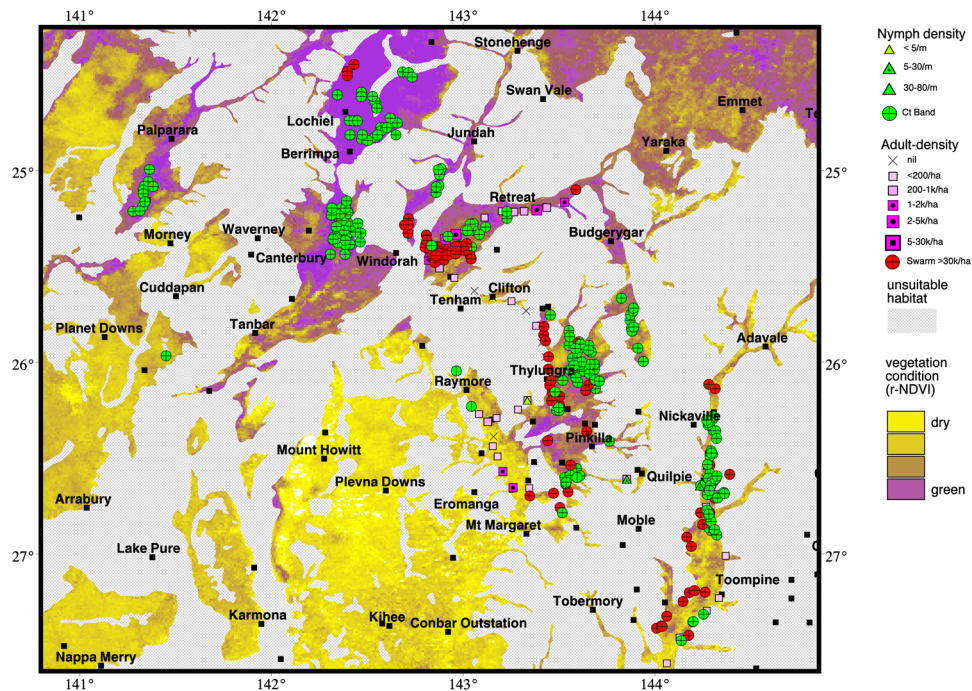
**Fig. 1** Seasonal frequency of *Chortoicetes terminifera* infestation in eastern Australia, using 1986 to 2007 locust survey and control data, covering 65 season-generations gridded to  $0.25 \times 0.25$  deg. Density threshold  $>30 \text{ m}^2$  for nymphs,  $>5000/\text{ha}$  for adults. Frequency graded from white = 0 to black = 15 seasons. Areas hatched green are unsuitable habitat. APLC operations area boundary is shown in red.

NDVI response is likely to coincide with band development. Nymphal bands rarely move more than 2 km during the entire duration of formation and their location is taken to be in habitat suitable for oviposition (APLC unpublished data). Adult swarms can move through habitat in any condition, although control of swarms has often been carried out in areas of nymphal infestations following fledging.

The indication from observations (e.g., Fig. 2) that high-density nymphs often occur in habitat areas during the time that vegetation response is detectable with NDVI imagery was tested using historical *C. terminifera* control and surveillance data. Control data were analyzed by comparison of monthly NDVI trends using grouping factors of seasonal rainfall, bioregion, and landuse. Locust records from survey presented response variables for regression against NDVI variates and grouping factors. Complementary models dealing with presence or absence and density data separately were used to account for zero inflation in the survey data.

### 3.1 Data Sources

Control data for nymph (bands) and adult (swarm) are observations that represent only locations of gregarious very high locust densities because insects are dense enough to be seen from the air. The APLC aerial control of bands generally occurs during instar stages 3 to 5. Surveillance data are obtained by APLC staff on regular vehicle surveys, using GPS-connected palmtop computers. Data are records of density classes for each lifestage based on counts from 250-m foot transects adjacent to roads, at intervals of  $\sim 10$  km. Surveys regularly sample most known habitat areas and include sampling in landscapes generally unsuitable for locust breeding.



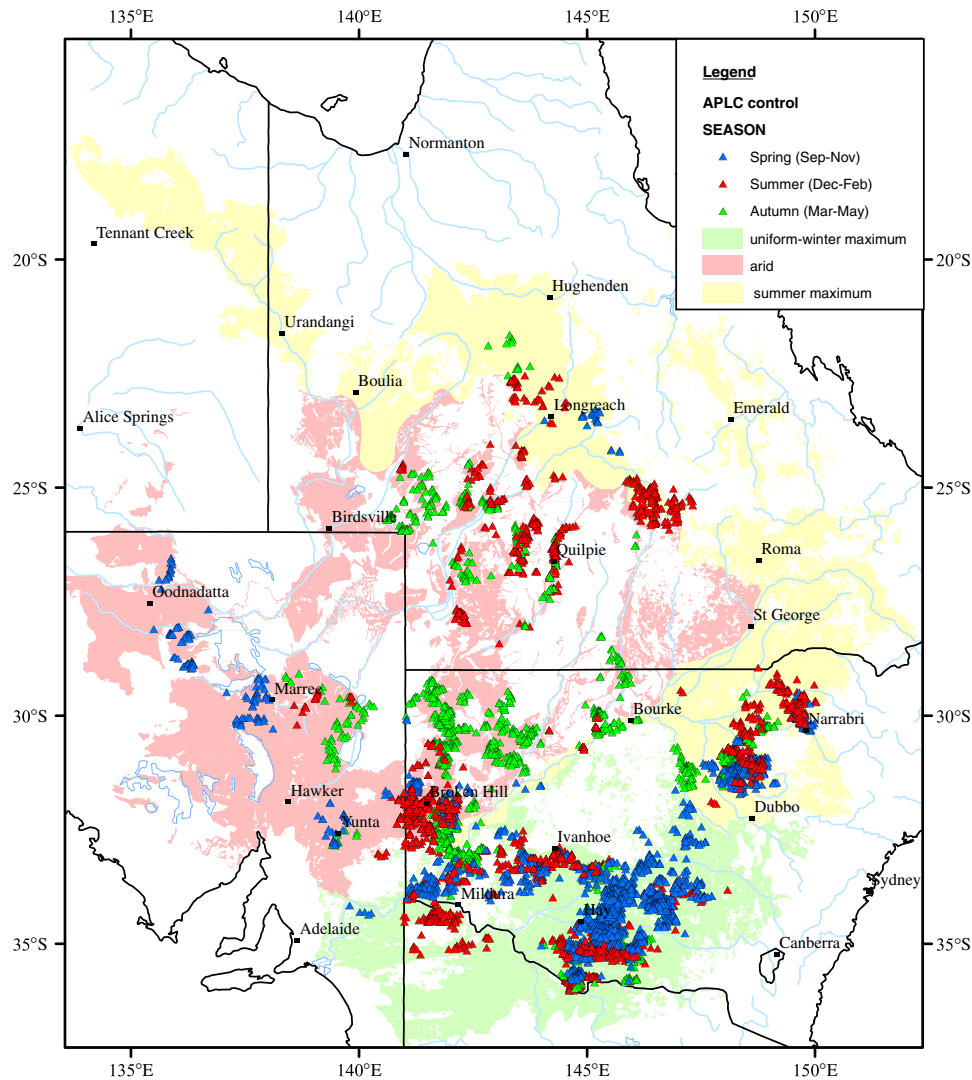
**Fig. 2** Example of NDVI image for February 2004 displayed as relative NDVI (r-NDVI), with non-habitat areas masked gray, showing APLC survey and control data for February 2004.

Monthly maximum NDVI and r-NDVI ArcInfo grids at ~1 km resolution were generated from an 18-year sequence (April 1991 to May 2009) of 14-day composite NOAA AVHRR imagery.<sup>52</sup> The data generation methods are given in the [Appendix](#). NDVI and r-NDVI values for the month of control and two previous months, along with values for a bioregional classification<sup>57,58</sup> and gridded land use data,<sup>59</sup> were calculated for point locations of all locust control events for this period. A one-month change in r-NDVI was calculated by subtracting previous month values from those in the month of observation. Control locations within bioregions were grouped by seasonal rainfall characteristics into arid (<350 mm annual total), uniform or winter dominant, and summer rainfall zones (Fig. 3). Land use data were used to separate areas of dry land cropping or irrigation from grazing areas.

The NDVI variates and bioregional values, with the addition of binary values from the APLC habitat map, were calculated for survey point data from summer months (December to February) for the period 1998 to 2009. Records for *C. terminifera* and nil counts were extracted (24,329 of 35,553 total records) for analysis. Samples from areas classed as nonhabitat were 29.2% of the total. The relationship among locust distribution, NDVI, and landscape factors was analyzed by generalized linear modeling (GLM) for locust presence or absence and ordinal regression for density categories. Nymph and adult data were analyzed separately. Data preparation and model methodology are detailed in the [Appendix](#). Presence or absence was modeled using a Bernoulli distribution with a logit link function, and ordinal linear regression, with estimated dispersion parameters, was applied to density data.

## 4 Results

For nymph and adult control, comparative data on r-NDVI monthly maxima, and change from the previous month are presented for each month by region (Table 1). Figure 4 shows overall seasonal variation in 3-month trends and Figs. 5–7 present relevant graphical comparisons of r-NDVI and NDVI discrimination of 1-month changes by the region for nymph and adult control. The trends in the two NDVI data types are the same, as r-NDVI is derived from NDVI, but large differences occur in their range for different regions. Comparison of r-NDVI values for



**Fig. 3** Map of APLC *Chortoicetes terminifera* control locations (October 1991 to April 2009) by season, showing seasonal rainfall regions. White areas represent habitats mostly unsuitable for locust breeding.

control in areas classed as having different land use is shown in Table 2. Results for maximal regression models of presence or absence of locusts from survey data are given in Table 3 and results for density categories are given in Table 4.

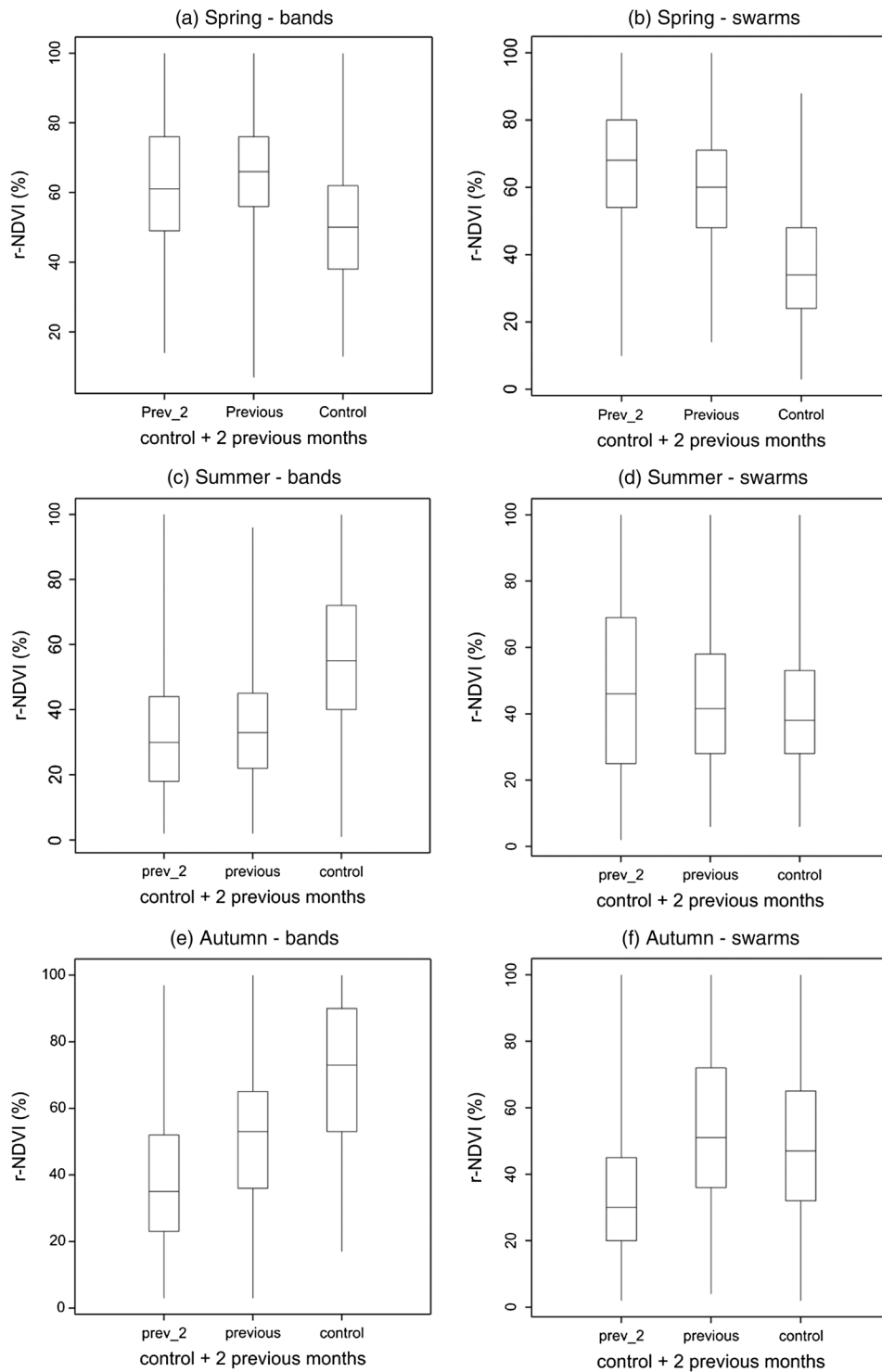
Seasonal and regional variations in the NDVI trends for control result from both the generational phenology and predominant locations of high-density populations. In the arid and summer rainfall regions, nymph control during summer and autumn regularly occurred in areas with high and significantly increased monthly  $r$ -NDVI values from the previous month. Swarm control generally occurred when NDVI was declining, but there was a positive association in the arid region during summer months (Figs. 5 and 6).

Control events during spring generally took place where NDVI values had declined, consistent with the predominance of control during September to November in the southern temperate region [Fig. 4(a) and 4(b)]. NDVI trend was reversed in summer, when both nymph and adult control during each month (December to February) in the arid and summer rainfall regions occurred following increases in NDVI (Figs. 5 and 6). December presents a transitional response pattern in those regions (Fig. 5) with increased NDVI at second generation nymph control locations. For swarms, there was an increase in NDVI in the arid region and a decrease in the summer rainfall region, where most swarms were fledged from spring nymphs in northern NSW.



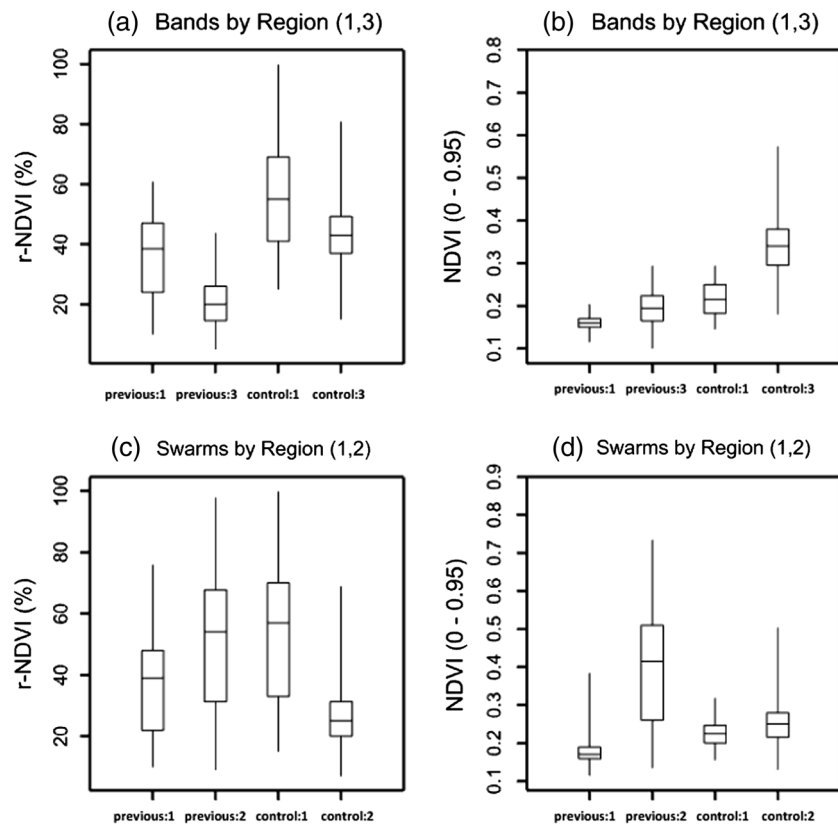
**Table 1** Relative NDVI (r-NDVI) values at APLC nymph and adult control locations (October 1991 to April 2009) by rainfall region in each month. Mean and standard error are shown for monthly values at time of control events and change from month previous to control. Significance levels of change for angular transformed values (paired t-test \* $p < 0.001$ , \*\* $p < 0.05$ ). Missing values indicate insufficient numbers for testing.

Month	r-NDVI	Rainfall regions								
		Arid (1)			Uniform/winter (2)			Summer (3)		
		Nymph	Adult	Nymph	Adult	Nymph	Adult	Nymph	Adult	
October	Mean	55.16 ± 1.14	45.61 ± 4.30	59.58 ± 0.55	—	42.86 ± 1.28	—	51.52 ± 1.73		
	Change	6.35 ± 1.14*	-2.33 ± 1.27	-8.49 ± 0.57*	—	23.37 ± 0.99*	—	-19.59 ± 2.24*		
November	Mean	36.28 ± 0.51	43.82 ± 1.14	41.31 ± 0.56	35.25 ± 0.67	—	25.04 ± 0.69			
	Change	-20.5 ± 1.94*	-13.04 ± 0.92*	-27.80 ± 0.49*	-25.25 ± 0.68*	—	-30.38 ± 1.04**			
December	Mean	56.75 ± 1.92	55.34 ± 2.27	45.17 ± 3.24	26.47 ± 0.64	43.45 ± 1.67	19.25 ± 1.36			
	Change	20.39 ± 1.54*	19.57 ± 1.71*	9.00 ± 6.53	-24.26 ± 1.24*	22.92 ± 2.25*	-16.07 ± 5.27*			
January	Mean	68.32 ± 0.85	62.12 ± 2.08	38.64 ± 1.11	41.75 ± 3.91	48.07 ± 0.99	44.50 ± 2.34			
	Change	27.08 ± 0.66*	5.84 ± 2.34**	9.99 ± 0.92*	3.37 ± 4.29	17.98 ± 1.25*	16.72 ± 1.90*			
February	Mean	64.41 ± 2.68	51.02 ± 1.37	—	35.63 ± 0.67	18.07 ± 3.38	40.91 ± 0.94			
	Change	44.24 ± 3.37*	6.02 ± 1.21*	—	3.90 ± 0.78*	0.93 ± 2.45	-6.94 ± 1.12*			
March	Mean	77.27 ± 1.18	55.98 ± 0.92	73.87 ± 1.53	28.44 ± 0.88	51.58 ± 1.18	33.39 ± 2.50*			
	Change	22.56 ± 1.04*	-10.22 ± 0.90*	22.2 ± 1.16*	-6.49 ± 0.58*	10.05 ± 1.84*	15.22 ± 2.12*			
April	Mean	87.13 ± 1.75	60.76 ± 1.67	64.91 ± 2.02	68.13 ± 6.17	48.00 ± 2.57	28.02 ± 1.40			
	Change	35.66 ± 2.97*	3.67 ± 1.72**	-2.00 ± 1.32	19.36 ± 6.52*	-14.57 ± 2.35	-18.91 ± 1.81*			



**Fig. 4** Seasonal trends in r-NDVI for nymph (band) and adult (swarm) control (1991 to 2009), showing median, interquartile range, and data range (maximum monthly r-NDVI) at control and 2 previous months (previous, prev\_2). Seasons—(a, b) spring (September to November), (c, d) summer (December to February) and (e, f) autumn (March to May).

The pattern of significant increases to high r-NDVI levels for nymph control in the arid region continued during autumn months (Fig. 7). For bands controlled during March and April, r-NDVI mean values were 77.27% and 87.13%, representing increases of 22% and 35% over the previous month (Table 1). In the uniform-winter rainfall region during March, band control showed a significant increase to 73.87% of r-NDVI, an exception to the variation in other months.



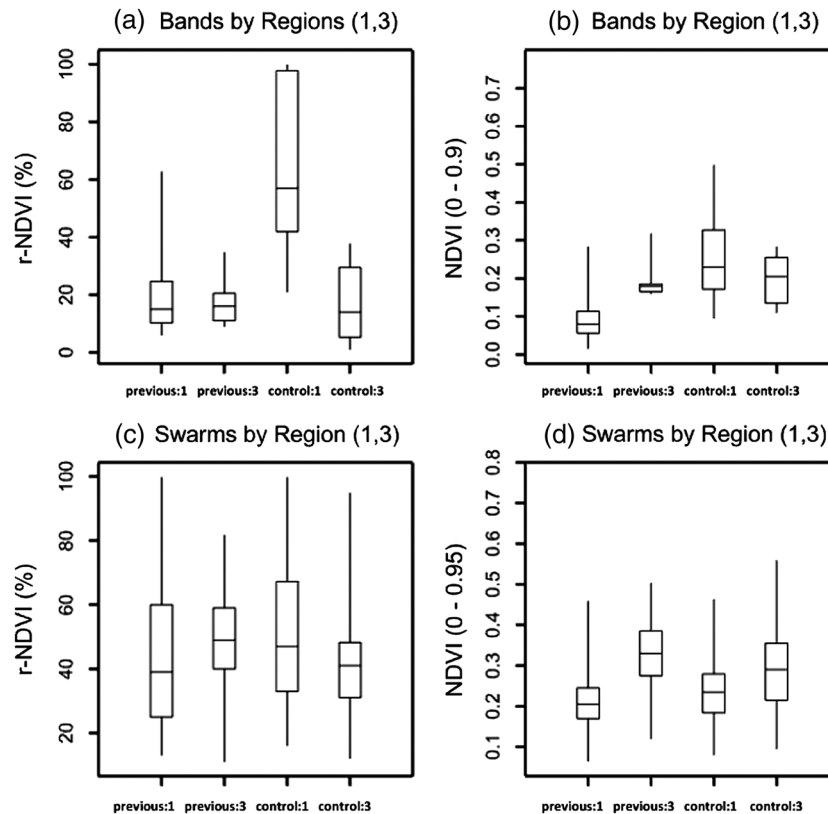
**Fig. 5** Comparison of r-NDVI and NDVI values for December control and previous month (1991–2008). Nymph (band) control (a, b) by region (1-arid, 3-summer rainfall) and adult (swarm) control (c, d) by region (1, 2-uniform-winter maximum). Plots show median, interquartile range, and data range for maximum monthly r-NDVI (a, c) and NDVI (b, d).

Nymphs at this time often represent a third generation, the initiation and survival of which are linked to green conditions produced by unseasonal heavy rainfall.

Results from modeling survey data show that a 1-month change in r-NDVI had a significant positive relationship both with the presence of nymphs and with nymph density. The order of mean deviance in significant fitted terms for both nymph models was a 1-month change in r-NDVI (r-DIFF in Tables 3 and 4), region, habitat and r-NDVI, with all terms significant at the  $p < 0.001$  level. The negative regression coefficient for r-NDVI ( $-0.004$ ) in both nymph models is an order of magnitude smaller than the effect of the change variate (r-DIFF). In contrast, the full fitted models for adult presence or absence and density showed a reversal in the order of significant terms, with r-NDVI coefficient remaining significant at the  $p < 0.001$  level, but r-DIFF not significant (presence-absence  $p = 0.038$ , density  $p = 0.845$ ).

In the full models of presence or absence, habitat stratification was a significant explanatory term ( $p < 0.001$ ). The negative coefficients for the factor of non-habitat in all models, relative to habitat as a reference level, indicate the importance of habitat in *C. terminifera* distributions. Mean predictions for factors show that nymphs are detected far more frequently in mapped habitat ( $0.066 \pm 0.002$  for habitat and  $0.020 \pm 0.002$  for non-habitat) and this pattern was maintained in all regions. For adults, the predictions for the factor habitat were much closer ( $0.477 \pm 0.004$  for habitat and  $0.366 \pm 0.007$  for non-habitat). Accumulated deviances for ordinal regression of nymph density categories (estimated dispersion 2.17) reduced the significance of habitat to 0.051 (Table 3) suggesting that, despite 90.3% of bands occurring within mapped habitat, the factor did not discriminate between density levels.

An alternative ordinal regression for nymph density, fitting only habitat and r-NDVI produced a positive coefficient ( $0.029 \pm 0.004$ ,  $p < 0.001$ ), close to that for r-DIFF in the full fitted model, suggesting that the two correlated NDVI variables separately yield significant regressions. Comparison of 1-month change values of r-NDVI with NDVI for nymph data showed



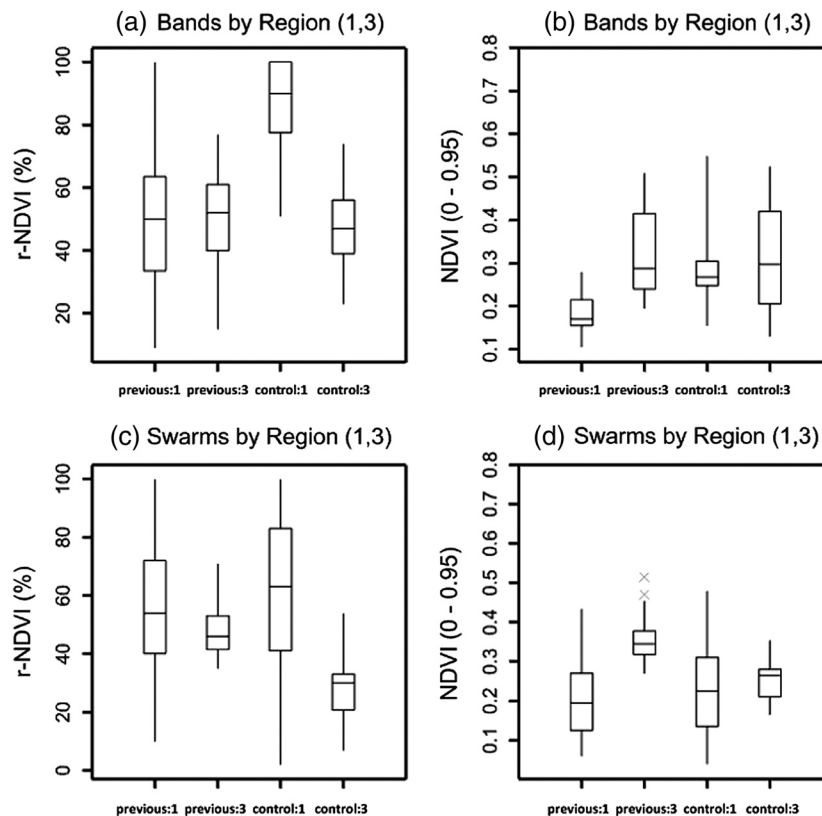
**Fig. 6** Comparison of r-NDVI and NDVI values for February control and previous month (1992–2009). Nymph (band) control (a, b) and adult (swarm) control (c, d) by region (1-arid,3-summer rainfall). Plots show median, interquartile range, and data range for maximum monthly r-NDVI (a,c) and NDVI (b, d).

higher mean deviance for r-NDVI, both for single-term models with these variates (presence or absence—r-NDVI 423.81, NDVI 168.59; density—r-NDVI 201.57, NDVI 128.03) and full-fitted models (all significant at the  $p < 0.001$  level).

## 5 Discussion

The consistent association of control during spring with declining NDVI occurred because most control was in southern, winter-dominant rainfall areas, and nymphs arise from oviposition during the previous autumn. Nymphal development therefore usually takes place during the senescence of ephemeral pasture vegetation following winter–spring rainfall. Most control of swarms during spring occurs after the fledging of nymphs in the same regions and is therefore associated with further declines in NDVI.

Regional variation in the pattern of r-NDVI associated with control, for nymphs in particular, results from different seasonal rainfall patterns and the dependence in arid areas on irregular significant rainfall to initiate breeding sequences. Given the very high rainfall variability characteristic of arid areas, ground vegetation often remains dry for periods of several months before storms produce brief growth responses and associated population increases. For nymph control in the arid region during the months December to April, mean r-NDVI values were high (56.75% to 87.13%), with significant increases over the previous month of 20% to 44% (Table 1). In contrast, mean r-NDVI in locust habitat during summer from survey data was  $36.45 \pm 0.02$ . Band control occurred at 100% of r-NDVI in numerous locations in each of these months. The 2-month lag changes in r-NDVI only show a sustained increase during autumn months (Fig. 4). This increase in all regions 2 months prior to control of both nymphs and adults probably reflects breeding initiated by significant late summer rainfall and slower locust development rates.



**Fig. 7** Comparison of r-NDVI and NDVI values for April control and previous month (1992–2009). Nymph (band) control (a, b) and adult (swarm) control (c, d) by region (1-arid,3-summer rainfall). Plots show median, interquartile range, and data range for maximum monthly r-NDVI (a, c) and NDVI (b, d).

Dry land cereal and irrigation cropping occur largely in the uniform-winter and summer rainfall regions. Differences in r-NDVI between areas subject to cropping and pastoral land use were compared to nymph and adult control. The higher range of NDVI values due to both bare ground and dense crop at different times results in lower r-NDVI values in cropped areas. There were significantly higher r-NDVI values in pastoral land use for band control in all seasons in the summer rainfall region, but this effect was only detectable in the uniform winter rainfall region during summer (Table 2).

Comparison of r-NDVI and NDVI discrimination of vegetation change is shown for representative months in Figs. 5–7. Median NDVI values for arid region nymph control during December and February were  $<0.25$ , and increases as a proportion of data ranges  $<10\%$ , whereas r-NDVI medians were  $>50\%$ , and increases  $>40\%$ . In December, the median r-NDVI value for band control in the arid region was higher than that in the summer rainfall region [Fig. 5(a) and 5(b)], but NDVI value significantly lower. This applies also in April, which presents an extreme example of a 1-month increase to a median of 90% of r-NDVI.

Models applied to survey data showed generally low regression coefficients for significant NDVI variates, reflecting the high random variance produced by the sporadic presence of nymphs and more ubiquitous presence of adults. Nymph models did not take into account the development stage or the observation day, which may also have affected the NDVI coefficients. Models applied to survey data are a compromise to deal with zero inflation and categorical density classes, so the results are presented as indicative of the influence of NDVI, habitat, and regional differences in locust distributions. However, a 1-month change in r-NDVI, habitat, region, and r-NDVI were consistently significant in regressions for nymph data. For adult data, change in r-NDVI is less significant than the other variables, supporting the results from control data. Based on the known ecology and phenology of *C. terminifera*, the regressions represent meaningful biological effects.

**Table 2** Relative NDVI (r-NDVI) values by season and rainfall region at APLC nymph and adult control locations (October 1991 to April 2009) in different land use categories. Land use (0.25 deg gridded data, classed as pasture (grazing on native or improved pastures) or cropped (subject to dry land cropping or irrigation in 1998, 2000, or 2006). Mean and standard error are shown at month of control, *t* statistic and significance values shown for two-sample *t*-tests with unequal variance on angular transformed maximum monthly r-NDVI values.

Season	Land use	Rainfall regions			
		Uniform/winter (2)		Summer (3)	
		Nymph	Adult	Nymph	Adult
		<i>n</i> (mean)	<i>n</i> (mean)	<i>n</i> (mean)	<i>n</i> (mean)
Spring	Pasture	775(51.29 ± 0.59)	188(38.47 ± 1.03)	117(39.87 ± 1.44)	126(28.71 ± 1.04)
	Cropped	322(51.16 ± 0.88)	205(32.30 ± 1.02)	71(47.77 ± 2.35)	99(27.59 ± 1.46)
	<i>t</i> -test	ns	<i>t</i> = 4.25, <i>p</i> < 0.001	<i>t</i> = -2.97, <i>p</i> = 0.004	ns
Summer	Pasture	136(39.24 ± 1.08)	337(31.96 ± 0.91)	173(49.62 ± 1.36)	205(41.97 ± 1.08)
	Cropped	14(37.79 ± 3.85)	143(27.64 ± 0.87)	163(42.27 ± 1.13)	78(38.26 ± 1.87)
	<i>t</i> -test	ns	<i>t</i> = 3.96, <i>p</i> < 0.001	<i>t</i> = 3.95, <i>p</i> < 0.001	ns
Autumn	Pasture	19(67.11 ± 2.12)	149(31.73 ± 1.51)	100(53.23 ± 1.87)	52(30.38 ± 1.52)
	Cropped	4(56.75 ± 2.36)	59(30.20 ± 1.59)	36(44.00 ± 2.15)	16(28.06 ± 2.33)
	<i>t</i> -test		<i>t</i> = 0.73, <i>p</i> = 0.47	<i>t</i> = 3.37, <i>p</i> < 0.001	<i>t</i> = 0.76, <i>p</i> = 0.46

**Table 3** General linear models fitted to *Chortoicetes terminifera* nymph and adult data from APLC surveys, summer 1998 to 2009. Factor reference levels—habitat 1, region 1 (arid). Model variates r-DIFF (r-NDVI change from previous month), r-NDVI and factors (habitat 1, nonhabitat 0; rainfall regions (arid 1, uniform-winter 2, summer 3). Regression coefficients (estimate) and significance level (*t* probability). Significance levels of deviance (*chi* probability).

		Nymph presence/absence			Adult presence/absence		
		Estimate	Standard error	<i>t</i> pr.	Estimate	Standard error	<i>t</i> pr.
Regression coefficients	Constant	-2.463	0.081	<0.001	0.031	0.038	0.409
	r-DIFF	0.036	0.002	<0.001	-0.002	0.001	0.031
	r-NDVI	-0.005	0.002	<0.001	-0.003	0.001	<0.001
	Habitat 0	-1.219	0.096	<0.001	-0.465	0.034	<0.001
	Region 2	0.413	0.075	<0.001	0.359	0.038	<0.001
	Region 3	-0.478	0.067	<0.001	-0.201	0.031	<0.001
Accumulated deviance	Analysis	df	Mean deviance	chi pr.	df	Mean deviance	chi pr.
	r-DIFF	1	338.93	<0.001	1	56.800	<0.001
	r-NDVI	1	72.44	<0.001	1	52.632	<0.001
	Habitat	1	233.23	<0.001	1	182.116	<0.001
	Region	2	124.49	<0.001	2	190.953	<0.001
	Residual	22962	0.428		22962	1.356	

**Table 4** Ordinal regression models (logit link, dispersion estimated) fitted to *Chortoicetes terminifera* data from APLC surveys for summer 1998 to 2009. Factor reference levels—Habitat 1, Region 1 (arid). Model variates r-DIFF (r-NDVI change from previous month), r-NDVI and factors (habitat 1, non-habitat 0; rainfall regions (arid 1, uniform-winter 2, summer 3). Regression coefficients (estimate) and significance levels (*t* probability). Significance levels of deviance (*F* probability).

		Nymph density (4 classes)			Adult density (6 classes)		
		Estimate	s.e.	<i>t</i> pr.	Estimate	s.e.	<i>t</i> pr.
Regression coefficients	r-DIFF	0.029	0.005	<0.001	-0.000	0.002	0.845
	r-NDVI	-0.004	0.005	0.441	-0.011	0.002	<0.001
	Habitat 0	-0.834	0.274	0.002	-0.249	0.076	0.001
	Region 2	-1.715	0.223	<0.001	0.293	0.075	<0.001
	Region 3	-0.281	0.190	0.142	-0.132	0.069	0.057
Analysis		df	Mean deviance	F pr.	df	Mean deviance	F pr.
Accumulated deviance	r-DIFF	1	201.571	<0.001	1	62.487	<0.001
	r-NDVI	1	10.392	0.028	1	147.155	<0.001
	Habitat	1	8.163	0.051	1	23.835	0.002
	Region	2	152.378	<0.001	2	69.750	<0.001
	Residual	1401	2.177		10,983	2.543	

The persistence of seasonal rainfall regions as significant terms in most models is likely to result from the different levels of r-NDVI in each during summer (means—arid  $37.56 \pm 0.18$ , uniform winter  $24.86 \pm 0.18$ , and summer  $39.83 \pm 0.23$ ). Coefficients for the uniform winter and summer rainfall regions vary relative to the arid region in different models, reflecting interaction with other terms.

## 6 Conclusion

An effective forecasting system for a locust species with a large geographic distribution and extensive areas of potential habitat relies on obtaining timely information on environmental correlates of population increase, measurable over large areas. Data presented here show that satellite NDVI data indicate habitat conditions in which significant *C. terminifera* population increase is possible and therefore provide a measure of relevant environmental conditions at all locations.

Nymph control in the arid region during summer was consistently associated with high and significantly increased relative NDVI values. Nymphal bands are the primary target of current APLC control intervention strategy because they are localized areas of very high insect densities and are relatively immobile. The trend of swarm control occurring with declining NDVI conforms to a phenological sequence of gregarious populations initiated by egg laying after heavy rainfall and swarms forming after the peak in vegetation response.

In low vegetation cover arid environments, NDVI never reaches values equivalent to areas of forest or crop, even after heavy rainfall, making a relativized index appropriate for detecting vegetation greenness. The median NDVI for locust habitat in the arid region during summer from survey data was 0.13 (interquartile range 0.1–0.17). The r-NDVI is suitable for visual discrimination by providing a wider range of data values, showing the condition of the vegetation independent of type, density or rainfall amount. The advantage of a relative index is in removing regional and local effects due to different ground vegetation densities and of static nonvegetation

surface features. There are limitations to r-NDVI in areas with very sparse ground vegetation, where the range of NDVI values is so small that any change can result in high r-NDVI.

Although rainfall data are available within a day of recording, allowing for immediate logistic planning, the reporting network in the arid zone remains sparse. In addition, heavy storm rainfall often produces temporary flood-out areas, which can extend areas of vegetation growth many kilometers beyond rain areas. Flooding of inland rivers produces subsequent flood plain and drainage-line vegetation, hundreds of kilometers downstream and many weeks after rainfall events. As a direct measurement of vegetation, NDVI is independent of these factors.

Increases in NDVI, and in particular the discrimination available in r-NDVI, are most relevant for locating nymphal populations in the arid parts of *C. terminifera* habitat. These are the areas where large pastoral holdings mean that landholder reporting is often limited and where ground surveillance requires logistic and resource planning. Access to fortnightly image data allows the identification of early vegetation response, providing time for planning and direction of ground surveillance prior to late instar stages when control is usually conducted.

Interpretation of imagery can be complicated by differences in vegetation type and seasonal response even within locust habitats. In cropped or irrigated areas, for example, the NDVI response is primarily driven by crop phenology and fallow regimes, more than by rainfall response, and the range in data values is high compared to grasslands. Some woody vegetation formations (e.g., mallee), as well as ephemeral forbs in sparse arid ground cover, produce shoot growth in late winter, whereas others respond to summer rainfall. Information on vegetation and habitat type is therefore important for interpretation of NDVI. Models using *C. terminifera* survey data also support the applicability of the interim map of locust habitat as a useful stratification of vegetation/soil types less likely to support locust breeding.

The timing of *C. terminifera* control coincides generally with a peak in vegetation response and NDVI values in various locust habitats. Although the control data used to demonstrate this association are subject to spatial dependence in the timing and location of events, this reflects the localized nature of gregarious population development. These effects were not modeled in the data presented here and produce inflated significance values, but  $p < 0.001$  values would likely remain significant at  $p < 0.5$  level with fewer degrees of freedom.

Statistical analysis of the survey data provides support for the relevance of NDVI indicated for control data. In particular, during summer, a 1-month change in r-NDVI has a significant positive association with *C. terminifera* nymph distribution, but for adult distributions, r-NDVI is more significant in regressions. Results show that habitat and regions based on seasonal rainfall are significant factors in distributions of both nymphs and adults.

At present, the use of r-NDVI and sequential change images provides a simple tool within a GIS for visual assessment of vegetation condition and response. Given that the human-computer interface with map displays remains a primary site of interpreting forecasting information, r-NDVI increases discrimination of vegetation condition and change because of the amplification of variations that occur within a small range of NDVI values. The data analyses also provide useful information for the interpretation of regional and seasonal variations in NDVI relative to possible *C. terminifera* occurrence. Other relativized NDVI indices, such as monthly or seasonal anomaly data, also enhance exceptional conditions, but usually introduce an extra layer of data processing and interpretation.

Future research on various vegetation indices derived from NDVI or other sensors, such as those used to decompose the herbaceous and evergreen-woody fractions from IR channel reflectance in rangeland vegetation, could potentially improve both the discrimination of suitable habitat and the herbaceous component in NDVI response to rainfall.<sup>60,61</sup> The increased resolution and overpass frequency of MODIS NDVI imagery allows detection of vegetation response along minor drainage lines that are often the main sites of green vegetation in arid landscapes and also short-lived responses to small rainfall amounts that provide crucial bridging food resources during prolonged dry periods. The use of vegetation and soil moisture information from various other sensors, as well as more detailed datasets on soil characteristics, present opportunities for further research, potentially leading to predictive modeling of vegetation-locust outcomes, or of suitable oviposition sites.

The relationship between NDVI and habitats of the other Australian locusts, or its potential applications, has not been analyzed in detail. *A. guttulosa* does not form nymphal bands and



overwintering adult swarms generally inhabit forested areas. However, successful recruitment and survival of nymphs have been associated with repeated rainfall in the Australian tropical savannas,<sup>8</sup> and egg development and abdominal fat content have been correlated with NDVI.<sup>62</sup> NDVI could therefore offer a means of monitoring habitat favorability during summer. For *L. migratoria*, gregarious population development is sporadic and often associated with summer crops in Queensland. Ecological conditions that favor its population increase and gregarization in Australia may operate on local scales not suited to synoptic NDVI imagery. The applicability of r-NDVI for monitoring *C. terminifera* habitat is a consequence of the particular ecology of this species and the nature of vegetation in arid and semiarid Australia, so may not be generally applicable for species in other countries. For example, no close relationship was found between AVHRR NDVI and historical data on high-density populations of *S. gregaria* and this may be a consequence of the very low vegetation densities over much of the species range.<sup>63</sup>

## Appendix

### A1 NDVI Data Processing

An archived 14-day time-series of calibrated (following the method of Rao and Chen)<sup>64</sup> AVHRR NDVI image files for the period October 1991 to December 2001 (ERIN NDVI)<sup>52</sup> and APLC imagery from DOLA for January 2002 to May 2009 were converted to ArcInfo Grids (ArcInfo 8, ESRI). Initial values in the range <40 and >249, representing cloud and non-vegetated pixels, were recoded to 0 to allow extraction of maximum and minimum values. Previous comparison of DOLA and ERIN NDVI data showed a maximum of 2.5% variation in corresponding values between datasets and this effect was ignored.<sup>65</sup> Historical maximum and minimum NDVI pixel values were calculated over the entire 440 image series and used to generate an equivalent set of 14-day images with values as a proportion of the historically recorded range (r-NDVI). Images were paired to match calendar months as closely as possible, and to minimize data loss due to cloud and some gaps in imagery. Some 14-day compositing periods extended across months, but the long time series is taken as reducing the influence of this effect. Monthly NDVI and r-NDVI images were generated using the maximum NDVI value because the peak of sometimes short-lived vegetation responses, rather than an averaged value, was the parameter of interest. Integer NDVI values were recalculated to the original 0–1 terrestrial range using the formula  $(ndvi-50)/200$ .

### A2 Locust Data

All APLC *C. terminifera* control record locations ( $n = 6319$ ) for the 18-year period were used to assign maximum NDVI and r-NDVI values for the same month and previous 2 months. Gridded land use data for the years 1996, 1998, and 2005 (0.25 degree resolution, ABARES)<sup>59</sup> were combined to identify all areas classed as having irrigation or dry land cropping in any of these years. The IBRA (5.1) bioregional classification was calculated for each control point to provide a regional grouping based on climatic and ecological similarities. IBRA bioregions were grouped by seasonal rainfall pattern into arid (<350 mm), uniform or winter dominant, and summer dominant patterns. Total annual rainfall and month of maximum rainfall were modeled for each control coordinate (ANUCLIM)<sup>66</sup> and some data points were reassigned to ensure points <350 mm total rainfall were in the arid region. Generation of all data values at point locations was done using modules of ArcInfo 8 with direct sampling of grid values without interpolation.

All survey data for the 1998 to 2009 period were recorded in the same schema (density for each life stage detected in a single species record) and with the same GPS positional accuracy ( $\pm 100$  m). The data model represents 250-m transects as single point features. Highest nymph density encountered was recorded (scale 0, 1 to 5, 6 to 30, 31 to 80, 80 to >5000  $m^{-2}$ ), whereas adult density (scale 0, 1 to 5, 6 to 25, 26 to 125, 126 to 250, 251 to 750, 751 to >2500) is based on count over the entire transect. The data classes approximate an exponential series.

Summer survey data were analyzed because locusts are more likely to be produced in response to recent rainfall and because unpredictable gregarization often occurs during summer. For nymph occurrence, data were zero inflated ( $n = 2247$ , 9.2% of extracted records), whereas adults were present in 62.3%. Records where either of the NDVI variates was missing were excluded, as were those with identical NDVI values for consecutive months, that was assumed to result from the same image contributing to both maximum values.

### A3 Modeling

Control data were analyzed by month of control on a regional basis to identify variations based on the NDVI variates and regionalization factors using Genstat 15 (VSN Int.) statistical software. Change in NDVI variates was calculated for the control event and previous 2 months and summarized by comparison of mean values (Table 1). Significance of differences from 1-month lag data was obtained from paired  $t$ -tests of mean differences after angular transformation of the proportional values. Comparison of r-NDVI in areas with different land use was tested using two-sample  $t$ -test of means with unequal variance.

Nymph and adult density data from survey records were reclassified as a binary presence/absence variate and a GLM was fitted using a Bernoulli distribution (logit link function) and a full model using r-NDVI variates and regionalization factors, with terms added iteratively. Regression coefficients were derived with a fixed dispersion parameter of 1. Density data, with nil counts removed, were fitted by an ordinal regression model (logit link) and estimated dispersion parameters. This method was chosen because of the uneven numerical distances between density categories. Exploratory models were fitted with each term iteratively, and then full models using all terms were fitted to the regression with accumulated deviances calculated.

### Acknowledgments

I thank Lucy Randall (ABARES) for the ERIN NDVI imagery from 1991 to 2001 and Lindsay Penrose (ABARES) for statistical advice. Janet Stein (Fenner School, ANU) generated ANUCLIM modeled mean annual rainfall data for control points. Bob Forrester, ANU Statistical Consulting Unit, provided guidance on GLM techniques appropriate to locust survey data.

### References

1. Australian Plague Locust Commission (APLC) Department of Agriculture, Fisheries and Forestry—Australia, *Annual Report 1999–2000*, AGPS, Canberra (2003).
2. D. M. Hunter, “Advances in the control of locusts (Orthoptera:Acrididae) in eastern Australia: from crop protection to preventative control,” *Aust. J. Entomol.* **43**(3), 293–303 (2004), <http://dx.doi.org/10.1111/aen.2004.43.issue-3>.
3. R. A. Farrow, “Population dynamics of the Australian plague locust, *Chortoicetes terminifera* (Walker) in Central Western New South Wales III\*. Analysis of population processes,” *Aust. J. Zool.* **30**(4), 569–579 (1982), <http://dx.doi.org/10.1071/ZO9820569>.
4. D. E. Wright, “Economic assessment of actual and potential damage to crops caused by the 1984 locust plague in south-eastern Australia,” *J. Environ. Manage.* **23**, 293–308 (1986).
5. D. A. H. Murray, M. B. Clarke, and D. A. Ronning, “Estimating invertebrate pest losses in six major Australian grain crops,” *Aust. J. Entomol.*, in press (2013).
6. D.P. Clark, “The influence of rainfall on the densities of adult *Chortoicetes terminifera* (Walker), in central western New South Wales, 1969–73,” *Aust. J. Zool.* **22**(3), 365–386 (1974), <http://dx.doi.org/10.1071/ZO9740365>.
7. R.A. Farrow, “Population dynamics of the Australian Plague Locust, *Chortoicetes terminifera* (Walker), in Central Western New South Wales I. Reproduction and migration in relation to weather,” *Aust. J. Zool.* **27**(5), 717–745 (1979), <http://dx.doi.org/10.1071/ZO9790717>.
8. D. M. Hunter and R. J. Elder, “Rainfall sequences leading to population increases in *Austracris guttulosa* (Walker) (Orthoptera:Acrididae) in arid north-eastern Australia,” *Aust. J. Entomol.* **38**(3), 204–218 (1999), <http://dx.doi.org/10.1046/j.1440-6055.1999.00105.x>.

9. D. M. Hunter and M. Melville, "The rapid and long lasting growth of grasses following small falls of rain on stony downs in the arid interior of Australia," *Aust. J. Ecol.* **19**(1), 46–51 (1994), <http://dx.doi.org/10.1111/aec.1994.19.issue-1>.
10. D. M. Hunter, P. W. Walker, and R. J. Elder, "Adaptations of locusts and grasshoppers to the low and variable rainfall of Australia," *J. Orthopt. Res.* **10**(2), 347–51 (2001), [http://dx.doi.org/10.1665/1082-6467\(2001\)010\[0347:AOLAGT\]2.0.CO;2](http://dx.doi.org/10.1665/1082-6467(2001)010[0347:AOLAGT]2.0.CO;2).
11. D. P. Clark, "Night flights of the Australian plague locust, *Chortoicetes terminifera* Walk. in relation to storms," *Aust. J. Zool.* **17**(2), 329–352 (1969), <http://dx.doi.org/10.1071/ZO9690329>.
12. D.P. Clark, "Flights after sunset by the Australian plague locust, *Chortoicetes terminifera* (Walk.), and their significance in dispersal and migration," *Aust. J. Zool.* **19**(2), 159–176 (1971), <http://dx.doi.org/10.1071/ZO9710159>.
13. R.A. Farrow, "Origin and decline of the 1973 plague locust outbreak in central western New South Wales," *Aust. J. Zool.* **25**(3), 455–489 (1977), <http://dx.doi.org/10.1071/ZO9770455>.
14. D. P. Clark, "The plague dynamics of the Australian plague locust, *Chortoicetes terminifera* (Walk.)," in *Proc. Int. Study Conf. on Current and Future Problems of Acridology, 1970*, C. F. Hemming and T. H. C. Hemming, Eds., pp. 275–287, Centre for Overseas Pest Research, London (1972).
15. V. A. Drake and D. R. Reynolds, *Radar Entomology: Observing Insect Flight and Migration*, CABI, Wallingford, UK (2012).
16. V. A. Drake, H. K. Wang, and I. T. Harman, "Insect monitoring radar: stationary beam operating mode," *Comput. Electron. Agric.* **35**(2–3), 111–137 (2002), [http://dx.doi.org/10.1016/S0168-1699\(02\)00014-5](http://dx.doi.org/10.1016/S0168-1699(02)00014-5).
17. H. K. Wang and V. A. Drake, "Insect monitoring radar: retrieval of wingbeat information from conical-scan observation data," *Comput. Electron. Agric.* **43**(3), 209–222 (2004), <http://dx.doi.org/10.1016/j.compag.2004.01.003>.
18. Australian Plague Locust Commission (APLC) Department of Agriculture, Fisheries and Forestry—Australia, *Annual Report 1987–1988*, AGPS, Canberra (1989).
19. M. Fries, W. Chapco, and D. Contreras, "A molecular phylogenetic analysis of the Oedipodinae and their intercontinental relationships," *J. Orthopt. Res.* **16**(2) 115–125 (2007), [http://dx.doi.org/10.1665/1082-6467\(2007\)16\[115:AMPAOT\]2.0.CO;2](http://dx.doi.org/10.1665/1082-6467(2007)16[115:AMPAOT]2.0.CO;2).
20. S. J. Simpson and G. A. Sword, "Phase polyphenism in locusts: mechanisms, population consequences, adaptive significance and evolution," in *Phenotypic Plasticity of Insects: Mechanisms and Consequences*, D. Whitman and T. Ananthakrishnan, Eds., pp. 147–190, Science Publishers Inc., Plymouth, UK (2009).
21. R. A. Farrow and B. C. Longstaff, "Comparison of the annual rates of increase of locusts in relation to the incidence of plagues," *Oikos* **46**, 207–222 (1986), <http://dx.doi.org/10.2307/3565469>.
22. P. M. Symmons and D. E. Wright, "The origins and course of the 1979 plague of the Australian plague locust, *Chortoicetes terminifera* (Walker) (Orthoptera: Acrididae), including the effect of chemical control," *Acrida* **10**, 159–190 (1981).
23. K. G. Wardhaugh, "The effects of temperature and photoperiod on the induction of diapause in eggs of the Australian plague locust, *Chortoicetes terminifera* (Walker) (Orthoptera: Acrididae)," *Bull. Entomol. Res.* **70**(4), 635–647 (1980), <http://dx.doi.org/10.1017/S0007485300007926>.
24. K.G. Wardhaugh, "Diapause strategies in the Australian plague locust, *Chortoicetes terminifera* (Walker)," in *The Evolution of Insect Life Cycles*, F. Taylor and R. Karban, Eds., pp. 89–104, Springer-Verlag, New York (1986).
25. P. Gregg, "Development of the Australian plague locust, *Chortoicetes terminifera*, in relation to temperature and humidity," *J. Aust. Entomol. Soc.* **22**(3), 247–251 (1983), <http://dx.doi.org/10.1111/aen.1983.22.issue-3>.
26. R. Allan, J. Lindesay, and D. Parker, *El Nino Southern Oscillation and Climate Variability*, CSIRO Publ., Melbourne (1996).
27. D. E. Wright, "Analysis of the development of the major plagues of the Australian plague locust, *Chortoicetes terminifera* (Walker) using a simulation model," *Aust. J. Ecol.* **12**(4), 423–437 (1987), <http://dx.doi.org/10.1111/aec.1987.12.issue-4>.

28. E. D. Deveson and P. W. Walker, "Not a one way trip: historical distribution data for Australian plague locusts support frequent seasonal exchange migrations," *J. Orthopt. Res.* **14**(1), 91–105 (2005), [http://dx.doi.org/10.1665/1082-6467\(2005\)14\[91:NAOTHD\]2.0.CO;2](http://dx.doi.org/10.1665/1082-6467(2005)14[91:NAOTHD]2.0.CO;2).
29. P. Laut et al., *Environments of South Australia*, Division of Land Use Research, CSIRO, Canberra (1977).
30. C. J. Tucker, "Red and photographic infrared linear combinations for monitoring vegetation," *Remote Sens. Environ.* **8**(2), 127–150 (1979), [http://dx.doi.org/10.1016/0034-4257\(79\)90013-0](http://dx.doi.org/10.1016/0034-4257(79)90013-0).
31. C. J. Tucker and P.J. Sellers, "Satellite remote sensing of primary production," *Int. J. Rem. Sens.* **7**(11), 1395–1416 (1986), <http://dx.doi.org/10.1080/01431168608948944>.
32. R. D. Graetz, R. Fisher, and M. G. A. Wilson, *Looking Back: The Changing Face of the Australian Continent 1972–1992*, CSIRO Office of Space Sciences, Canberra (1992).
33. R. D. Graetz, "Satellite remote sensing of Australian rangelands," *Remote Sens. Environ.* **23**(2), 313–331 (1987), [http://dx.doi.org/10.1016/0034-4257\(87\)90044-7](http://dx.doi.org/10.1016/0034-4257(87)90044-7).
34. R. D. Graetz et al., "The application of Landsat image data to rangeland assessment and monitoring the development and demonstration of a land image-based resource information system (LIBRIS)," *J. Arid Environ.* **10**, 53–80 (1986).
35. Z. Kalensky, "Regional and global land cover mapping and environmental monitoring by remote sensing," *Int. Arch. Photogramm. Eng. Rem. Sens.* **31**(B4), 413–426 (1996).
36. United States Geological Survey USGS LCI, Landcover Institute, <http://landcover.usgs.gov/landcoverdata.php> (20 June 2012).
37. European Commission. Joint Research Centre—Land Resource Centre, Global Environment Monitoring, <http://bioval.jrc.ec.europa.eu/products/glc2000/glc2000.php> (20 June 2012).
38. D. E. Pedgley, "Testing feasibility of detecting locust breeding sites by satellite," *Final report to NASA on ERTS-1 experiment*, COPR, London (1973).
39. K. Cressman, "The use of new technologies in Desert Locust early warning," *Outlooks on Pest Management* **19**(2), 55–59 (2008), <http://dx.doi.org/10.1564/19apr03>.
40. R. Sivanpillai et al., "Mapping locust habitats in the Lli Delta, Kazakhstan, using Landsat imagery," *Agric. Ecosyst. Environ.* **117**, 128–134 (2006), <http://dx.doi.org/10.1016/j.agee.2006.03.028>.
41. J. Ma et al., "Monitoring East Asian migratory locust plagues using remote sensing data and field investigations," *Int. J. Rem. Sens.* **26**(3), 629–634 (2005), <http://dx.doi.org/10.1080/01431160310001595019>.
42. D. M. Hunter and M. Melville, "The rapid and long lasting growth of grasses following small falls of rain on stony downs in the arid interior of Australia," *Aust. J. Ecol.* **19**(1), +46–51 (1994), <http://dx.doi.org/10.1111/aec.1994.19.issue-1>.
43. D.M. Hunter, P.W. Walker, and R.J. Elder, "Adaptations of locusts and grasshoppers to the low and variable rainfall of Australia," *J. Orthopt. Res.* **10**(2), 347–351 (2001), [http://dx.doi.org/10.1665/1082-6467\(2001\)010\[0347:AOLAGT\]2.0.CO;2](http://dx.doi.org/10.1665/1082-6467(2001)010[0347:AOLAGT]2.0.CO;2).
44. L. McCulloch and D. M. Hunter, "Identification and monitoring of Australian plague locust habitats from Landsat," *Rem. Sens. Environ.* **13**(2), 95–102 (1983), [http://dx.doi.org/10.1016/0034-4257\(83\)90015-9](http://dx.doi.org/10.1016/0034-4257(83)90015-9).
45. K. P. Bryceson, "The use of Landsat MSS data to determine the distribution of locust eggbeds in the Riverina region of New South Wales, Australia," *Int. J. Rem. Sens.* **10**(11), 1749–1762 (1989), <http://dx.doi.org/10.1080/01431168908904005>.
46. K. P. Bryceson, "Digitally processed data as a tool in detecting potential Australian plague locust outbreak areas," *J. Environ. Manage.* **30**(3), 191–207 (1990), [http://dx.doi.org/10.1016/0301-4797\(90\)90001-D](http://dx.doi.org/10.1016/0301-4797(90)90001-D).
47. K. P. Bryceson and R. Cannon, "The acquisition and use of low cost meteorological satellite data in the Australian Plague Locust Commission," *Comput. Electron. Agric.* **5**, 47–64 (1990), [http://dx.doi.org/10.1016/0168-1699\(90\)90047-S](http://dx.doi.org/10.1016/0168-1699(90)90047-S).
48. K. P. Bryceson, D. M. Hunter, and J. G. Hamilton, "Use of remotely sensed data in the Australian Plague Locust Commission," in *Pest Control and Sustainable Agriculture*, S. A. Corey, D. J. Dall, and W. M. Milne, Eds., pp. 435–439, CSIRO, Melbourne (1993).
49. K. P. Bryceson and D. E. Wright, "An analysis of the 1984 locust plague in Australia using multitemporal LANDSAT multispectral data and a simulation model of locust

- development,” *Agric. Ecosyst. Environ* **16**(2), 87–102 (1986), [http://dx.doi.org/10.1016/0167-8809\(86\)90096-4](http://dx.doi.org/10.1016/0167-8809(86)90096-4).
50. K. P. Bryceson, “Likely locust infestation areas in western New South Wales, Australia, detected by satellite,” *Geocarto Int.* **6**(4), 21–37 (1991), <http://dx.doi.org/10.1080/10106049109354337>.
  51. K. P. Bryceson, “Digitally processed data as a tool in detecting potential Australian plague locust outbreak areas,” *J. Environ. Manage.* **30**(3), 191–207 (1990), [http://dx.doi.org/10.1016/0301-4797\(90\)90001-D](http://dx.doi.org/10.1016/0301-4797(90)90001-D).
  52. Department of the Environment, Water, Heritage and the Arts, *NOAA AVHRR 1 km 14 day NDVI Archive 1992–2009*, Australian Government, Archive generated by the Environmental Resources Information Network (ERIN) (2009).
  53. M. L. Roderick, I. R. Noble, and S. W. Cridland, “Estimating woody and herbaceous vegetation cover from time series satellite observations,” *Global Ecol. Biogeogr.* **8**(6), 501–508 (1999), <http://dx.doi.org/10.1046/j.1365-2699.1999.00153.x>
  54. E. Deveson, L. Ognjanovic, and S. Cridland, “NOAA NDVI image sequences detect ground vegetation response to rainfall in locust habitats,” APLC Technical Report No. 1/1998 (1998).
  55. E. Deveson et al., “Field evaluation of NDVI relative greenness imager—Broken Hill 2002-03,” APLC Technical Report No. 2/2005 (2005).
  56. E. Deveson and D. Hunter, “The derivation of a digital map of locust habitats,” APLC Technical Report No. 1/1996 (1996).
  57. R. Thackway and I. D. Cresswell, *An Interim Biogeographic Regionalisation for Australia: a framework for setting priorities in the National Reserves System Cooperative Program Version 4s*, Australian Nature Conservation Agency, Canberra (1995).
  58. Environment Australia, *Revision of the Interim Biogeographic Regionalisation for Australia (IBRA) and development of Version 5.1—Summary Report*, Environment Australia, Canberra (2000).
  59. ABARES—Australian Bureau of Resource and Agricultural Economics and Science (ABARES) DAFF, Australian Natural Resources Data Library, 2010, [http://adl.brs.gov.au/anrdl/metadata\\_files/pa\\_luav4g9abl07811a00.xml](http://adl.brs.gov.au/anrdl/metadata_files/pa_luav4g9abl07811a00.xml) (25 March 2013).
  60. T. K. Gill, “Satellite estimates of tree and grass cover using MODIS vegetation-indices and ASTER surface-reflectance,” Ph.D. Thesis, University of Queensland (2008).
  61. T. Gill and S. Phinn, “Estimates of bare ground and vegetation cover from Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) short-wave infrared reflectance imagery,” *J. Appl. Rem. Sens.* **2**(1), 023511 (2008), <http://dx.doi.org/10.1117/1.2907748>.
  62. M. J. Steinbauer, “Relating rainfall and vegetation greenness to the biology of spur-throated and Australian plague locusts,” *Agric. Forest Entomol.* **13**(2), 205–218 (2011), <http://dx.doi.org/10.1111/afe.2011.13.issue-2>.
  63. J. A. Tratalos and R. A. Cheke, “Can NDVI GAC imagery be used to monitor desert locust breeding areas?” *J. Arid Environ.* **64**(2), 342–356 (2006), <http://dx.doi.org/10.1016/j.jaridenv.2005.05.004>.
  64. C. R. N. Rao and J. Chen, “Revised Post Launch Calibration of the Visible and Near Infrared Channels of the Advanced Very High Resolution Radiometer (AVHRR) on the NOAA 14 Spacecraft,” *Int. J. Rem. Sens.* **20**(18), 3485–3491 (1999), <http://dx.doi.org/10.1080/014311699211147>.
  65. E. Deveson, “An evaluation of MODIS imagery,” APLC Technical Report No 1/2005 (2005).
  66. T. Xu and M. F. Hutchinson, “New developments and applications in the ANUCLIM spatial climatic and bioclimatic modelling package,” *Environ. Model. Softw.* **40**, 267–279 (2013), <http://dx.doi.org/10.1016/j.envsoft.2012.10.003>.

Biography and photograph of the author is not available.