Note

The authors are most grateful for these unusually detailed and comprehensive reviews.

Referees comments are in plain text, authors' responses are in bold below the referee comment.

Referee #1

B.K. Wylie

Scientific Questions

"...there is currently no other method available, LNS was used" pg 3 ln 6. 1) Literature: Prominent articles that I am aware of focused on isolating management are included below. I was surprised the authors only found one or 2 of these. They do cite Wessels et al 2007 & 2008 (pg 2) which seem to me to be a viable and comparable approach):

a. Western US Rangelands

i. Wylie, B.K., Boyte, S.P., and Major, D.J., 2012, Ecosystem performance monitoring of rangelands by integrating modeling and remote sensing: Rangeland Ecology and Management, v. 65, no. 4, p. 241-252, at http://dx.doi.org/10.2111/REM-D-11-00058.1.

ii. Boyte, S.P., Wylie, B.K., and Major, D.J., 2015, Mapping and monitoring cheatgrass dieoff in rangelands of the Northern Great Basin, USA: Rangeland Ecology and Management, v. 68, no. 1, p. 18-28, at http://dx.doi.org/10.1016/j.rama.2014.12.005.

iii. Rigge, M.B., Wylie, B.K., Zhang, L., and Boyte, S.P., 2013, Influence of management and precipitation on carbon fluxes in Great Plains grasslands: Ecological Indicators, v. 34, p. 590-599, at http://dx.doi.org/10.1016/j.ecolind.2013.06.028.

iv. Gu, Y.; Wylie, B.K. Detecting ecosystem performance anomalies for land management in the upper Colorado River basin using satellite observations, climate data, and ecosystem models. Remote Sens. 2010, 2, 1880–1891. v. Rigge, M.B., Wylie, B.K., Gu, Y., Belnap, J., Phuyal, K.P., and Tieszen, L.L., 2013, Monitoring the status of forests and rangelands in the western United States using ecosystem performance anomalies: International Journal of Remote Sensing, v. 34, no. 11, p. 4049-4068, at http://dx.doi.org/10.1080/01431161.2013.772311.

b. Boreal forests

i. Wylie, B.K., Rigge, M.B., Brisco, B., Murnaghan, K., Rover, J.A., and Long, J.B., 2014, Effects of disturbance and climate change on ecosystem performance in the Yukon River Basin boreal forest: Remote Sensing, v. 6, no. 10, p. 9145-9169, at http://dx.doi.org/10.3390/rs6109145.

ii. Wylie, B.K., Zhang, L., Bliss, N.B., Ji, L., Tieszen, L.L., and Jolly, W.M., 2008, Integrating modelling and remote sensing to identify ecosystem performance anomalies in the boreal forest, Yukon River Basin, Alaska: International Journal of Digital Earth, v. 1, no. 2, p. 196-220, at http://dx.doi.org/10.1080/17538940802038366.

iii. NDVI prediction 1. Bunn, A.G., Goetz, S.J. and Fisk J., 2005. Observed and predicted responses of plant growth to climate across Canada. Geophysical Research Letters, 32, L16710, 14.

c. Africa

i. Hermann, S.M., Anyamba, A. and Tucker, C.J., 2005. Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. Global Change Biology, 15, 394404.

ii. Wessels, K.J., S.D. Prince, et al., 2007, Can humaninduced land degradation be distinguished from the effects of rainfall variability? A case study in South Africa. Journal of Arid Environments, 68, 271297. iii. Archer, E.R.M. Beyond the "climate versus grazing" impasse: Using remote sensing to investigate the effects of grazing system choice on vegetation cover in the eastern Karoo. J. Arid Environ. 2004, 57, 381–408.

Authors' Response: The referee lists very relevant studies that do seek to isolate management effects from climatic variability. The referee also correctly points out that only two of these works were cited in the manuscript. The two that were cited are the most closely aligned with the focus of the current manuscript. However, we believe that the reader missed the point made was in regard to the limitations which exist in current methods. For example, in the first paper provided, a rule-based approach was used. The aim of the current manuscript was to produce a repeatable method which does not rely of intimate knowledge of the rangeland system. To accomplish this we sought to allow objective, unsupervised data clustering to decide homogeneous units. Furthermore, the current manuscript develops land capability classes which are not a reflection on vegetation types whatsoever, as had been presented in many of the supplied references, but rather is solely based upon measurable characteristics of the regional environment. This way long term transitions in land condition which result in changes in vegetation type (e.g. invasive species and encroachment of unpalatable woody species) are included in our definition of degradation.

Pg 4 ln 8-9: It seems that the nearest neighbor approach would merely retain the blockiness of the 5 k x 5 k data. Why not use an interpolation to smooth 5k 5k pixel boundaries? Say cubic or bilinear interpolation? Why not include slope and aspect? Known ecological difference occur related to certain conditions (south vs north aspect with moderate to steep slopes) in many ecosystems, particularly temperature limited (Arctic and Boreal) and moisture limited ones. In the northern hemisphere you would be showing all southern aspects as degraded when they are just drier because of higher transpiration demands from higher temperatures than north facing slopes. The same would be true for southern hemisphere, only with north slopes being drier..

Authors' Response: Interpolation was not used because the data was used in a cluster algorithm, which sought to distinguish homogeneous areas based upon actual data. In the Burdekin, as in the rest of Australia, a high quality climate data set exists for which necessary data smooth already exist. The use the average mean LNS value over multiple years also creates a smoothing effect that is more closely related to actual climate values.

Authors' Response: The study region is largely flat so the use of slope and aspect only drive up model error. Furthermore soil properties used to define land capability classes are related to topographic features. Additionally measure of soil erosion, another closely related variable with slope and aspect were used for comparison with LNS results.

Authors' Response: Finally, fine scale differences in aspect and slope are a naturally occurring phenomenon in each LCC. Low LNS values in these areas are also a valuable indication of degradation and may be compared across LCCs.

Pg 7 ln 15: it would be interesting to field check these all year reference sites.

Authors' Response: Great point, noted.

Pg 11 ln 1: Convection thunderstorm precipitation is HARD to map accurately. Often in remote areas with few weather stations, gridded precipitation can be unreliable when distant from a weather station.

Authors' Response: The Australian climate data has an overall accuracy of 84% and the study region falls in an area where a dense network of weather stations exist.

Pg 11 ln 17: "largest spatial variations" Think of ecological tendencies for larger means to have larger variances. What if you use CV (coefficient of variation)?

Authors' Response: This comment is in response to the standard deviation values in northern basins and the proposed CV provides the same information, specifically because CV is simply the standard deviation divided by the mean.

Pg 11 ln22-27: "~ need for comparison to pixel based estimated productivity" This sounds exactly what Wylie et al, Rigge et al. Gu et al. are doing but instead of a process-based model (classically heavily depend on precipitation which is notoriously problematic to map in remote landscapes) data driven regression trees were used to predict undisturbed productivity or potential productivity.

Authors' Response: A data driven regression tree is another future alternative to the development of LCCs.

Pg 12 ln 39: "~relationship to hillslope erosion)" Not convinced unless slope/aspect are taken into account in LCC.

Authors' Response: In figure 7, the agreement is presented. As stated earlier elements related to topography may be related to the chosen soil properties.

TECHNICAL CORRECTIONS

The miss-numbered figures 6 and 7 seemed out of place in an otherwise very thoughtful paper.

Authors' Response: Corrected

Pg4 ln 36: Why not see if the 2 difference clusters/land groupings are consistent spatially? "mean square variance of their maximum NPP" was confusing. Re-word? I was confused if you only had one max value per LCC how you could get a variance of, that but later it became clear that you were looking a the variance of max-each pixel in the LCC. One statistical buddy told me that maximized variables have weird statistical properties and should be avoided (you also mention the maximum is susceptible to selecting "outliers"). We have used mean values from the upper quartile to avoid such issues. I see later (Fig3) you use 85 percentile. Why did you choose to use the maximum for the difference in clusters vs land grouping? I think it is "OK" but if you apply this elsewhere I would consider changing this.

Authors' Response: The maximum referred to in the text is the best estimator of the potential value, which is the 85 percentile. NPP values higher than this were omitted (as stated in the manuscript), so no assumptions are made about their distribution. The goal was to 'model' the unmanaged portion of each LCC. The mean square variation was used for exactly the reason the referee pointed out (i.e. minimizing the effect of outliers while still analyzing variation within the population of maximum values). The differences in the maximum values found were then assumed to be naturally occurring differences, unrelated to management. In a highly managed rangeland such as the BDT, this assumption should hold true.

Pg 5 ln 27-28: Why not downscale 250 m to 1km, run the regression at 1km (ndvi vs npp)? At least then you are comparing apples to apples. . . 250m variation is going to just be different than 1 km variation.

Authors' Response: This was done, the regression was performed at 1km, then downscaled to 250m. The spatial scaled of 250m was used because degradation related human management is most relevant at spatial scales finer than 1km for many reasons (e.g. grazing enclosure size, differences across property boundaries, highly variable vegetation, etc.)

Pg 6 ln 4: "reference pixels" Glad to see acknowledgement of the limitations but I do not think the readers understand where the reference pixels come from because Fig 3 has not been presented. I was confused at this point before Fig 3 was introduced. (also true at Pg 4 ln 12)

Authors' Response: Pg 6 ln 4: Changed "reference pixels" to "the potential"

Authors' Response: Pg 6 ln 12: Figure 3 is introduced on the same line at Pg 4 ln 12, so no correction is needed there

Pg 7 ln 1-7: In the US, the BLM (major federal land management agency for western arid rangelands) has locked in as percent bare ground as a good indicator of range condition. Are there any estimates of this you could use? I know there is a soil property mapping effort/research going on in Australia (Henderson et al. 2005, Geoderma 124:383-398) or continuous land cover (http://landcover.usgs.gov/pdf/canopy_density.pdf; http://glcf.umd.edu/data/treecover/) which could be used? Maybe remote sensing vegetation indices??. I am concerned that by not including slope and aspect in you r LCC determination that you maybe incorrectly identifying drier north slopes as degraded.. I guess your soil erodibility data is OK but soil texture differences could be a major driver in those determinations, not management. . ..

Authors' Response: Bare ground data in Australia is typically limited to scales that aren't relevant to regional degradation mapping (e.g. 30m - Landsat, 20m – ASTER versus the 250m –MODIS used in the manuscript). The major problem with using additional aspects of the degradation, such as bare ground is that, if they may be derivatives of the same vegetation indices used for validation of the argument is circular!.

Authors' Response: The substantial agreement of hillslope erosion, a metric highly related to slope, should alleviate most of the danger. To a lesser extent it is impossible to remove all elements of weather.

Pg 7 ln 24: "but between-LCC" Fig 4 miss labeled or text is wrong. Fig 4b has these statistics but was labeled "within LCC".

Authors' Response: Pg 7 ln 24: Changed "Figure 4a" to "Figure 4b"

Authors' Response: Pg 7 ln 24: Changed "Figure 4b" to "Figure 4a"

I think the association with rain does not add much, particularly to assess the 2 clustering approaches. Why not plot variance vs your maximum NPP or reference NPP or mean cluster NPP? I think you are just using precipitation as proxy for productivity here. Higher variances with higher means is a common phenomenon in ecological data, thus often the coefficient of variance is used.

Authors' Response: Precipitation was used because it is the primary environmental factor which drives differences in potential productivity. This means that if the LCCs

can reduce the within-group variation and maximize the between group variation, they are outperforming the GLM map. This gets to a previous point made in the manuscript that it is impossible for all symptoms of the environment to be removed, instead we must manage the impact of the most important environment variables

Pg 9 ln 16. I like your quantification of degradation in units of NPP.

Authors' Response: Thanks.

Pg 9 ln 10: Fig 5f: I think I see possible difference associated with slope / aspect differences. . .

Authors' Response: The river area was masked so steep slopes associated with riparian zone were minimized. As the text states, it was only the interfluves that were included. It is true that severe erosion can take place on river banks and riparian health has become a major problem in the study region and has resulted in abundant resources to remedy resulting erosion from these zones. This type of degradation was excluded owing to its finer scale than the 250m data that were available.

Referee # 2

Anonymous Referee #2

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General comments

Overall I found that the manuscript accomplished its stated objectives using a novel approach to address the main limitation of LNS, was for the most part clearly written, and stands to make a contribution both conceptually in understanding the prevalence and rates of degradation, as well as methodologically through improving remotely sensed rangeland monitoring, areas of research in much need of advancement. In order of importance, I particularly welcome the use of shifting annual reference NPP pixels to demonstrably improve LCC classification (although the reliability of some reference sites might be questioned), the attempt to evaluate LCC classification using independently-derived datasets measuring elements of land potential, and the generally pragmatic, conservative decisions made at several steps that improve the robustness of the analysis. This being said, I do think the manuscript could be stronger in several respects. Some assumptions are unaddressed or under-stated, the precipitation gradient in the region was not well utilized, and the organization and presentation of results could be much clearer, especially the tables.

Specific comments

“The method is limited spatially only by the capacity to classify the land,” (page 1, line 24): I’m not sure exactly what this means, but I doubt it’s true. A key assumption of the analysis is the accuracy of MODIS NPP in the study area. In tropical grasslands both dry and wet, this data can be unreliable for different reasons. In fact, it could explain why weak NPP and degradation gradients were observed. If there are relevant assessments for the region, cite them. If not, best to evaluate the MODIS data to the extent feasible, or use more than one method for NPP.

Authors’ Response: Regarding the spatial limitation of LNS, the limitation is the spatial resolution of the satellite data that are used. If Landsat data were frequent enough to be used to estimate NPP, and was available with adequate frequency, the LNS analysis could be undertaken at that scale.

Authors’ Response: The referee also states a key difficulty for virtually all remote sensing studies - reliability of the data. While the errors in the LNS procedure far outweigh those associated with the sensor, it is nevertheless true that the MODIS NPP product, based as it is on a light-use efficiency model, is frequently inaccurate. In the present case it was assumed that NPP errors would be minimized in the limited area (compared with global) that were analyzed.

Authors’ Response: We do agree that rewording/removing will help avoid additional confusion.

Authors’ Response: Pg 1 line 24: Sentence deleted. “The method is limited spatially only by the capacity to classify the land.”

Another assumption is that use of foliage projective cover (FPC) in defining LCCs did not unduly alter the analysis and conclusions. The soil and weather data are arguably independent of degradation, vegetation condition is not. While I understand the logic in using FPC, and it is not necessarily problematic, I’d prefer a mention of what factors the classification was robust to when included (or not), and a correlation matrix of factors used for LCC classification at minimum.

Authors’ Response: Foliage projective cover was used as a reference point to start to separate pre-2000 vegetation groupings. The point was to limit the opportunity of different, existing vegetation groups from being compared with each other and thus minimize false interpretation as degradation.

Authors’ Response: A correlation matrix for 50 classes for each year over 14 years would be tedious (50x14= 700 cells) for the reader to evaluate. A correlation matrix for just one LCC could be included but would not be representative of any other LCC.

The manuscript missed an opportunity to use the (large) rainfall gradient in the region productively. Analyses were presented and interpreted at river basin scales, which to me is not the natural unit of aggregation for analysis in this case (as hydrology is not the primary focus). I would have preferred to see, for example, mean precipitation isohyets delineated at increments from the coast, and degradation trends analyzed specifically within and between these areas. Addressing rainfall explicitly would have greatly increased the amount of information produced by the analysis.

Authors' Response: Climate (including rainfall) was included in the creation of LCCs, although not in the form of climatological isohyets across the entire region, rather as annual rainfall. It is true, however, that long-term environmental differences, as captured to some extent by climatology, may create more homogeneity within LCCs, and we acknowledge that this should be explored in future studies.

Authors' Response: Second, river basins provided a more natural comparison with management units which are of interest to policy-makers as well as managers and an important factor of concern in the Burdekin Dry Tropics is erosion leading to sediment transport, as mentioned in the Introduction, which contributes to the silting of the Great Barrier Reef.

With regard to the manuscript's presentation, most importantly, some numbers do not appear to add up, and their derivation must be checked and clarified. Table 2 gives -1.71 (non-degraded) and -3.90 (degraded) MgCm-2yr-1 as the average LNS values for these 2 degradation classes, which firstly form the basis for the whopping "2.14 MgCm-2yr-1" typo (hopefully) in the abstract, text, and Table 2.

Authors' Response: The 2.08 MgCm-2yr-1 is the average value for the entire study region, not the total. We think this is clear in the table.

Secondly, Tables 5 and 4 respectively provide -97.5 (non-degraded) -209.1 (degraded) gCm-2yr-1 as apparently the same values. If river basins must be used to organize the tables, they would be more effective if reorganized. Cutting down the table text and combining tables to align figures on degraded area, trend categories, and/or degradation classes would present the results much more clearly. Finally, including the reference NPP, rainfall, or some other indicator of overall productivity potential would make the reported values more meaningful. Alternatively, summarize such relevant statistics by basin in an appendix.

Authors' Response: The -209.1 gCm-2y-1 value from Table 4 refers to degraded areas, while the -97.5 value from Table 5 refers to the non-degraded areas – as the referee points out - but we are unsure why there could be confusion regarding these. Tables 4 and 5 are straightforward, presenting the average NPP loss, percentage loss and the area affected in each basin and the entire region. The point is that each river basin has different degrees of degradation and that degradation may be interpreted differently (e.g. NPP loss, percent loss) for each basin.

Authors' Response: Tables could be combined, but removing key data such as the percent NPP loss would make for confusing analysis because LNS cannot be reliably interpreted across an LCC without using a scaled calculation of loss, such as a

percent. Also NPP loss is essential for evaluation because it ties the results to a physical metric which may be compared to other land condition assessments. Part of the new approach presented in the manuscript is the scaled values of NPP and how they are interpreted. The LNS values represent how far the observed NPP is from the reference NPP.

Finally, it would have been nice to see a map with degradation class-by trend combinations, to show where is degraded, where is being degraded, and where is recovering.

Authors' Response: These were presented separately to avoid repeating the results.

Finally, some tables and figures should be shifted to supplementary materials.

Authors' Response: The tables and figures have been reviewed with this in mind and we concluded they are sufficiently important to the text that they are better left where they are. Their inclusion will not make the paper unusually long.

Technical corrections

Page 4, line 27: GLMLCC is static, not dynamic as in the UMDLCC approach here

Authors' Response: Changed this text to make that distinction once again, although it was implied in the Methods and made explicitly in the Discussion.

Page 5, line 18: "soil erodibility" was apparently not used

Authors' Response: Soil bulk density, soil water holding capacity and clay percentage were used in the LCCs. Soil erodibility was used (see figure 7) in the evaluation of LNS results.

Page 5, line 34: missing end parenthesis; what is a "distributary"?

Authors' Response: Page 5, line 34: Changed "distributary" to "tributary"

Page 7, line 5: "accounts," not "allows"

Authors' Response: Page 7, line 5: Changed "allows" to "accounts"

Page 8, lines 3-4: as compared to a reference mean of . . . what?

Authors' Response: Sorry, we can't find this text.

Page 8, lines 9-10: reword; typos

Authors' Response: Page 8, lines 9-10: Changed "The sum of LNS values for entire class, as opposed to LNS per unit area revealed how the importance the size of each class in contributing to the overall reduction in NPP." to "The sum of LNS values for an entire class, as opposed to the LNS value per unit area, revealed the importance of class size in the overall reduction in NPP."

Page 8, lines 14-16: “had”?

Authors’ Response: Page 8, lines 14-16: Changed “had” to “were”

Page 8, line 21: “smaller”? I think you mean “lower”

Authors’ Response: Page 8, line 21: changed “smaller” to “lower”

Page 9, lines 4-10: Does not match the figure legend.

Authors’ Response: Page 9, lines 4-10: Changed “Among degraded areas there was evidence of managed grazing, including abrupt differences in LNS along station boundaries (Figure 5b), but there were also gradients of LNS within some stations (Figure 5c), and others with low LNS spread across boundaries (Figure 5d). Other areas with evidence of management included forest clearing (Figure 5e) near station boundaries. There were also locations classified as degraded with little evidence of direct grazing management such as between the drainage lines of streams (Figure 5f).” to “Among degraded areas there was evidence of managed grazing, including abrupt differences in LNS along station boundaries (Figure 5b), but there were also gradients of LNS within a single station (Figure 5c), and others with low LNS spread across multiple boundaries (Figure 5d). Other areas with evidence of management included forest clearing (Figure 5e) near station boundaries. There were also locations classified as degraded with little evidence of direct grazing management such as between the drainage lines of streams (Figure 5f).”

Page 10, line 11: “were occurred in”?

Authors’ Response: Page 10, line 11: Changed “were occurred in” to “occurred”

Page 10, line 18-24: naturally ‘bare’ ground is undergoing degradation?

Authors’ Response: Page 10, line 18-24:Changed “The only negative trend was in the ‘bare’ class while ‘removed’ had the largest positive trend.” to “The only negative trend was in the ‘bare’ class, presumably an indication that a small amount of vegetation was present, while ‘removed’ had the largest positive trend.”

Page 10, line 33-36: reword

Authors’ Response: Page 10, line 33-36: Changed “This indicates that degradation, as detected with LNS, were sites that were persistently below the potential, not simply subject to some short-term environmental deficiency, such a single-year with spatially patchy lower rainfall.” to “This indicates that degradation, as detected with LNS, corresponded to sites that were persistently below the potential. This emphasized that these sites were not simply subject to some short-term environmental deficiency, such a single-year with spatially patchy lower rainfall.”

Page 12, line 12: Table 2, not Table 1

Authors' Response: Page 12, line 12: Changed "Table 1" to "Table 2"

Page 12, lines 4-20: These numbers do not match the tables.

Authors' Response: The numbers do match, but I will ensure the number is presented exactly as in the table

Authors' Response: Page 12, lines 4-20: Changed "65%" to "65.3"

Also, permanent degradation cannot be inferred here.

Authors' Response: It is inferred owing to the irreversible nature of degradation

Authors' Response: Page 12, line 15: Changed "presumably" to "a possible indicator"

Page 12, line 29: "strong" correlation? What is the evidence?

Authors' Response: The evidence is in table 8.

Authors' Response: Page 12, line 29: Changed "strong correlation" to "good agreement" to be more precise.

Page 32: Clarify that points are years, not LCCs or something else

Authors' Response: Page 32: Changed "...lines." To "...lines for each year 2000 to 2013."

Page 34: Figure 3. . .?

Authors' Response: Previously Corrected

Page 35: Figure 4. . .?

Authors' Response: Previously Corrected

Degradation of net primary production in a semi-arid rangeland

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Abstract. Anthropogenic land degradation affects many biogeophysical processes including reductions of net primary production (NPP). Degradation occurs at scales from small fields to continental and global. While measurement and monitoring of NPP in small areas is routine in some studies, for scales larger than 1km^2, and certainly global, there is no regular monitoring and certainly no attempt to measure degradation. Quantitative and repeatable techniques to assess the extent of deleterious effects and monitor changes are needed to evaluate its effects on, for example, economic yields of primary products such as crops, lumber and forage, and as a measure of land surface properties which are currently missing from dynamic global vegetation models, assessments of carbon sequestration and land surface models of heat, water, and carbon exchanges. This study employed the Local NPP Scaling (LNS) approach to identify patterns of anthropogenic degradation of NPP in the Burdekin Dry Tropics (BDT) region of Queensland, Australia from 2000 to 2013. The method starts with land classification based on the environmental factors presumed to control (NPP) to group pixels having similar potential NPP. Then, satellite remotely sensing data were used to compare actual NPP with its potential. The difference in units of mass of carbon and percentage loss wereas the measure of degradation. The method is limited spatially only by the capacity to classify the land. The entire BDT (7.45x10^6 km^2) was investigated at a spatial resolution of 250x250m. The average annual reduction in NPP due to anthropogenic land degradation in the entire BDT was -2.14 MgC m^{-2} year^{-1} or 17% of the non-degraded potential, and the total reduction was -214 MgC year^{-1}. Extreme average annual losses of 524.8 gC m^{-2} year^{-1} were detected. Approximately 20% of the BDT was classified as ‘degraded’. Varying severities and rates of degradation were found among the river basins, of which the Belyando and Suttor were highest. Inter-annual, negative trends in reductions of NPP, occurred in 7% of the entire region, indicating on-going degradation. There was evidence of areas that were in a permanently degraded condition. The findings provide strong evidence and quantitative data for reductions in NPP related to anthropogenic land degradation in the BDT.

Commented [HJ1]: The referee presents a key difficulty for virtually all remote sensing studies: reliability of remotely sensed data. There is unreliability associated with MODIS NPP which is reported in hhhhhh. Spatially unreliability is difficult to quantify due to the many reason it can occur. It should be pointed out that MODIS NPP data has been used in many remote sensing applications in relevant journal articles, including those cited in the manuscript Wessels 2008, Prince et al. 2009.
I do agree that rewording/removing will help avoid additional confusion.

1 Introduction

Land degradation is a deleterious process in which unfavorable conditions for humans occur (Pickup, 1998, 1996; Safriel, 2007; Safriel and Adeel, 2005) as a result of direct and indirect human and natural processes. In drylands (aridity index < 0.65), poor land management such as excessive cultivation, overgrazing and unmanaged fires have far reaching effects on biogeophysical processes (Prince, 2002). While degradation is always undesirable, there is evidence that, in some cases, it cannot be reversed (Prince, 2016) when the causes are removed – a much more serious outcome. However, it is not known how widespread this condition is. There are many other aspects of dryland degradation that are little understood, including its location, severity and actions needed for remediation (Reynolds et al., 2007) or, at least, to prevent a net increase (Lal et al., 2012; UNCCD, 2012). The extent of soil or pasture degradation through overgrazing, anywhere in the world, has been estimated by experts' subjective opinion, rather than systematic quantitative criteria (Gifford, 2010).

'Degradation' implies an undesirable condition compared with a starting point (Prince 2016) but degraded compared to what? To detect a relative condition, a reference is needed, in this case not degraded (Bastin et al., 2012; Boer and Smith, 2003; Prince et al., 2007; Stoms and Hargrove, 2000) without which states of degradation have no meaning. However, the detection of non-degraded reference sites that are at their potential is problematic (Wessels et al., 2007). There are several approaches that seem reasonable but have severe limitations, particularly when applied to large areas: visual assessment of satellite imagery is entirely subjective and therefore unrepeatable; field surveys, such as the National Resources Inventory (Nusser and Goebel, 1997), are limited to small areas (Budde et al., 2004; O'Connor et al., 2001; Prince, 2004) that can be assessed by an evaluator on the ground; process modeling of potential production followed by comparison with actual production (Bai et al., 2008; Boer and Puigdefabregas, 2005) suffers from the need for data and parameters that are generally not available (Prince, 2002).

The particular type of degradation investigated here is anthropogenic reduction of net primary production (NPP) which, in addition to its own importance, is an indicator of a wider range of degradative processes (Prince, 2002) such as soil compaction, salinization, water and wind erosion that generally also reduce NPP (Pickup, 1996; Walker and Janssen, 2002). The objective of this study was to identify and characterize the extent and severity of degradation of vegetation productivity in the extensive rangelands, in excess of 10,000 km^2, of the Burdekin Dry Tropics (BDT) in Queensland, Australia. The Local NPP Scaling (LNS) method (Prince, 2004; Prince et al., 2009; Wessels et al., 2008) was used to address the problem of identification of reference sites. LNS starts with classification of the region into land capability classes (LCCs) in which the biogeophysical environment is, as near as possible, the same, so assessments are made with areas of the same type and potential. The reference NPP is identified as the maximum value in each LCC, then the comparisons are made with this standard. Inaccuracies and even invalidity of the LNS technique can arise under certain conditions, although some methods are available that can minimize these, but they can never be entirely prevented. On the other hand, bearing in mind the fundamental requirement for non-degraded comparison, and also that there is currently no other method available, LNS was used.

Specifically this study: (1) identified the spatial extent of non-degraded and degraded land; (2) distinguished significant land trends in inter-annual reductions in NPP; and (3) linked total NPP reductions to specific land processes and states in the BDT.

2 Material and methods

2.1 Study area

The BDT region is located in north Queensland, Australia and covers approximately 7.45×10^6 km^2. The terrain is largely flat with gradually increasing elevation inland (Mellick and Hanlon, 2005). Six large river basins are contained in the BDT (Figure 1): the Upper Burdekin (2.26×10^6 km^2), Belyando (2.08×10^6 km^2), Cape Campaspe (1.18×10^6 km^2), Suttor (1.07×10^6 km^2), Bowen Broken Bogie (0.63×10^6 km^2) and Lower Burdekin (0.23×10^6 km^2). Average seasonal rainfall varies spatially from 400 to 1500mm with a steep decreasing gradient from the coast inland. More than 70% of rainfall falls during summer months (December-February) and runoff variability is high (Petheram et al., 2008; Rustomji et al., 2009). Discharge from rivers and creeks occurs in large pulses associated with intense but brief storms. During the study from 2000 to 2013, years with low (e.g. 2002-2007; $\leq$ 500mm year^{-1}) and high (e.g. 2008-2012; $\geq$ 600mm year^{-1}) accumulations occurred (Figure 2).

In the BDT, NPP is strongly influenced by regional variations in moisture availability (Hutley et al., 2000), fire frequency (Beringer et al., 2007), and soil properties. Native vegetation varies from dense to sparse forest to shrub-land and open grassland. Approximately 83% of the BDT is savanna consisting of mixed grass and trees. There are smaller areas that consist exclusively of shrubs (1%), grasses (8%), or rain-fed crops (8%). The ratio of tree-to-grass cover is a defining attribute that differentiates local environments in savanna ecosystems (Accatino et al., 2010). The croplands, both irrigated and rain-fed, are found in northeastern, higher rainfall areas.

The major land use (85-90% of the BDT) is livestock production on unimproved pastures (Mellick and Hanlon, 2005). According to the State of Queensland (2011), approximately 12% of the BDT has grazing practices likely to result in degradation.

2.2 Land capability classification

Land capability classes (LCCs) are areas that are homogeneous with respect to the selected environmental factors. The factors used here were meteorological, soil, and vegetation. The Australian Bureau of Meteorology distributes daily, synoptic weather reports consisting of rainfall (Weymouth et al., 1999), minimum and maximum temperature, water vapor pressure deficit at 9am and 3pm, and solar exposure (Jones et al., 2009), gridded at 5x5km spatial resolution. Daily inputs were summed for the growing season from November to April and rescaled to 250x250m using a nearest-neighbor interpolation. Data from three national scale, 1x1km, gridded, soil property maps (ACLEP, 2011) were used: (1) plant available water-holding capacity, calculated as the sum of the water-holding capacity of the A and B soil horizons (0 to 1m); (2) clay content (0 to 0.3m); and (3) soil bulk density (0 to 0.3m, spanning A and B horizons) as a measure of porosity. Foliage projective cover (FPC) was obtained from Danaher et al. (2004) although it was only available for one year prior to the study period. Pixels with over 50% FPC (mostly dense tropical forest) were not included.

A k-means unsupervised clustering was used to classify meteorological data, soil properties, and FPC for each growing season. To ensure equal numerical weighting, all environmental data were normalized prior to clustering. The environmental data were then partitioned using unsupervised clustering (n=50, maximum iterations = 100, change threshold = 0.05%, minimum of 1,000 pixels), which resulted in 50 clusters. These are referred to as UMD Land Capability Classes (UMDLCC). The pixels found within each homogeneous UMDLCC were examined using linear regression and Person correlation to determine if any underlying relationships remained between NPP and the environmental data used to create them. Only LCCs where the correlation was below 0.4 were included in the final UMDLCC for that year. Pixels with correlations above 0.4 were reclassified. This procedure was repeated for each year.

Few maps exist that could be used for validation of the homogeneity of LCCs in the BDT. One such is the Grazing Land Management (GLM) Land Types (DPI&F, 2004; Whish, 2011) which classifies areas based on vegetation, soil, and terrain characteristics to create static types within which the response to grazing pressure is similar. Since the principles used to create GLM were similar to those of the UMDLCCs, an additional LNS was performed using GLM land types (GLMLCC). The vector GLM map was converted to a raster format at a 250x250m spatial resolution. GLM land types consisting of fewer than 1,000 pixels were removed, resulting in 50 GLMLCCs – the same number of LCCs as the UMDLCC. These were compared with the UMDLCC.

Commented [HJ2]: Changed text to make that distinction. That was distinction was previously implied in the methods and explicitly made in the discussion.

The two LCCs were compared using the mean square variance of their maximum NPP to determine the extent to which each reduced within-LCC variance and maximized between-LCC variance. Inter-annual wet season rainfall (Nov to Apr) was averaged throughout the BDT (Figure 2), and then compared with the two variance components of both UMDLCC and GLMLCC. A paired t-test was used to determine whether there were significant differences in within-LCC and between-LCC variance in maximum NPP for the two LCCs.

A second comparison was made using the Vegetation Assets, States and Transitions (VAST) classification of Australia, version 2 (Lesslie et al. 2013). VAST is a national level map of changes to vegetation since European settlement, which began in 1750, showing the degree of anthropogenic modification of native vegetation until 2011. VAST uses the following classes: wilderness, biophysical naturalness, land use, land cover, and extent of native vegetation. There are four classes of increasing human modification: 1-‘modified’, 2-‘tranformed’, 3-‘replaced’, and 4-‘removed’. Areas without naturally occuring native vegetation are designated 5-‘bare’ and areas with no change as 0-‘residual’.

Erosion is strongly linked to land degradation in drylands (Lal, 2003; Ravi et al., 2010), and this is the case in Australian rangelands (Bui et al., 2011; Dregne, 1995; Gillieson et al., 1996; Webb et al., 2009). A datbase of erosion was used to better understand the nature of the degradation that was detected. Four environmental variables related to natural and human-related erosion processes were used: sediment load at 500x500m (NLWRA, 2002); soil erodibility, rainfall erosivity and hillslope erosion, each at 250x250m (Lu et al., 2001); and gully density at 500x500m (Hughes et al., 2001). Gully density and sediment load were downscaled from their original spatial resolutions to 250x250m using a nearest-neighbor interpolation.

2.3 Measurement of NPP using satellite data

Moderate Resolution Imaging Spectrometer (MODIS) NPP data (MOD17A3) (Running et al., 2004) were obtained from the Land Processes Distributed Active Archive Center satellite data archives (http://modis.gsfc.nasa.gov/data/; *accessed 06/05/2014*). These data have 1x1km resolution and so, to maintain the highest possible spatial resolution, the data were rescaled to 250x250m using coefficients of the regression of growing season 250x250m NDVI (MOD13Q1) on 1x1km, NDVI (MOD13A2).

LNS is spatially and temporally scale-dependent since the NPP in a pixel is the sum of its finer scale components, similarly for the individual years in the 14 years that were studied may be different. Therefore, in this application, degradation at finer spatial and temporal scales than 250x250m and 14 years may have been missed, as would any pattern of LNS at finer scales (such as confinement of degradation to small, but repeated ridges in a ~~distributary~~tributary). While this might be a drawback for fine scale applications, such as the effects of livestock congregation at water and gates, in the BDT, livestock management is normally applied to areas large enough to contain at least several 250x250m pixels. Other limitations for which there are no perfect solutions include the effect of gradients in environmental factors, such as meteorological variables,

Commented [HJ3]: Changed “distributary” to “tributary” that are dissected by the classification into arbitrary ranges. Pixels are more likely to be selected as the potential as reference sites if they are in the most favorable part of the gradient, often at the edge of LCC. While this effect is minimized using a large number of LCCs, it cannot be removed entirely. A warning situation would be if reference pixels were confined to one part of an LCC. In all of these cases, care is needed to review the LCCs using alternative sources such as high-resolution imagery that can provide visual warning. Additional limitations can arise if small features occur that are not large enough to be placed in a different LCC, also the situation where the entire LCC is degraded or entirely non-degraded. Various methods can be used to minimize these and other problems, but they cannot all be entirely prevented and in some cases the extent of the effect cannot be measured.

2.4 Local Net primary production scaling (LNS)

LNS values are the difference between each pixel and its reference NPP (Figure 3). It is therefore zero (equal to the reference NPP, i.e. not degraded) or negative (below the reference, i.e. degraded). The LNS values can be expressed as the actual reduction of NPP in gC m^{-2} $year^{-1}$ or as a percentage of the reference. LNS was calculated for each year (2000-2013), producing 14 LNS maps, using both the UMDLCC and GLMLCC maps.

The potential, non-degraded reference NPP was obtained using the frequency distribution of NPP in each LCC (Figure 3). The 85^{th} percentile was arbitrarily selected as the best estimator. Pixels with NPP higher than the reference, possibly caused by residual pixels with high NPP in areas that were not typical of the rest of the LCC, were omitted. A possible limitation of LNS is if no pixels are at their maximum; then the reference would be below the true potential. Masking rivers, open water, roads, human settlements, and other human land features not representative of the LCC minimized this effect, but it cannot be entirely eliminated and so interpretation of the results must take this into account.

LNS percent values were averaged from 2000 to 2013 to determine the mean NPP reduction for each pixel over the 14 years. To facilitate discussion, values that were ≤ -30% were arbitrarily classified as ‘degraded’. All other pixels, those where LNS was between 0% and -29% were classified as ‘non-degraded’. A time-series of annual LNS percent values for every pixel was used to identify significant ($\alpha<0.10$) inter-annual trends in LNS over the 14-years. Pixels were classified according to their trends into three categories: (1) no significant inter-annual trends (‘no LNS trend’); (2) significant positive inter-annual trends (‘positive LNS trend’); and (3) significant negative inter-annual trends (‘negative LNS trend’). The trend classification was combined with the two levels of degradation to create six classes: (1) ‘non-degraded and positive LNS trends’, (2) ‘non-degraded and no LNS trend’, (3) ‘non-degraded and negative LNS trend’, (4) 'degraded and positive LNS trend', (5) 'degraded and no LNS trend', and (6) 'degraded and negative LNS trend'.

Spatial agreement between average LNS values and ecological indicators related to land condition (e.g. hillslope and gully erosion) or susceptibility to poor condition (e.g. rainfall erosivity and soil erodibility) were examined using Cohen's kappa (k) fuzzy numeric (Cohen, 1960). This elaboration of the simple kappa test includes 'near misses' and ~~allows~~ accounts for coincidences that occur by chance. Values range from 0.0 to 1.0 with increasing agreement. All kappa calculations were performed using the Map Comparison Kit (Visser and de Nijs, 2006).

Commented [HJ4]: Page 7, line 5: Changed "allows" to "accounts"

3 Results

3.1 UMDLCC

The average number of pixels per UMDLCC varied each year from 3,182 (0.01×10^6 km^2) in 2004 to 141,690 (0.56×10^6 km^2) in 2013. Their locations differed each year owing to inter-annual differences in weather patterns. Approximately half were non-contiguous, interspersed between other LCCs, but generally in no more than two river basins. Most reference pixels were selected in more than one year and a small number were selected in all years.

The inter-annual, between-LCC variance in reference NPP was higher for UMDLCC compared with GLMLCC. Conversely, within-LCC variance for UMDLCC was lower than for GLMLCC, indicating that the pixels selected as reference within UMDLCCs were more homogeneous than GLMLCC and more distinct between. A paired t-test showed that these differences were significant (Table 1),

Inter-annual rainfall was significantly related to between-LCC and within-LCC variance in reference NPP for both LCCs (Figure 4), accounting for nearly equal proportions of within-LCC variance in reference NPP for UMDLCC and GLMLCC (Figure 4~~a~~b), but between-LCC variance was better accounted for by UMDLCC (81%) than for GLMLCC (66%; Figure 4a~~b~~).

The comparison of UMDLCC and the VAST land classification, albeit based on different data and aims, provided an independent comparison. 35.8% of UMDLCC reference pixels were in the VAST 'residual' class that has, theoretically, been undisturbed since 1750. The remaining 64.2% were in classes with varying degrees of vegetation changes from native pasture: 1-'modified' (29.6%); 2-'transformed' (19.2%); and 3-'replaced' (15.3%). The remaining reference sites, less than one percent, were in the 4-'removed' or 5-'bare' classes ~~which may~~with LCCs where all pixels were degraded, or have been caused by inadequate or inaccurate data used to create the LCCs, errors in the VAST classification, or a result of re-gridding VAST pixels from 1x1km to 250x250m spatial resolution.

3.2 LNS

The -30% LNS percent value used to differentiate ‘degraded’ areas from ‘non-degraded’ areas was equivalent to an average annual reduction in NPP of -169.6 gC m^{-2} $year^{-1}$ (standard deviation=25.5). Between 2000 and 2013 the average annual LNS across the entire BDT, including both ‘degraded’ and ‘non-degraded’ areas, was -2.14 MgC m^{-2} $year^{-1}$ (Table 2). The average reduction in ‘degraded’ areas was more than twice that in the ‘non-degraded’ areas and the LNS of the positive LNS trend class was lower than the negative and no LNS trends.

The sum of LNS values for an entire class, as opposed to the LNS value per unit area, revealed the importance of class size in contributing to the overall reduction in NPP. ~~The sum of LNS values for entire class, as opposed to LNS per unit area revealed how the importance the size of each class in contributing to the overall reduction in NPP.~~ The ‘degraded’ class had a total reduction in NPP of -1.1 GgC from 2000 to 2013 and occupied $1.46x10^6$ km^2 (Table 3). The larger area occupied by the ‘non-degraded’ class resulted in a greater total reduction in NPP (-1.9 GgC; Table 3), although much less severe reduction in NPP per unit area (Table 2). In the same way, non-degraded areas with no LNS trend ~~had~~ were by far the greatest total reduction in NPP owing to the large area occupied by this class.

Commented [HJ5]: Page 8, lines 9-10: Changed “The sum of LNS values for entire class, as opposed to LNS per unit area revealed how the importance the size of each class in contributing to the overall reduction in NPP. “ to “The sum of LNS values for an entire class, as opposed to the LNS value per unit area, revealed the importance of class size in contributing to the overall reduction in NPP.”

Commented [HJ6]: Page 8, lines 14-16: Changed “had” to “were”

The majority of degraded pixels had LNS values between -30% and -49%, with only a small proportion below -50%. The largest number of the non-degraded pixels were in the -10% to -29% LNS classes. For the degraded pixels, the average LNS in NPP units was less than half that of the non-degraded pixels (Tables 4 & 5). Similarly, reductions in NPP as a percent of the reference were ~~smaller~~ lower (more severe) for degraded than non-degraded pixels.

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3.3 Spatial variation in LNS

The extent of ‘degraded’ and ‘non-degraded’ areas varied between the six major river basins (Tables 4 & 5). Two of these, Belyando and Suttor, comprised 67% of all ‘degraded’ areas in the entire BDT while the Bowen Broken Bogie had the lowest (2%) (Table 4). Despite being the first and third largest basins in the BDT (‘degraded’ plus ‘non-degraded’ pixels) the Upper Burdekin and Cape Campaspe had only the third and fourth most ‘degraded’ pixels (Table 4), respectively. However, ‘non-degraded’ area decreased with decreasing size of each river basin (Table 5).

The severity of reductions in NPP, indicated by the average LNS, varied surprisingly little between river basins (Tables 4 & 5). The most severely degraded were in the Lower Burdekin, Bowen Broken Bogie, and Upper Burdekin (Table 4). The Upper Burdekin also had the most severe reductions of non-degraded pixels (Table 5). The Belyando and Cape Campaspe had the least severe reductions in NPP of degraded and non-degraded pixels, respectively. The average LNS and its percentage of the reference NPP for degraded and non-degraded pixels, however, were all within one standard deviation; suggesting that the reductions in NPP for each river basin did not differ substantially.

Among degraded areas there was evidence of managed grazing, including abrupt differences in LNS along station boundaries (Figure 5b), but there were also gradients of LNS within a single station (Figure 5c), and others with low LNS spread across multiple boundaries (Figure 5d). Other areas with evidence of management included forest clearing (Figure 5e) near station boundaries. There were also locations classified as degraded with little evidence of direct grazing management such as between the drainage lines of streams (Figure 5f).~~Among degraded areas there was evidence of managed grazing, including abrupt differences in LNS along station boundaries (Figure 5b), but there were also gradients of LNS within some stations (Figure 5c), and others with low LNS spread across boundaries (Figure 5d). Other areas with evidence of management included forest clearing (Figure 5e) near station boundaries. There were also locations classified as degraded with little evidence of direct grazing management such as between the drainage lines of streams (Figure 5f).~~

Commented [HJ8]: Page 9, lines 4-10: Changed "Among degraded areas there was evidence of managed grazing, including abrupt differences in LNS along station boundaries (Figure 5b), but there were also gradients of LNS within some stations (Figure 5c), and others with low LNS spread across boundaries (Figure 5d). Other areas with evidence of management included forest clearing (Figure 5e) near station boundaries. There were also locations classified as degraded with little evidence of direct grazing management such as between the drainage lines of streams (Figure 5f)." to "Among degraded areas there was evidence of managed grazing, including abrupt differences in LNS along station boundaries (Figure 5b), but there were also gradients of LNS within a single station (Figure 5c), and others with low LNS spread across multiple boundaries (Figure 5d). Other areas with evidence of management included forest clearing (Figure 5e) near station boundaries. There were also locations classified as degraded with little evidence of direct grazing management such as between the drainage lines of streams (Figure 5f)."

3.4 Inter-annual trends in LNS

Across the entire BDT there was substantial inter-annual variation in LNS, particularly in areas with low values (Figure 6a). In years with high rainfall (e.g. 2000, 2008, 2009 and 2011) compared with low rainfall (e.g. 2003, 2005 and 2013), there were fewer pixels with low LNS, but the severity of reductions was greater. In areas with little topographic variation, such as the central BDT, there was more spatial variation in low values between years. Positive trends were found predominately in the western and southern Upper Burdekin and southern Belyando basins. Negative trends were most common in the northern Belyando, central Upper Burdekin, and southern Suttor river basins. 79.4% of the BDT had no significant trend in LNS.

The magnitudes of negative and positive inter-annual trends in LNS varied substantially between river basins (Fig. 6b, Tables 6 & 7). The Suttor had by far the lowest negative trends (but the largest standard deviation; Table 6). The Upper Burdekin and Cape Campaspe had the least negative trends (Table 6). Positive trends were highest in the Bowen Broken Bogie and lowest in the Belyando (Table 7).

Some patches of positive and negative LNS trends were found in large areas that spanned multiple river basins (Figure 6b). These may have been a result of environmental conditions (e.g. low rainfall, soil properties) in some combination other than that used to create the LCCs, or a single variable not used in the classification, that crosses the LCC boundaries, for example, more friable soils.

There were strong contrasts in the average LNS of the negative and positive trend classes between river basins (Tables 6 & 7). The average LNS of negative trends in the Suttor was nearly twice that of the Upper Burdekin. The Suttor river basin had most severe LNS reductions in the negative trend class (Table 6). On average, for negative trends, the Bowen Broken Bogie, Upper and Lower Burdekin had the least severe reductions in NPP while the most severe were in the southern river basins: Belyando, Cape Campaspe, and Suttor (Table 6). Surprisingly, the Belyando had less severe reductions in NPP in areas with negative trends (Table 6) than in areas with positive trends (Tables 7). In the Belyando, the percent LNS for positive trends were less than -30%, suggesting that numerous low LNS values were found among positive trends.

3.5 Comparisons of LNS and environmental characteristics

For the entire BDT, the overall spatial distribution of annual hillslope erosion was strongly correlated (*k* = 0.7) with LNS. Other environmental variables indicative of degradation (gully density, rainfall erosivity, and sediment load) were also high overall, (*k* = 0.6). For individual pixels, maps of correlation revealed strong regional differences (Figure 7). The Suttor had the greatest spatial agreement between LNS and each environmental variable, while the Bowen Broken Bogie had the least. Strong agreement between annual hillslope erosion and LNS ~~were~~ occurred ~~in~~ throughout the BDT (Figure 7a), particularly in the central Upper Burdekin, Cape Campaspe, Suttor and Belyando. The spatial agreement between LNS and gully density (Figure 7b) were largely similar to that of LNS and hillslope erosion except the presence of large clusters of low kappa values in the northern basins. The spatial pattern in kappa values for LNS and rainfall erosivity (Figure 7c) and sediment load (Figure 7d) resembled rainfall gradients in the region, northeast to southwest.

Commented [HJ9]: Page 10, line 11: Changed "were occurred in" to "occurred"

VAST classes were generally correlated with LNS (Table 8). The average LNS declined with increasing human modification. 'Removed' and 'bare' had the lowest average LNS of any VAST class. The only negative trend was in the 'bare' class, presumably an indication that a small amount of vegetation was present, while 'removed' had the largest positive trend.~~The only negative trend was in the 'bare' class while 'removed' had the largest positive trend~~. Inter-annual trends in LNS further differentiated the two classes; 'bare' had the only negative trend while 'removed' had the largest positive trend, which may be a result of the strongest regrowth from the lowest starting value of all the classes.

4 Discussion

4.1 Land capability classification (LCC) and local NPP scaling (LNS)

The basis of selection of the reference NPP and detection of anthropogenic reductions in LNS is the classification of the landscape into uniform units (LCCs) with respect to the environmental factors that affect NPP. The procedure was generally successful in creation of classes of environmentally uniform pixels, differing only in the long-term degree of degradation. The same reference sites were frequently selected in multiple, sometimes consecutive, years for the 14 years included in the study and therefore potentially for a longer term. This indicates that degradation, as detected with LNS, corresponded to sites that were persistently below the potential. This emphasized that these sites were not simply subject to some short-term environmental deficiency, such a single-year with spatially patchy lower rainfall. ~~This indicates that degradation, as detected with LNS, were sites that were persistently below the potential, not simply subject to some short-term environmental deficiency, such a single-year with spatially patchy lower rainfall.~~ The value of incorporating inter-annual variation of precipitation in the classification rather than a climatological average is illustrated by the comparison of GLM. UMDLCC proved better able to minimize within-LCC variance while also maximizing the between-LCC variance (Table 1, Figure 4a & Figure 4b). The large numbers of UMD reference sites that fell in the VAST 'residual' class and the larger reductions in NPP in VAST classes with higher levels of human modification, offer further evidence of the reliability of the UMDLCC classification (Table 8). Furthermore, the spatial coincidence of differences in management with differences in LNS found by visual inspection of high resolution imagery suggests that the procedure was able to distinguish regional, anthropogenic land degradation from natural variation in environmental factors.

Commented [HJ10]: Page 10, line 33-36: Changed "This indicates that degradation, as detected with LNS, were sites that were persistently below the potential, not simply subject to some short-term environmental deficiency, such a single-year with spatially patchy lower rainfall." to "This indicates that degradation, as detected with LNS, corresponded to sites that were persistently below the potential. This emphasized that these sites were not simply subject to some short-term environmental deficiency, such a single-year with spatially patchy lower rainfall."

Nevertheless, undetected errors may arise in the classification process, some of which are noted in the Methods section. Changes in land cover during the study period are unlikely to have caused errors since the rates of pasture clearing decreased dramatically throughout the Burdekin region from 1988 to 2002 and remained relatively low during the study period (2000 to 2012, ~~(~~DSITIA, 2014). A more fundamental problem might arise because the classification procedure did not allow for any interactions between environmental factors in different parts of the study area. A possible example of this from the BDT is the location of the largest spatial variations in LNS and its inter-annual trends near the coastline (e.g. Lower Burdekin and Bowen Broken Bogie) where rainfall is highest. This is an example of a drawback of statistical classification which can only account for additive effects of the environment whereas, for example, moisture availability can alter the response of production to management (Ibrahim et al., 2015), maybe non-linearly. This points to an advantage of replacing the statistical derivation of LCCs with a process-based model that can convolve the environmental factors in realistic mechanisms. Such a model run in “potential” mode, which is without any anthropogenic effects, could create a reference NPP for each pixel. At the present time, however, the environmental variables and parameters needed for a useful process model are only rarely available.

4.2 Extent of degradation of NPP in the BDT

Across the entire BDT region, from 2000 to 2013, the average annual reduction in NPP below the reference was 2.14 MgC m^{-2} $year^{-1}$ (Table 2). The average LNS in the non-degraded class (arbitrarily set at LNS between 0 and -29%) was -97.5 gC m^{-2} $year^{-1}$ and the degraded class (LNS <30%) -209.1 gC m^{-2} $year^{-1}$ (Tables 4 & 5). However, owing to the greater area of ‘non-degraded’ land in the entire BDT (80.3%) compared to the ‘degraded’ class (19.7%) (Table 2), the total NPP reduction in non-degraded areas was actually greater. Reductions in NPP, as indicated by low LNS, affect the carbon pool in several ways: by reduced rates of sequestration (Dregne, 1983); by reduction in biomass of live and dead vegetation; by loss of soil organic matter (Burke et al., 1995; Smith et al., 2012; Su et al., 2005); or by a shortened growing season, for example among introduced, less-adapted, pasture species (Falge et al., 2002a; Falge et al., 2002b). The large reduction in NPP found here is in agreement with reports of episodes of widespread land degradation occurring in the BDT (McKeon et al., 2004a; Smith et al., 2007; Stone et al., 2007).

Overall, positive temporal trends in LNS were twice as common as negative trends (Tables 6 & 7). The ‘Non-degraded with no trend’ class had the largest total area (65.3%). This class was widespread in every river basin, indicating that most of the BDT region was not affected by severe degradation. In other areas, for example in Belyando and Bowen Broken Bogie, the average LNS of ‘Degraded with positive trends’ areas suggests that significant areas were recovering from earlier degradation (Table 7). Nevertheless, some areas were degrading between 2000 and 2013 and in some, their negative trends intensified through the study period, as indicated by the extent of the ‘Degraded with negative trends’ class (Table ~~1~~2). Areas classified as ‘Degraded with negative trends’ occupied 24.7% of the entire BDT –candidate areas for actions to reverse or at least arrest the trend. There were a few instances of ‘Degraded with no trends’, ~~presumably~~ a possible indicator sites in a state of long-term, maybe permanent, irreversible degradation or approaching this state. Permanent degradation is a serious condition since it is generally reversible only with intensive remediation (Prince, 2002; Reynolds et al., 2007) which often costs more than the value of the restored land, however, there were a few areas of ‘Degraded with positive trends’ which may be examples of land that has been rehabilitated.

Commented [HJ11]: The numbers do match, but I will ensure the number is presented exactly as in the table
Page 12, lines 4-20: Changed “65%” to “65.3”

Commented [HJ12]: Page 12, line 12: Changed “Table 1” to “Table 2”

Commented [HJ13]: It can due to the very irreversible nature of degradation
Page 12, line 15: Changed “presumably” to “a possible indicator”

4.3 Anthropogenic and environmental degradation

While substantial reductions in NPP were found across the BDT region as whole, there was considerable variation between river basins. The link between anthropogenic disturbance and rates of degradation (detected here by low LNS) has been noted by Hill et al. (2005) and Kairis et al. (2015) and specifically in the BDT by McKeon et al. (2009). Independent evidence for anthropogenesis presented here includes correlation with the VAST map which, although not a map of vegetation degradation, does distinguish varying degrees of human-related modification of native vegetation (Thackway and Lesslie, 2005). The ~~strong correlation~~good agreement of ranks of average LNS and the VAST classes (Table 8) is evidence that LNS was able to separate human-related degradation from natural variation, at least up to the end of the period of time used for the VAST map (2011). In addition, there was qualitative evidence from visual inspection of high resolution remotely-sensed imagery, such as abrupt differences across station boundaries (e.g. Figure 5b & Figure 5c) and coincidences of visible disturbance around livestock water points. The relationship between degradation, accelerated rates of erosion, and reduced vegetation cover is well-known (Lal, 2001) and erosion is the most widespread and recognizable characteristics of land degradation (Ravi et al., 2010), also a primary impact on loss of soil carbon (Rajan et al., 2010). In the present study, there was a strong overall correlation of average LNS with hillslope erosion and gully density (Figure 7). In the BDT others have linked erosion with poor grazing management (Bartley et al., 2006) and unsustainable agricultural production (Montgomery, 2007).

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Page 12, line 29: Changed "strong correlation" to "good agreement" to be more precise.

Assigning causal relationships to land degradation and natural or anthropogenic factors is difficult due to the close coupling between humans and their environment (Reynolds et al., 2007). The LNS procedure offers one approach that attempts to isolate actual degradation of NPP from less favorable environmental conditions. However, without additional data on land usage, such as livestock numbers and management practices, the causes of the reductions by human-related activities are hard to determine (Bastin et al., 2012). The most commonly-cited management practices to reduce degradation are reduction in domestic livestock, reduction of feral herbivores, removal of watering points (Bastin et al., 2012; Fensham and Fairfax, 2008; Silcock and Fensham, 2013), fallowing (Bastin et al., 2012; Bastin et al., 1993), or by encouraging vegetation that is particularly resistant to overgrazing or able to recover quickly after intense grazing (Bastin et al., 2012; McKeon et al., 2004b; Smith et al., 2007). Additional data are needed to interpret low LNS, particularly with field observation.

Given the extremely large areas of provincial, national, regional and global degradation that are frequently stated (Bai et al., 2008; Bridges and Oldeman, 1999; Kassas, 1995; Oldeman, 1994; UNEP, 1997; Zika and Erb, 2009) and the far-reaching effects of degradation on human livelihoods (Adeel, 2008; UNCCD, 1994), rigorous, quantitative and objective measurements are urgently needed. While reduction of NPP is a single type of degradation, it is a quantitative measure of the outcome of most forms of degradation relevant to human needs - but not all (e.g. loss of palatable species with no change in NPP;~~) (~~Asner and Heidebrecht, 2005). The widespread occurrence of degradation and its anthropogenic causes and effects require measurements having the large-area coverage and high spatial resolution provided by remote sensing, despite their limitations. LNS is founded on the concept of comparison of the actual conditions with their potential. As noted, there are several weaknesses in the technique that may affect the validity of the results, nevertheless, the fundamental concept of reduction from an explicit standard remains. There also remains a need for improvements in detection of appropriate reference standards, either by local scaling as in LNS or some other method.

The objectives of the many initiatives to arrest and remediate degradation have been summarized in the concept of Zero Net Land Degradation (ZNLD) (Stavi and Lal, 2015). ZNLD seeks to slow current rates of degradation such that the rates of land rehabilitation are, at the very least, equivalent to rates of deterioration (Lal et al., 2012), locally or elsewhere. Achievement of ZNLD depends on comprehensive monitoring to identify land states and trends of degradation. The study presented here used one approach to such regional assessment. While the feasibility of global land degradation neutrality has been debated (Grainger, 2015), the BDT is an example of a region that has seen a reversal of an overall trend toward degradation in productivity.

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Table 1. Mean, standard deviation, and t-test of mean square variance of reference NPP (gC m^{-2} $year^{-1}$) for UMDLCC and GLMLCC, partitioned into between-LCC and within-LCC.

Mean square variance	UMDLCC		GLMLCC		Significance level
	Mean	Std deviation	Mean	Std deviation	
Between LCCs	4.15×10^8	1.1×10^8	1.76×10^8	0.5×10^8	$t_{13}=12.6$ $p<0.0001$
Within LCCs	4.38×10^4	1.1×10^4	7.71×10^4	2.3×10^4	$t_{13} = 9.6$ $p<0.0001$

Table 2. Average LNS (Mg C m^{-2} $year^{-1}$) in the Burdekin Dry Tropics (BDT) region for all six combinations of degraded and non-degraded LNS conditions and three inter-annual LNS trends – no trend, positive and negative trends. The percentage of BDT area in each land condition is shown in parentheses.

Trend category	Degradation condition (Mg C m^{-2} $year^{-1}$)		
	Non-degraded LNS	Degraded LNS	Average
No LNS trend	-1.70 (65.3%)	-3.85 (14.1%)	-2.08 (79.4%)
Positive LNS trend	-1.90 (10.0%)	-3.95 (3.6%)	-2.44 (13.6%)
Negative LNS trend	-1.48 (5.0%)	-4.14 (2.0%)	-2.24 (7.0%)
Average	-1.71 (80.3%)	-3.90 (19.7%)	-2.14 (100%)

Table 3. Area and percentage of Burdekin Dry Tropics in each LNS range.

Degradation Condition	LNS Range	Total area (km^2) and percent of BDT	Total reduction in NPP (GgC)
Non-degraded	0 to -9%	$1.12x10^6$ (15.8%)	-1.9 (80.3%)
	-10 to -19%	$2.40x10^6$ (33.9%)	
	-20 to -29%	$2.10x10^6$ (29.6%)	
Degraded	-30 to -39%	$0.96x10^6$ (13.6%)	-1.1 (19.7%)
	-40 to -49%	$0.35x10^6$ (5.0%)	
	-50 to -59%	$0.10x10^6$ (1.5%)	
	-60 to -69%	$0.03x10^6$ (0.4%)	
	-70 to -79%	$0.01x10^6$ (0.1%)	
	< -80	$0.00x10^6$ (<0.0%)	

Table 4. Degraded LNS class. Area, severity, and variation in LNS and LNS percent. sd – standard deviation

River basin (in decreasing order of area)	Total area in km^2 and percent of the class	Average LNS in gC m^{-2} $year^{-1}$	Average LNS as a percentage of reference NPP
Upper Burdekin	$2.28x10^5$ (16%)	-225.3 (sd=42.8)	-36% (sd=6)
Belyando	$6.60x10^5$ (45%)	-200.2 (sd=47.5)	-40% (sd=8)
Cape Campaspe	$2.05x10^5$ (14%)	-205.3 (sd=45.6)	-39% (sd=9)
Suttor	$3.17x10^5$ (22%)	-215.3 (sd=52.0)	-40% (sd=9)
Bowen Broken Bogie	$0.33x10^5$ (2%)	-225.7 (sd=45.7)	-36% (sd=7)
Lower Burdekin	$0.25x10^5$ (2%)	-226.7 (sd=55.1)	-38% (sd=8)
Entire BDT region	$14.79x10^5$ (100%)	-209.1 (sd=48.7)	-39% (sd=8)

Table 5. Non-degraded LNS class. Area, severity, and variation in LNS and LNS percent. sd – standard deviation

River basin (in decreasing order of area)	Total area in km^2 and percent of the class	Average LNS in gC m^{-2} $year^{-1}$	Average LNS as a percentage of reference NPP
Upper Burdekin	20.34×10^5 (34%)	-105.3 (sd=45.0)	-17% (sd=7)
Belyando	14.15×10^5 (24%)	-92.2 (sd=39.2)	-18% (sd=7)
Cape Campaspe	9.74×10^5 (16%)	-88.3 (sd=41.2)	-16% (sd=8)
Suttor	7.57×10^5 (13%)	-97.4 (sd=41.2)	-18% (sd=8)
Bowen Broken Bogie	6.01×10^5 (10%)	-99.6 (sd=49.8)	-15% (sd=7)
Lower Burdekin	2.03×10^5 (3%)	-95.4 (sd=49.5)	-15% (sd=8)
Entire BDT region	59.83×10^5 (100%)	-97.5 (sd=43.9)	-17% (sd=7)

Table 6. Negative trends in area, inter-annual rate, and severity of LNS for river basins of the Burdekin Dry Tropics. sd – standard deviation.

River basin (in decreasing order of area)	Total area in km^2 and percentage of those areas with negative trends	Average trend in gC m^{-2} $year^{-1}$	Average LNS in gC m^{-2} $year^{-1}$ and as a percentage of reference NPP
Upper Burdekin	$1.26x10^5$ (24%)	-7.3 (sd = 2.8)	-102.0 (-16%)
Belyando	$2.10x10^5$ (40%)	-8.4 (sd = 3.3)	-134.0 (-27%)
Cape Campaspe	$0.71x10^5$ (14%)	-7.5 (sd = 2.6)	-131.7 (-24%)
Suttor	$0.77x10^5$ (15%)	-13.8 (sd = 10.0)	-184.2 (-34%)
Bowen Broken Bogie	$0.22x10^5$ (4%)	-9.7 (sd = 6.0)	-95.0 (-14%)
Lower Burdekin	$0.15x10^5$ (3%)	-9.5 (sd = 5.6)	-116.0 (-17%)
Entire BDT region	$5.21x10^5$ (100%)	-8.9 (sd = 5.4)	-120.5 (-25%)

Table 7. Positive trends in area, inter-annual rate, and severity of LNS for river basin of the Burdekin Dry Tropics. sd – standard deviation.

River basin (in decreasing order of area)	Total area in km^2 and percentage of those areas with positive trends	Average trend in gC m^{-2} $year^{-1}$	Average LNS in gC m^{-2} $year^{-1}$ and as a percentage of reference NPP
Upper Burdekin	$2.70x10^5$ (27%)	7.6 (sd = 2.7)	-124.5 (-20%)
Belyando	$2.50x10^5$ (25%)	6.8 (sd = 3.3)	-151.1 (-31%)
Cape Campaspe	$1.53x10^5$ (15%)	7.3 (sd = 3.0)	-113.4 (-21%)
Suttor	$1.67x10^5$ (16%)	8.7 (sd = 3.7)	-139.6 (-26%)
Bowen Broken Bogie	$1.46x10^5$ (14%)	10.1 (sd = 3.6)	-118.4 (-19%)
Lower Burdekin	$0.31x10^5$ (3%)	8.6 (sd = 3.4)	-117.2 (-18%)
Entire BDT region	$10.16x10^5$ (100%)	7.9 (sd = 3.4)	-130.7 (-23%)

Table 8. VAST class comparison with inter-annual trends in LNS and average LNS. sd – standard deviation.

VAST classes	Average trend in gC m^{-2} $year^{-1}$	Average LNS in gC m^{-2} $year^{-1}$	Average LNS as a percentage of reference NPP
0-'Residual'	0.3 (sd = 4.7)	-110.2 (sd = 63.7)	-19.7% (sd = 11.1)
1-'Modified'	1.0 (sd = 4.8)	-110.2 (sd = 61.5)	-19.4% (sd = 10.5)
2-'Transformed'	1.1 (sd = 5.1)	-115.2 (sd = 62.6)	-21.6% (sd = 11.7)
3-'Replaced'	0.6 (sd = 6.1)	-123.6 (sd = 66.1)	-24.9% (sd = 12.6)
4-'Removed'	1.5 (sd = 5.3)	-171.5 (sd = 98.2)	-32.7% (sd = 17.7)
5-'Bare'	-0.9 (sd = 7.3)	-130.2 (sd = 78.6)	-23.9% (sd = 14.5)

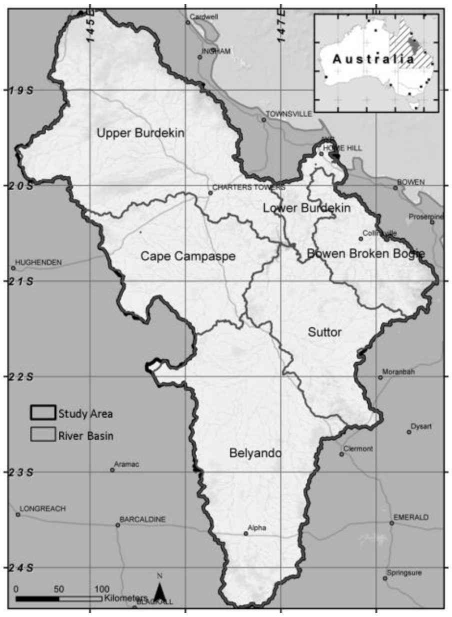

Figure 1. Location of the Burdekin Dry Tropics (BDT) region in the State of Queensland, Australia, the six major river basins, and major roads and towns.

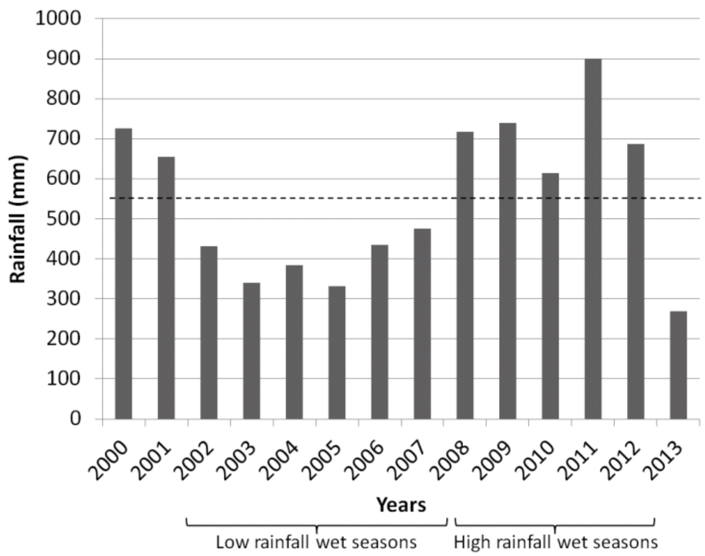

Figure 2. Annual average rainfall in BDT for 2000-2013. The dashed line is the 14 year average.

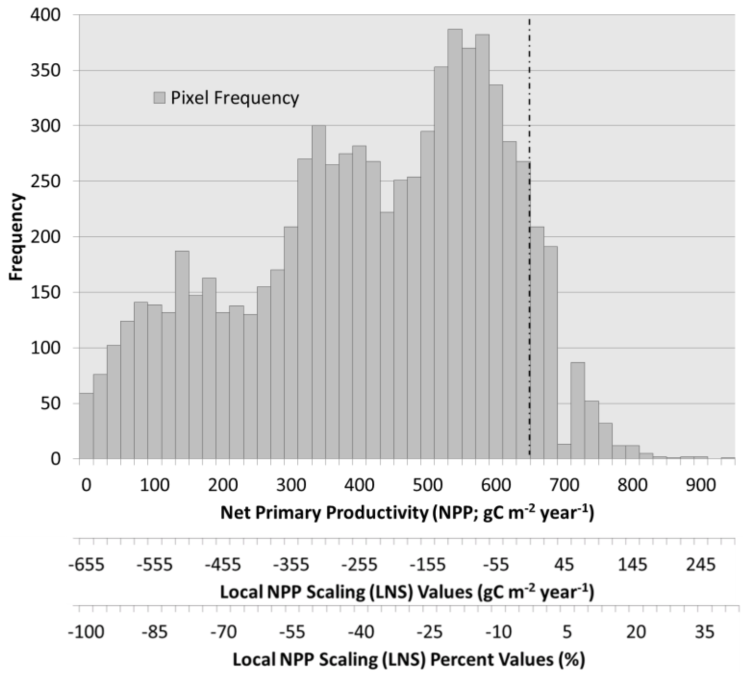

Figure 3. Example of the use of the frequency distribution of NPP of pixels in a single Land Capability Class (LCC) to calculate Local NPP Scaling (LNS) values. The vertical line denotes the reference NPP at the 85 percentile of the distribution. The abscissa is labelled in LNS, NPP and percentage LNS units.

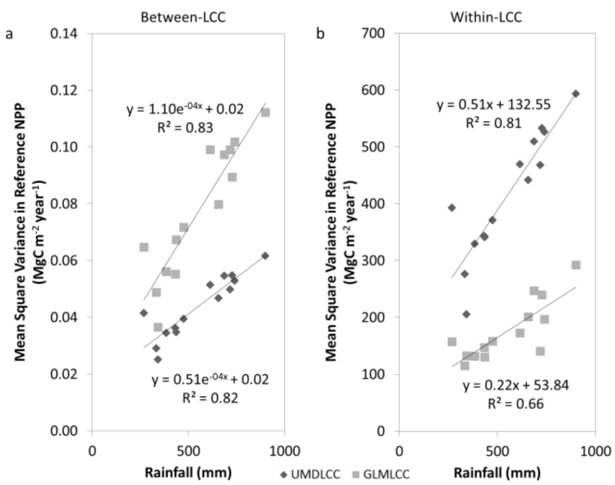

Figure 4. Mean square variance in reference NPP (MgC m^{-2} $year^{-1}$) for UMDLCC and GLMLCC in relation to rainfall; (a) 'between-LCC' and (b) 'within-LCC' with best-fit regression lines for each year 2000 to 2013lines.

Commented [HJ15]: Page 32: Changed "...lines." To "...lines for each year 2000 to 2013."

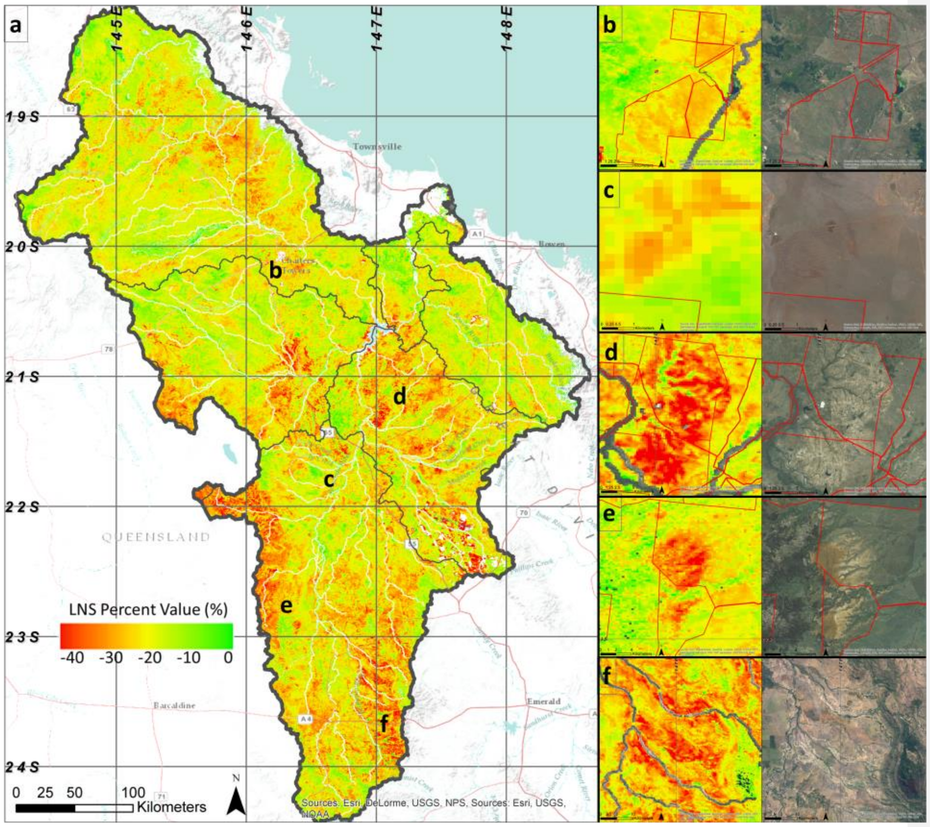

Figure 5. Local Net Production Scaling (LNS) in the Burdekin Dry Tropics (BDT) (a) and enlargements of the areas indicated in (a): (b) high and low LNS values on either side of a station boundary; (c) variation within a single station showing gradients from low to high; (d) low LNS in eroded drainage area; (e) hillslope erosion resulting in bare surface with little to no vegetation cover; (f) area of tree removal with visible erosion and reduced cover. Black lines are the boundaries of river basins and red lines are station boundaries.

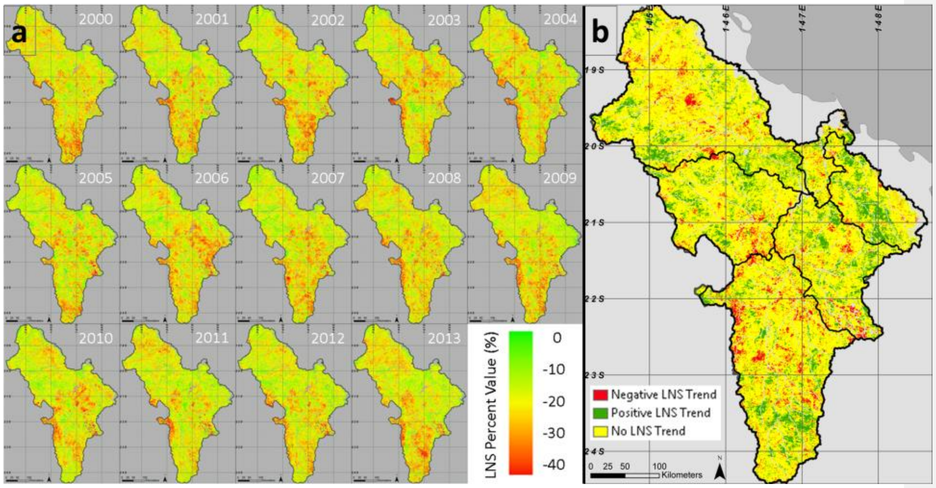

Figure ~~3~~6. Time-series of maps of the Burdekin Dry Tropics from 2000-2013 showing (a) annual LNS percent values from 2000 to 2013 and (b) inter-annual trends in LNS classified into negative, positive, and no LNS trend.

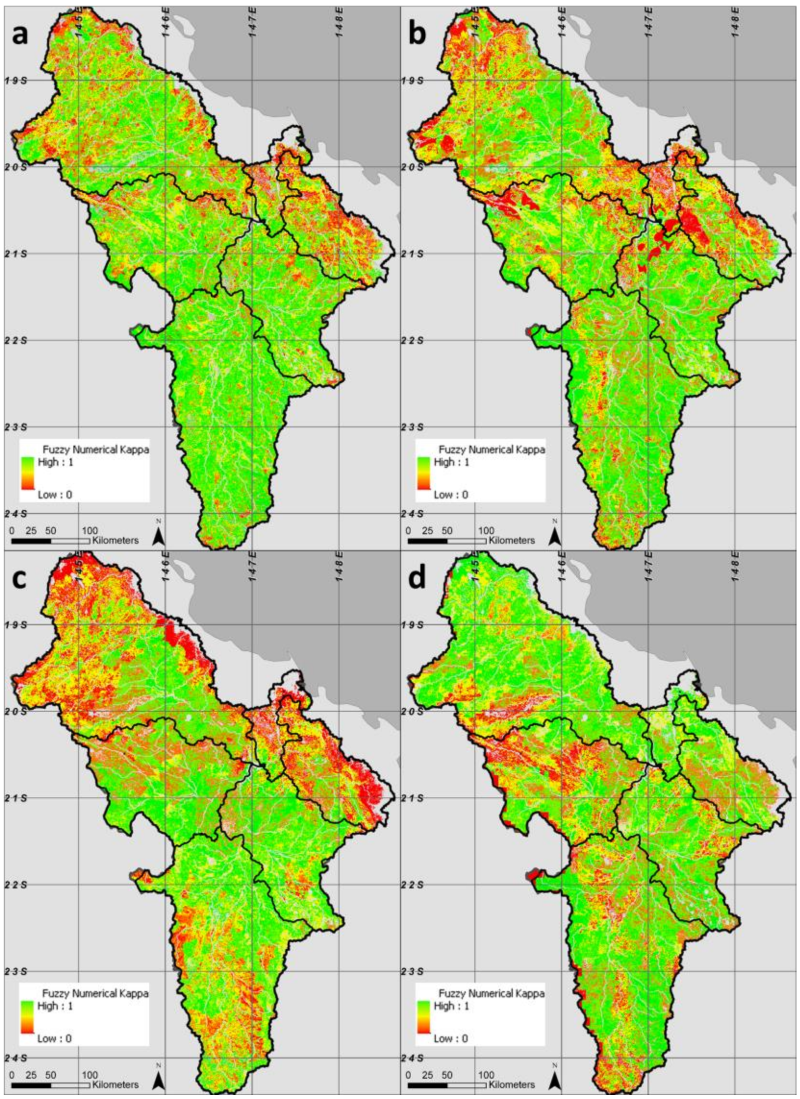

Figure 47. Similarities between (a) annual hillslope erosion, (b) gully density, (c) rainfall erosivity, and (d) sediment load and percentage LNS as indicated by fuzzy numeric kappa.