Biogeosciences
Discussions

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Interactive comment on "Assessing vegetation structure and ANPP dynamics in a grassland-shrubland Chihuahuan ecotone using NDVI-rainfall relationships" *by* M. Moreno-de las Heras et al.

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We would like to thank Reviewer 1 for his/her interest in our manuscript and helpful comments. We detail below a point-by-point response to all his/her comments/suggestions. Modifications to adapt the paper to Referee1's comments can be tracked in the marked MS submitted as supporting information for this response.

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Point-by-point reply:

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Comment 1: "This is an interesting study aiming to model the contribution of shrubby and grassy patches to the yearly time course of MODIS-NDVI in drylands and then to use remotely sensed proxies to quantify the Aboveground Net Primary Productivity (ANPP) of each Plant Functional Type (PFTs) over the last 13 years and across a 18km2 area in the Chihuahuan "desert". The context of the study is that of a well-documented conversion from grasslands to shrublands over the last century triggered by a combination of overgrazing, summer drought and modification of the fire regime, and that of the impact of these vegetation changes to ecosystem functioning. This is clearly stated in the paper."

Response to Comment 1: We very appreciate the positive evaluation of the scope and contents of our study.

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Comment 2: "Overall, I find the analysis looks like a long and winding road. Essentially, authors have to solve an inverse problem. They assume that the MODIS-NDVI signature at a 230m resolution results from the growth response of a mosaic of two PFTs: shrubs and grasses. Given a growth response model for these two PFTs, the NDVI time series is decomposed in two parts and the contribution of each PFT is estimated. To solve this problem, I think a more straightforward approach could be used. First, I would have slightly refined the two differential equations (eq. 1 and 2) capturing the key ecohydrological processes of the system (see below). Second, I would have extracted the NDVI time series from a set of calibration sites where cover of each PFT is known (to be chosen among the 27 sites) and used these remotely-sensed data to optimize the few parameters governing the plant biomass dynamics (eq. 1). Third I would have assessed the performance of the model when applied to the entire area".

Response to Comment 2: We studied the spatial organization and dynamics of herbaceous and shrub ANPP in a grassland-shrubland ecotone using detailed analysis of the

relationships between time series of antecedent precipitation and MODIS NDVI. The final purpose of our work was to generate a new, parsimonious, semi-empirical approach for the analysis of grassland-shrubland ecotone dynamics that could be easily implemented using coarse-grained remote sensing data in dryland systems affected by shrub encroachment. The main assumption of our approach was that herbaceous and shrub vegetation respond differently to antecedent precipitation (i.e. herbaceous vegetation shows quick growth pulses in response to short-term rainfall while shrubs have a slow response to longer term antecedent precipitation) and therefore, grassland-shrubland ecotone dynamics may be reflected in the analysis of landscape-scale vegetation-rainfall relationships. We used a simple process-based model to briefly illustrate, from a conceptual point of view, the validity of the general assumption. This model was not further implemented for the rest of the study. Conversely, actual analysis of the relationships between antecedent precipitation and vegetation dynamics in the field was applied using a semi-empirical study approach, based on the biophysical principles illustrated with the model. First, we determined empirically the length of the antecedent rainfall series that best described vegetation growth for herbaceous and shrub vegetation in control sites using NDVI values as a proxy of green biomass. We used these vegetation-type specific relationships as lumped (or black-box) spatiotemporal criteria to (i) classify landscape types and (ii) decompose NDVI time series into herbaceous and shrub components of landscape ANPP. Performance of both the semi-empirical landscape classification and NDVI decomposition methods was evaluated against ground-based data on spatial distribution of vegetation types (27 points, one year, 2013) and ANPP temporal series (2000-11 series for two approx. 1000 m2 core sites), obtaining a very strong agreement with field data. Remote-sensed classification of landscape types and ANPP estimations were further applied to analyse the spatiotemporal dynamics of vegetation across the ecotone.

The referee suggests, as an alternative way of analysis, direct use of the model (or a refined version of the simple model presented in the paper) to extract the shrub and herbaceous components from the NDVI time series after calibration at control sites. We

believe that the application of this alternative way would hardly be feasible for this study. The use of simple process-based models such as the one presented in equations 1 and 2 (Rietkerk's dynamic model, Rietkerk et al. 2002) is justified for hypothesis generation and steady evaluation of general assumptions (as we did in this study). Direct application of a fully physically based modelling approach for decomposing/estimating ground-based NPP for different types of vegetation in mixed systems probably would require completely explicit plant-competition equations (i.e. the model should be able to predict plant-plant interactions between herbaceous and shrub components) and details of soil-surface processes (e.g. runoff redistribution, soil erosion) that feedback on herbaceous-shrub interactions in grassland-shrubland desert ecotones. All these interactions and processes cannot be included in just two simple differential equations and would rather require the use of a variety of complex and spatially distributed coupled models for surface hydrology, soil moisture and plant production, for which we have little data to parameterise such a framework. Application of such very complex approach would add further difficulties, not least due to the inherent uncertainties in and availability of model parameters as discussed by Stewart et al. (2014). The referee suggests using discrete (one year) ground-measured abundances of shrubs and herbaceous vegetation for parameter optimization and model calibration in some of the 27 control sites we established in the field in 2013. However, model parameterization would require also other type of information (e.g. temporal trends of spatially distributed soil moisture and vegetation cover, detailed soil and surface hydrology data) that is not available for those sites. We are familiar with the use of complex ecohydrological models. Particularly, we are currently involved in the development of a complex, coupled-modelling approach for the analysis of grassland-shrubland transitions using a variety of models for surface hydrology (MAHLERAN, Wainwright et al. 2008), soil moisture (Soilwat, Parton 1978), and plant production (Daycent, Parton et al. 1998). However, the development of that framework constitutes a totally different and independent work, and the use of such very complex approach for this study is largely unfeasible. Developing this complex approach will require a significant programme of data collection,

among others the large-scale decomposed ANPP trends for herbaceous and shrub vegetation obtained in this study across the Five Points SEV ecotone.

In the interim, we consider that we applied a very efficient study approach, which facilitates optimization of results with a low degree of complexity, limited data availability and robustness to parameter uncertainty. Our lumped semi-empirical approach is parsimonious (i.e. we used time series of rainfall and NDVI, together with limited ground-based NPP datasets and vegetation-type abundances) and has a demonstrated ability to determine accurately the spatiotemporal dynamics of herbaceous and shrub vegetation for our site (i.e. agreement of our landscape classification and decomposed NDVI series with ground-based distribution of vegetation types and ANPP values is very strong, Figures 4 and 5). The simplicity of the approach will facilitate extension and exploration of the methodology broadly, and does not depend on having calibration data available for a specific field site. In order to facilitate application of the approach in other sites, we have thoroughly prepared detailed computing/modelling codes for all critical parts of the study that are available as supporting information of this paper. Overall the methods are simple and straightforward so any researcher interested in this work can easily apply our study approach (which would be less feasible with a complex modelling approach).

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Comment 3: "Model structure: The low-dimensional model coupling plant biomass and soil moisture (eq. 1 and 2) falls a bit short to capture the key ecohydrological processes that control ecosytem reponse in these drylands. First, the lag between the pulse of resource (rainfall event) and the production of biomass is an important parameter to contrast shrub and grass response as thoroughly discussed in the paper. So I do not understand why this parameter is estimated in a second step - i.e. by correlating simulated biomass dynamics and observed rainfall data - and not included in the model structure. I am not convinced that the growth rate and the mortality rate are per se sufficient to properly estimate this lag".

Response to Comment 3: We used Rietkerk's dynamic model as a theoretical tool to illustrate briefly and in a simple way the dependency of the relationships between vegetation growth patterns and antecedent precipitation on vegetation type, particularly for dryland herbaceous vegetation and shrubs. The model is consistent with general observations of herbaceous and shrub growth patterns in drylands, indicating that herbaceous vegetation shows quick growth responses to short-term precipitation (i.e. weeks) while biomass dynamics of shrubs show slow responses to longer-term cumulative precipitation (i.e. months). In other words, the antecedent rainfall period (or lag as described by the referee) that best describe plant biomass dynamics is sensitively longer for shrubs than for herbaceous vegetation. The lag emerges from the biophysical behaviour of the different vegetation types, and consequently cannot be pre-imposed into the model structure. In fact, a process-based model that requires a pre-imposed lag parameter to reproduce or approach correctly biomass dynamics is missing critical information on plant-growth patterns (particularly in the growth and mortality rates, and possibly other parameters that can also impact the time-scale of the plant responses to precipitation).

We did not use the model to estimate lags, but more accurately, we applied this simple process-based model to illustrate conceptually the impact of the different plant-growth patterns for herbaceous and shrub vegetation (i.e. differences in plant growth and mortality rates) on the relationship between plant biomass and antecedent precipitation. In other words, the model is used to explain why production of herbaceous and shrub vegetation might show different lags to precipitation. The model indicates that (as it is largely documented in empirical studies in drylands, for example Ogle and Reynolds, 2004, Pennington and Collins, 2007, Forzieri et al., 2011, Garcia et al., 2010) shrubs have a more delayed growth pattern that is sensitive to much longer periods of antecedent precipitation when compared to herbaceous growth patterns. Actual differences in the response of plant dynamics to antecedent precipitation for this study were empirically determined in control sites using the temporal trends of NDVI as a proxy of green biomass. Spatiotemporal analysis of those empirical relationships was fur-

ther applied for classifying landscape types and deconvoling time series of NDVI into herbaceous and shrub ANPP series across the ecotone.

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Comment 4: "Model structure: Second, rain use efficiency is very dependent on the timing of rainfalls as illustrated in the last part of the paper that distinguishes monsoonal and non-monsoonal rainfalls. The model structure neither accounts for this. Third, differences between shallow-rooted grasses and the complex rooting systems of shrubs lead to more or less flexibility in using different water sources. In this context, a one layer soil model with similar threshold values for grass and shrub biomass production looks like a strong simplification".

Response to Comment 4: The model is indeed simple. We deliberately selected the simplest model which could help to understand in an easy way the link between differences in growing patterns of dryland herbaceous and shrub vegetation and plant biomass responses to antecedent precipitation, so the readers can track without difficulty the conceptual underpinning of the study approach. Explanation of these differences is straightforward. Plant-production inputs for vegetation types with fast growing patterns (i.e. herbaceous vegetation with high growing and mortality rates) have a very short residence time in the system and therefore show a "short memory" on antecedent rainfall conditions (sensu Alonso-Sanz and Martin, 2004). Conversely, plant production for vegetation types with low growth and mortality rates (i.e. shrubs and woody vegetation in general) has a "long memory" of precedent rainfall. Although simple, the model provides a good starting point for addressing differences in plant responses to antecedent precipitation for herbaceous and shrub vegetation in drylands.

We do not deny that other factors can also influence the relationships between plant biomass and antecedent rainfall. In fact, a quick exploration of the sensitivity of the Olr (the optimal rainfall accumulation length that best explains plant biomass dynamics; described as RaLmax in the previous version of the paper) on other model parameters

indicates that they can also influence to some extent the biomass-rainfall relationships (see the new Supplementary Figure 1). W0, kw, ki, and c have negligible effects on simulated Olr values, while reductions on bare soil infiltration (i0) and increases on water loss by direct evaporation and/or deep drainage (rw) can impact Olrhv and Olrs values, ultimately amplifying the differences we obtained between vegetation types. In addition, as a simplistic approach with a one-layer soil structure, the model simplifies some properties of real systems. For example, differences in rooting systems are not explicit for the different vegetation types, although their influence on the use of water can be, at least in part, absorbed by differences in apparent plant growth and mortality rates (Gilad et al. 2007). We would like to stress that we have used this simple modelling framework just for introducing, from a theoretical point of view, the general assumption of the study: "Our modelling results illustrate conceptually the distinct dependence of the relationship between plant biomass and antecedent precipitation on vegetation type, particularly when comparing the dynamics of dryland herbaceous and shrub vegetation" (Page 7, lines 17-19). We applied the model neither for estimating lags nor for classifying landscape types or decomposing the NDVI series into herbaceous and shrub ANPP components. Contrarily, we determined empirically reference vegetation-rainfall metrics (i.e. site-characteristic Olr values and the associated ARain antecedent rainfall series for the two different vegetation types) and further applied these calculations to implement our landscape classification and NDVI decomposition methods. The referee already noticed that our herbaceous and shrub ANPP estimations are sensitive to both seasonality and differences in apparent rooting depths of the vegetation types (both points are extensively discussed in section 5.3 of the paper). In fact, our semi-empirical approach consistently reproduces the observed distinct biophysical performance of the herbaceous and shrub components of vegetation in the grassland-shrubland ecotone studied with variable abundances of mainly Bouteloua eriopoda and Larrea tridentata plants.

In order to avoid incorrect interpretations of model application for this study, the general purpose for the use of Rietkerk's simplistic model in our study was clearly stated in the

introduction of the paper: "This paper is organized in two parts. First, we present the conceptual underpinning and theoretical basis of our study, by using a simple, process-based ecohydrological model to illustrate the biophysical control of the relationship between plant biomass dynamics and antecedent rainfall for dryland herbaceous and shrub vegetation. Secondly, we empirically determine reference optimal lengths of rainfall accumulation (in days) for herbaceous and shrub vegetation (Olrhv and Olrs) in a 18 km2 Chihuahuan ecotone, and use these vegetation-type specific NDVI-rainfall metrics to..." (Page 4, lines 25-31).

To clarify the scope and limitations of the model applied in the paper we have included/updated de following information (Page 7, lines 7-19): "Sensitivity analysis of Olr to other model parameters (Supplementary Fig.1 in the online supporting information of this study) indicates that W0, kw, ki, and c have negligible effects on simulated Olr values. Reductions on bare soil infiltration (i0) and increases on water loss by direct evaporation and/or deep drainage (rw) can impact Olrhv and Olrs values, ultimately amplifying the differences we obtained between vegetation types. Other factors not explicitly considered in our model, such as differences in root structure, may also reinforce herbaceous and shrub differences in time-scale plant responses to antecedent precipitation (Reynolds et al., 2004; Collins et al., 2014). The simple model presented in this study provides a good starting point for addressing general differences in plant responses to antecedent precipitation for different vegetation types in drylands. Overall, our modelling results illustrate conceptually the distinct dependence of the relationship between plant biomass and antecedent precipitation on vegetation type, particularly when comparing the dynamics of dryland herbaceous and shrub vegetation".

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Comment 5: "Model structure: Finally, given the linear relationship between ANPP and integrated NDVI over the growing season (Fig. 5), equation 1 might be viewed as a prognostic model of NDVI. This should be clearly explained to connect this model with the rest of the paper".

Response to Comment 5: We think that, more appropriately, NDVI provides a proxy of aboveground green biomass. This point is specifically stated in the paper both in the introduction (Page 3 lines 25-29: "Satellite-derived chlorophyll-sensitive vegetation indices, such as the Normalized Vegetation Index (NDVI), provide important information on vegetation structure (e.g. surface cover, aboveground green biomass, vegetation type) and dynamics over broad spatial domains (Anderson et al., 1993...")) and in the methods (Pages 8-9, lines 31-1: "We use temporal series of NDVI as a proxy of aboveground green biomass in our study area. NDVI is a remote-sensed chlorophyll-sensitive vegetation index that correlates with green biomass in semi-arid environments (Anderson et al., 1993; Huete et al., 2002...")). In addition, the very strong relationship obtained in this study between the time-integrated NDVI values and ground ANPP estimations (Figure 5) provides empirical evidence and validity of such links for our site.

In order to connect conceptual model simulations with the empirical results we have included the following text modification in the paper (Page 18, lines 26-28): "Our modelling results provide a biophysical explanation..." has been updated to "Given the strong relationship between time-integrated NDVI values and ground-based ANPP estimations in our site (Fig. 5b), our herbaceous and shrub exploratory modelling results provide a biophysical explanation...".

In addition, we have simplified concepts, so now they are concise and uniform throughout the paper, connecting the conceptual model simulations and the empirical results. For example, we have excised from the entire paper the term "NDVI-rainfall signature" that seemed to be confusing, and it has been replaced by the term "Olr" (for optimal length of rainfall accumulation). The "ARainhv" and "ARains" terms have also defined in the modelling section (Page 7, lines 1-3), and now they are used consistently across the paper.

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Comment 6: "Model structure. If I understood well, this model was not calibrated with

biomass data and so mortality and growth parameters were retrieved from published data. I wonder why authors did not use published values for the other parameters they do not include in the model (i.e. the delay effect)".

Response to Comment 6: Referee 1 is right. The model was not calibrated with field biomass/soil moisture data and parameter specifications were motivated by published modelling studies on dryland shrub-herbaceous systems. Particularly, parameter values were retrieved from studies that have applied theoretical modelling frameworks with a similar structure (i.e. simple one-layer models). The model was used as a conceptual tool to introduce our semi-empirical approach, so we did not try to calibrate the model with field data. Model simulations (Fig. 1a) approach consistently the general behaviour of the vegetation types analysed in this study (Fig. 3a). Growth peaks are smaller for the shrubs than for herbaceous vegetation, and shrubs also show in general a smaller reduction of plant biomass in dry periods after rainfall. In addition, the response of the shrubs is delayed when compared with the dynamics of herbaceous biomass. Indeed, the model provides a good starting point to explain, from a conceptual point of view, differences in plant responses to antecedent rainfall by herbaceous vegetation and shrubs.

The purpose of the application of this simple model is to offer a conceptual biophysical explanation of the time-scale dependencies of plant biomass-rainfall responses on vegetation type. The delayed responses emerge from the process representation, so the inclusion of any (additional) pre-imposed "delay-effect" parameters in the model is completely unnecessary (see also our response to Comment 3).

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Comment 7: "NDVI decomposition approach. There is some disconnect between the ecohydrological model (eq. 1 and 2) and the model of NDVI decomposition (eq. 3). Although the ecohydrological model highlights the key role of soil moisture dynamics the rest of the paper only focuses on rainfall data and on NDVI-rainfall relationship.

Why? Soil moisture dynamics is like a low-pass filtering of rainfall data and is more informative to model biomass response compared to rainfalls. For example, winter-spring recharge is probably essential to explain the spring growth of shrubs".

Response to Comment 7: Eqs. 3 and 4 describe the general assumptions of our NDVI decomposition approach. First, the time series of NDVI at any locations reflect the additive contributions of background soil, and the herbaceous and shrub components of vegetation for that particular site (eq. 3). Secondly, the primary determinant of the dynamics of both NDVI and green biomass in drylands is the rainfall pattern, and therefore the partial contributions of herbaceous vegetation and shrubs can be estimated as a function of their characteristic use or dependency on antecedent rainfall (eq. 4). In addition, our model (eqs. 1 and 2) describes the different dependency of herbaceous and shrub vegetation on antecedent rainfall and therefore is fully connected with our NDVI decomposition approach. We have re-worded a sentence in the methods to clarify this point (Page 12, lines 29-31): "and therefore the partial contributions of herbaceous vegetation and shrubs to NDVI can be estimated as a function of their vegetation-type characteristic use of rainfall" has been changed to "as a function of their characteristic dependency on antecedent rainfall".

We agree with the referee that soil-moisture dynamics are more informative than rainfall patterns for modelling dryland vegetation. Soil-moisture changes in time and space (both vertically and horizontally) vary quickly and rule vegetation dynamics in drylands, where the availability of water is the most limiting factor for plant production. However, the use of detailed records of broad-scale soil-moisture data for this study is not an option, since this type of data is not available in our site. Furthermore, such data are exceptionally rare, especially in dryland environments. This unavailability of data explains further the relevance of our study, which analyzes the coupling between remote-sensed vegetation greenness and rainfall patterns to explore broad-scale dynamics of herbaceous and shrub vegetation in a dryland ecotone. We explicitly detail in the introduction of the study the general links between remote-sensed dryland vegeta-

tion, soil-moisture dynamics and rainfall pattern/antecedent precipitation that justify our approach (Pages 3-4, lines 31-7): "In drylands, where vegetation dynamics are particularly well coupled with rainfall patterns, the relationship between time series of NDVI and precipitation provides specific information on the use of water for the production and maintenance of plant biomass (Pennington and Collins, 2007; Notaro et al., 2010; Veron and Paruelo, 2010). Investigations of the relationships between NDVI and rainfall suggest that arid and semi-arid vegetation responds to antecedent (or preceding cumulative) precipitation rather than to immediate rainfall, since plant growth is affected by the history of available soil moisture (Al-Bakri and Suleiman, 2004; Schwinning and Sala, 2004; Evans and Geerken, 2004; Moreno-de las Heras et al., 2012)".

We also agree with the referee that winter recharge of soil moisture is essential to explain, at least in part, biomass production for shrubs in the area. The results of our study fully support that assertion. In fact, analysis of the impact of seasonal rainfall on our remote-sensed estimations of shrub ANPP indicate that shrub production is highly sensitive to non-monsoonal winter precipitation, which contrasts with the close synchronization of herbaceous (forbs plus grasses) production with summer monsoonal rainfall for the area (please see Fig. 7 and Table 2). Please, note that our remote-sensed ANPP estimations for herbaceous and shrub vegetation in the ecotone were derived from the application of our NDVI decomposition method, revealing the very good performance of our study approach. The impact of winter rainfall on shrub ANPP is explicitly discussed in the paper and constitutes one of the main conclusions of our study: Page 21, lines 17-25 (Discussion): "Our results suggest that primary production is differently controlled by seasonal precipitation for herbaceous and shrub vegetation across the 18-km2 Chihuahuan Desert ecotone (Fig 7, Table 1). Monsoonal summer precipitation (June-September) controls ANPP for herbaceous vegetation (Fig. 7a), while ANPP for shrubs is better explained by the preceding year's non-monsoonal (October-May) plus the summer monsoonal precipitation in the present year (Fig 7b). Accordingly, field observations of ANPP for Chihuahuan landscapes found that grassland primary production is particularly coupled with monsoonal rainfall, while desert

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shrublands appear to be less dependent on summer precipitation (Fisher et al., 1988; Reynolds et al., 1999; Huenneke et al., 2002; Muldavin et al., 2008; Throop et al., 2012)". Page 22, lines 9-15 (Discussion): "Non-monsoonal precipitation (about 40% annual precipitation, primarily from November to February) typically falls in the form of long-duration low-intensity frontal rainfall that often percolates to deep soil layers (Snyder and Tartowsky, 2006). Larrea tridentata, the dominant C3 shrub in the studied ecotone, has a bimodal rooting behavior that facilitates the use of both shallow and deep soil moisture for plant production (Fisher et al., 1988; Reynolds et al., 1999; Ogle and Reynolds, 2004). Deep creosotebush roots (70-150 cm depth) may acquire winter-derived soil-water resources that are unavailable to grass species...". Page 24, lines 12-15 (Conclusions): "Analysis of remote-sensed NPP dynamics at the grassland-shrubland ecotone reflects a variable performance of dominant vegetation types. Herbaceous production is synchronized with monsoonal summer rainfall, while shrub NPP shows a flexible response to both summer and winter precipitation".

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Comment 8: "NDVI decomposition approach. The key point here is that I am not convinced that the so called "Arain" function captures adequately the growth response of individual PFT and its coupling with soil moisture dynamics. For example, in the creosotebush core sites, the adjusted NDVI-rainfall relationship is somewhat biphasic and seems to capture both grassland and shrub responses (Fig. 3B). I also wonder if the persistence of high NDVI in shrublands during the dry period is adequately captured by the model (it seems this is more pronounced in observed data (fig. 3A) compared to the simulated data fig. 1A). In short, I do not have the feeling that the NDVI decomposition based on these Arain empirical curves is the best option for the coherence of the paper".

Response to Comment 8: It is true that the NDVI-rainfall correlogram (Fig. 3b) captures also the response of herbaceous vegetation in the Creosotebush Core Site, although this effect is only evident for three years with very strong summer precipitation (cycles

2006-07, 2007-08 and 2008-09). Nevertheless, this does not constitute a weak point of our analysis, but just represents the normal response of this shrubland (and other shrubland sites) to its mixed nature with a herbaceous seed pool that germinates during particularly wet summers and can grow to partially cover the shrub interspaces. As expected, the decomposed NDVI series for herbaceous vegetation in the Creosotebush Core Site reflects significant growth peaks for the cycles 2006-07, 2007-08 and 2008-09, with high summer monsoonal rainfall (Fig. 5a). This is not a particular characteristic of our site, but a common feature of arid shrublands. In fact, the growth of non-dominant herbaceous vegetation is also reflected in the analysis of NDVI-rainfall relationships of other dry shrublands, for example in Mulga landscapes in central Australia (Moreno de las Heras et al., 2012). We have updated the text in the results and the discussion sections to clarify this point: Page 15, lines 10-14 (Results section): "For the Creosotebush Core Site (with dominant shrub vegetation and subordinated forbs and grasses), the short-term, 57-day antecedent rainfall series ARainhv also has an important impact on the strength of the NDVI-rainfall relationship, particularly for three consecutive growing cycles with strong summer precipitation (2006-07, 2007-08 and 2008-09, summer precipitation for the period is 40% above the long-term mean)" Page 19, lines 4-16 (Discussion section): "Olr variations in the reference SEV LTER Core Sites may, therefore, be expressed as a function of the dominant vegetation types (Fig. 3): the strong and quick responses of greenness to short-term precipitation (ARainhv) in the grass-dominated Black Grama Core Site characterize herbaceous growth for the area, while the slow responses of NDVI to medium-term precipitation (ARains) in the shrub-dominated Cresotebush Core Site define the characteristic pattern of vegetation growth for shrubs in the ecotone. The high correlation between ARainhv and NDVI values in the shrub-dominated Creosotebush Core Site (Fig. 3b) can be explained by the growth of non-dominant herbaceous vegetation (mainly forbs), which can be especially important during wet years (Muldavin et al., 2008; Baez et al., 2012). Similarly, Moreno-de las Heras et al. (2012) in dry open-shrublands of central Australia (Olrs values about 220 days) found the emergence of secondary Olrhv metrics on the study

of local NDVI-rainfall relationships (approx. 85 days antecedent rainfall length) caused by the growth of non-dominant herbaceous vegetation".

Both the theoretical model and the semi-empirical NDVI-decomposition procedure applied in this study are consistent with the idea that shrub green biomass (or greenness) can show a higher persistence along dry periods than herbaceous vegetation green biomass (or greenness). The low mortality rates of the shrubs in our model cause a longer persistence of shrub green biomass along dry periods than for herbaceous vegetation. The ARain function (eq. 4) of our NDVI decomposition method also captures this effect. The NDVI response of herbaceous vegetation is dependent on short-term antecedent rainfall (ARainhv, 57-days series for our site) which causes a sharp reduction of the decomposed herbaceous signal during dry periods. Conversely, the NDVI response of shrubs is dependent on longer-term precipitation (ARains, 145-days series for the studied ecotone), which makes the decomposed shrub signal much more flexible and persistent during dry periods. Overall, our semi-empirical NDVI decomposition approach correctly partitions the remote-sensed signal into the herbaceous and shrub components for our site, and this is clearly evidenced by the results of our study. A clear sign of the good performance of our approach is the strong agreement we obtained between the decomposed NDVI series for herbaceous and shrub vegetation and the ground-based ANPP estimations ($R2>0.65$, $P<0.00$; Fig. 5b), which constitutes a great achievement bearing in mind the very important spatial variability that affects the small-scale ANPP estimations obtained in the field for this study. Another evidence of the good performance of our study approach is the very strong agreement obtained between our landscape-type classification and the spatial distribution of vegetation types measured in the field ($R2$ approx. 0.90, $P<0.00$; Fig. 4).

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Comment 9: "NDVI decomposition approach. The performance of the model decomposing NDVI time series should be clearly presented. How much of the observed NDVI variance is captured by model 3? In addition, an examination of the magnitude, spatial

and temporal distribution of the residuals should be conducted. I also would like to know the sensitivity of model outputs to parameter uncertainty (growth rate, mortality rate, lag)?"

Response to Comment 9: Additive sums of the decomposed signals for herbaceous vegetation, shrubs and background soil equal 100% of the original MODIS NDVI signal for any ti. This is not a particular trait of our NDVI-decomposition procedure. All NDVI-partition procedures published in the literature decompose the 100% NDVI signal for any ti into different field attributes. A first evaluation criterion for the method is the agreement between the annual sums of decomposed NDVI for herbaceous and shrub vegetation and their ground ANPP estimations. Agreement (explained variance) excess 65% in the cases studied (Fig. 5b), which constitutes a great achievement for any NDVI decomposition procedure in dryland sites with patchy vegetation. We have modified Fig. 5 to include further details, particularly the root mean square error (RMSE) and normalized root mean square error (NRMSE) of our remote-sensing ANPP estimations. RMSE and NRMSE for our estimations are 26 g m-2 and 12%, respectively. This low degree of error is, at least, comparable with the errors reported for the most popular NDVI decomposition methodologies (for example, Roderick et al., 1999; DeFries et al., 2000, Hansen et al., 2002; Lu et al., 2003; with reported NRMSE values ranging 10-17%). Error-evaluation details have been added to the text in the results and discussion sections: Page 16, lines 14-17 (Results): "The annual sums of herbaceous and shrub NDVI components for the reference Core Sites show a strong linear agreement (R2 $\geq$ 0.65; P<0.001) with ground-based measurements of ANPP (Fig. 5b), while the remote-sensing ANPP estimations yield a root mean square error of 26 g m-2 (NRMSE 12%, Fig. 5c)". Page 20, lines 20-29 (Discussion): "Although affected by data dispersion, the annual sums of decomposed NDVI strongly agree with field estimations of ANPP for herbaceous and shrub vegetation (R2 $\geq$ 0.65, Fig. 5b), resulting in a small root mean square error for our remote-sensing ANPP estimates (26 g m-2, NRMSE 12%, Fig 5c) that is within the lower limit of reported errors by other NDVI decomposition studies (for example, Roderick et al., 1999; DeFries et al., 2000,

Hansen et al., 2002; Lu et al., 2003; with NRMSE ranging 10-17%)".

We did not apply any plant-growth or mortality rates in our NDVI decomposition method. The method is based on the use of vegetation-type optimal antecedent rainfall series ARainhv and ARains (see pages 12-13, lines 23-19). Provided that the responses of herbaceous and shrub vegetation to antecedent precipitation are well-discriminated (for example, in our case the responses are clearly different: optimal length of rainfall accumulation for the shrubs is more than 2.5 larger than for herbaceous vegetation) the results of the NDVI decomposition do not depend on delicate tuning of rainfall accumulation length for the ARainhv and ARains series (Olrhv and Olrs values, respectively).

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Comment 10: "Is there any significant change in the cover of shrubs over the examined period? Is the proposed method able to track these changes in areas where significant shrub encroachment has been reported over the last decade?"

Response to Comment 10: There is little evidence in other studies that shrub-encroachment for the Sevilleta LTER has been particularly active in the last decades. For example, a recent study on creosotebush plant architecture and age structure for our area indicates that the most important pulses of shrub encroachment in this site took place as a consequence of several large droughts between 1950 and 1970 (Allen et al., 2008). Droughts subsequently may have had a lesser impact because of the end of grazing in the mid-1970s for the area.

Our methods are not directed to determine vegetation cover, but herbaceous and shrub ANPP, as stated in the title of the paper. However, we can use our results to evaluate whether there is any directional change along the studied period using the contribution of shrubs to total ANPP. We have generated a new figure (Fig. 6) with detailed analysis of the temporal trends of herbaceous and shrub ANPP for our four types of landscapes (grass-dominated, grass-transition, shrub-transition and shrub-dominated). We have found significant (although very weak) positive correlations between shrub contribution

to total ANPP and time for the grass-transition and shrub-transition landscapes along the studied period (Fig. 6b). The same analysis at the individual pixel level, however, did not show any significant correlations, which overall suggests that shrub encroachment has not been particularly active in the area for the 2000-13 period. Overall, these results agree with and extend the findings of Allen et al. (2008) for our site. This information has been added to both the results and discussion sections: Page 17, lines 4-7 (Results): "Analysis of the temporal evolution of shrub contribution to total ANPP along 2000-13 reflects significant (although very weak) positive correlations with time for the grass- and shrub transition landscapes (Fig. 6b). The same analysis at the individual pixel level, however, does not show any significant correlations between shrub contribution to total ANPP and time". Page 23, lines 7-11 (Discussion): "Our results suggest that shrub encroachment has not been particularly active in the studied ecotone for 2000-13 (Fig. 6b). Accordingly, Allen et al. (2008) in a recent study on creosotebush plant architecture and age structure indicated that the most important pulses of shrub encroachment for this area took place between 1950 and 1970".

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Comment 11: "Another way of calibrating and/or validating model 3 is to use high resolution imagery and apply segmentation methods to precisely estimate the cover of shrubs. This could be discussed".

Response to Comment 11: Again, we did not apply our NDVI decomposition method to estimate cover but to estimate ANPP. Precise estimation of shrub cover for the site using high-resolution imagery probably would not be very useful for validation purposes of our ANPP estimations, although this type of data (optimally a few high resolution images distributed along the studied period) would constitute a very useful input for precisely testing the activity of the shrub-encroachment process in the area. The following information has been added to the discussion (Page 23, lines 11-14): "Precise estimation of shrub cover applying segmentation methods in time series of high-resolution imagery could help to accurately determine the intensity of the shrub-encroachment

phenomenon under the present variability in precipitation for our grassland-shrubland ecotone".

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Comment 12: "A very simple and empirical way to classify land cover based on NDVI time series is to conduct an ordination or a partitioning of the matrix of correlation between NDVI time series. I would be curious to compare the outcome of this analysis with that shown in figure 4".

Response to Comment 12: We are not sure about the particular characteristics of the alternative approach indicated by the referee. A common vegetation classification approach that has been applied using NDVI data since the late-1980s with variable results (i.e. very good in some cases but poor in some others) is based on ordination of phenology metrics (e.g. maximun and mininmum NDVI values, start and end of growing cycles, etc.). For example, A.J. Peters et al. applied this approach in the '90s to classify the Jornada LTER site (New Mexico) into areas dominated by a variety of vegetation types (e.g. grasslands, evergreen shrubs, deciduous shrubs). Those studies (Peters et al., 1995, 1997) are already cited in our paper. Particular application of that approach will not provide any new information for this study (we offer a high-quality and ground-validated classification of landscape types in our study that would not be easily improved by other classification methods based on the use of time series of coarse NDVI data) and would break the coherence of the study, which is based on the analysis of NDVI-rainfall relationships.

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Comment 13: "Is the change of ANPP along the ecotone consistent with the decrease of ANPP that has been associated with shrub encroachment in dry areas (Knapp & al. Global Change Biology 2008)?"

Response to Comment 13: We have generated a new figure (Fig. 6) with details of the

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temporal variation of both grass and shrub ANPP along the studied period for the different landscape types in our ecotone. Differences in remote-sensed ANPP for the landscape types are tested using repeated-measures ANOVA. The change in ANPP along our ecotone is consistent with the results reported by Knapp et al. (2008) and in other studies carried out in similar Chihuahuan sites (Jornada LTER, Huenneke et al. 2002). The grass-dominated landscapes generally support higher levels of ANPP, although it is quite variable from year to year (Fig. 6a). Differences are clear for highly productive years, but for growing cycles with low primary production we found no significant differences or reversed differences (i.e. higher production in the shrub-dominated sites). The text in the paper has been updated with the following information in the results and discussion sections: Pages 16-17, lines 25-3 (Results): "Remote-sensed estimations of ANPP are significantly impacted by landscape type ($F_{3, 334}=48.6$, $P<0.01$), with grass-dominated sites supporting in general higher levels of vegetation production (Fig. 6a). However, landscape-type effects are variable in time (landscape type x time interaction: $F_{14, 1515}=57.2$, $P<0.01$). Year-to-year variability of ANPP is particularly large for the grass-dominated sites, which show higher levels of ANPP than the transition and shrub-dominated landscapes for highly productive years (Fig. 6a). For growing cycles with low primary production there are no significant ANPP differences or the differences are reversed, with shrub-dominated sites showing higher production than grass-dominated sites (e.g. 2003-04 cycle, Fig. 6a)". Page 21, lines 11-16 (Discussion): "Analysis of the spatiotemporal dynamics of ANPP in our ecotone indicates that grass-dominated sites, although very importantly affected by year-to-year variability, generally support higher primary production than transition and shrub-dominated landscapes, particularly for wet years with high ANPP levels (Fig. 6a). This result is consistent with other shrub-encroachment studies which have found associations between shrub proliferation and ANPP reductions in dry American grasslands (Huenneke et al., 2002; Knapp et al., 2008)".

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Comment 14: "Is the year-to-year variability in ANPP higher for grass-dominated sites? Coefficient of variation in yearly ANPP along the ecotone could be reported".

Response to Comment 14: Year-to-year variability in ANPP is higher for the grass-dominated sites (as evidenced by Fig. 6), which also agrees with results obtained in other grassland-shrubland desert ecotones (for example, Huenneke et al. 2002, Knapp et al. 2008). Text modifications in our study for this comment are detailed in the above response to Comment 13.

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Comment 15: "To complete figure 5, add panels showing the relative contribution of grass and shrubs to total ANPP. This figure could be divided into two".

Response to Comment 15: We have added a panel in that figure (Fig. 5e) showing the relative contribution of shrubs and herbaceous vegetation to total ANPP.

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Comment 16: "Figure 1 should present the soil moisture dynamics".

Response to Comment 16: We disagree with this suggested change. The paper is based on the analysis of NDVI-rainfall relationships for the study of grassland-shrubland ecotone dynamics, deliberately because there are no soil-moisture data available across the whole extent of the study. Nor would there be in most areas where the technique could be applied. We have not applied (or discussed) any soil-moisture data in this study as they would have to be modelled and we do not have any spatial data to validate them to any degree of confidence. We believe that the presentation of soil-moisture dynamics in our modelling results does not add any critical information for our study and, at the same time, would be very confusing for the readers.

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Comment 17: "Typos. Capital letters for panels in legend of figures".

Response to Comment 17: Now, all the panels in figures (as well as in legends and text citations) are indicated (cited) using lower-case letters.

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Comment 18: "Typos. Variables in fig 4B".

Response to Comment 18: We have corrected the typo.

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Comment 19: "Figure 5C and 5B should show increasing values of ANPP from left to right in the color palette".

Response to Comment 19: Scale bars now show increasing values from left to right.

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References cited in this response letter that are not cited in the revised paper:

Alonso-Sanz, R., Martin, M. 2004, Three-state one-dimensional cellular automata with memory, Chaos, Solitons and Fractals, 21: 809-834.

Parton, W.J., 1978. Abiotic section of ELM. In: G.S. Innis (Editor), Grassland Simulation Model. Ecological Studies 26. Springer-Verlag, New York.P.31-53.

Parton, W.J., Hartman, M.D., Ojima, D.S., Schimel, D.S., 1998. DAYCENT: Its land surface sub-model: description and testing. Glob. Planet. Chang. 19, 35-48.

Wainwright, J., Parsons, A. J., Müller, E. N., Brazier, R. E., Powell, D. M., Fenti, B. 2008, A transport-distance approach to scaling erosion rates: 1. Background and model development, Earth Surface Processes and Landforms 33, 813–826.

Please also note the supplement to this comment:
http://www.biogeosciences-discuss.net/12/C777/2015/bgd-12-C777-2015-supplement.pdf

Interactive comment on Biogeosciences Discuss., 12, 51, 2015.