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Connecting the dots
Miguel Angel Salinas Melgoza

UNIVERSITY OF TWENTE.

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Modeling the effects of topography on carbon stocks to promote efficiency in local REDD+ planning

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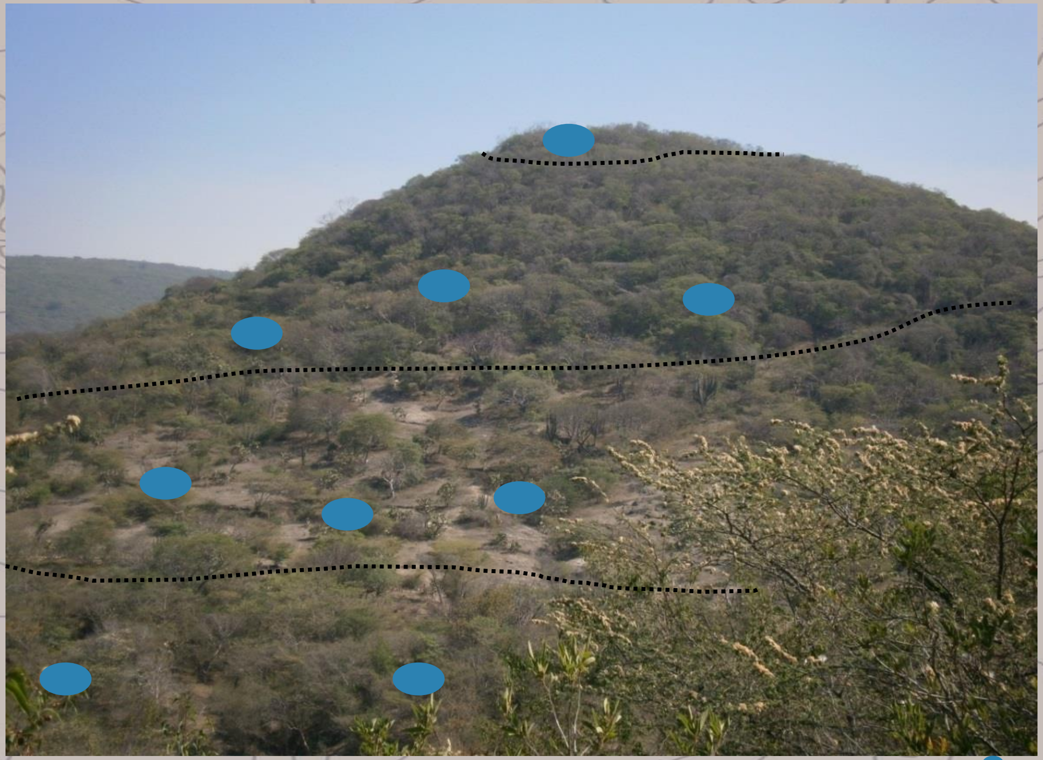

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CONNECTING THE DOTS

MODELING THE EFFECTS OF TOPOGRAPHY ON CARBON STOCKS TO PROMOTE EFFICIENCY IN LOCAL REDD+ PLANNING

DISSERTATION

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the degree of doctor at the University of Twente,
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on account of the decision of the graduation committee,
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by

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born on September 15th, 1974
in Uruapan, Michoacán, México

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Colophon

Cover image: The contours of El Carbunco, Tonaya community. Photo by Miguel Angel Salinas Melgoza. 2014.
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LIST OF ABBREVIATIONS

CGIAR	Consultative Group for International Agricultural Research
CIFOR	Center for International Forestry Research
CO_2	Carbon Dioxide
CoP	Conference of the Parties
ENAREDD+	Mexican Emission Reductions Strategy
GHG	Greenhouse Gas
HML	Human Modified Landscapes
ICRAF	International Council for Research in Agroforestry
JIRA	Junta Intermunicipal del Rio Ayuquila
LULUCF	Land Use, Land Use Change and Forestry
MRV	Monitoring, Reporting and Verification
NREL	National Emissions Reductions baseline
REALU	Reducing Emissions from All Land Uses
RED	Avoided Deforestation
REDD	Avoided Deforestation and Including Reductions in Forest Degradation
SDG	Sustainable Development Goals
SC	Shifting Cultivation
UNFCCC	The United Nations Framework Convention on Climate Change
WOTRO	Netherlands Organization for Scientific Research,programme ´Science for Global Development

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When I started to write these lines, I felt that giving recognition and thanks to so many people was going to be a difficult task. With a beer in my hand it was easier, but I am sure that I have forgotten to include a lot of people. Looking back , I see that during the time spend doing my PhD there were slower moments and faster moments, but there was always something going on; all of them where productive times.

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I spend most of my time in CIGA-UNAM but part also at CSTM-UT. There are very important people who I want to recognize for their incredible effort. First, in Mexico, the administrative support people who helped me get into the field at the right time; Frank, Geraldy, Juan Carlos, Nidia and Salud many thanks. Then, the very nice people from CSTM who I met, some of whom are still at the UT, to them my deepest gratitude. Annemiek, you were the first face I met when I arrived the very first time in the Netherlands. You and Barbera were really helpful in doing things for me when I was abroad, many thanks. I left behind happy days in Voortsweg 299, time spent with new friends; I miss them.

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Abstract

Tropical forests are of global concern in the context of climate change. This is because forests can both emit carbon dioxide (CO_2), an important greenhouse gas (GHG), and sequester it in the biomass of trees. The ability of a given type of forest to hold stocks of carbon is strongly influenced both by topography of the landscape and by the human uses that are present. Topography is not just indicated in the literature as a template within the landscape that defines the patterns of density biomass, but also as a driving factor of human uses. While altitude, slope and terrain convexity, among others, show a relationship with biomass patterns, human activities such as shifting cultivation, grazing and extraction of woody products tend to follow the topographical configuration of the landscape. This is because different topographical characteristics provide different biophysical conditions which support different human activities. However, the relative contribution of the topographical and human factors on biomass patterns is not very clear.

Forests have been given a prominent role in climate change policy because if human activities within the forest are reduced, emissions will decrease and carbon stocks may increase. International policy addressing this issue, Reducing Emissions from Deforestation and forest Degradation in tropical countries (REDD+), considers not only the reduction of deforestation and forest degradation but also sustainable management of forests, forest conservation and enhancement of forest carbon stocks. In Mexico REDD+ is being implemented using a landscape or territorial approach, although the definition of this is not very clear.

This thesis was carried out in seasonally dry tropical forest (SDTF), which is a type of deciduous tropical forest whose structure and functioning is determined by the availability of water in the system throughout the year. Although it is known that historically in Mexico this type of tropical forest has suffered from much deforestation and degradation as a result of human activities, few studies have been carried out in this biome in comparison to humid tropical rainforests, partly because it has much less commercial value in terms of timber. There is a need for predictive models of biomass levels in this type of tropical forest in Mexico to support the establishment of REDD+ and to enhance its standing carbon stocks.

Estimates of standing (above ground) biomass for the study area comes from 144 sampling plots, distributed over six rural communities located in the Ayuquila region of Jalisco, Mexico, which is one of the REDD+ early action areas. These early action areas are laboratories where different demonstration activities related to the implementation of REDD+ are being carried out. As a measure of the carbon environmental services I used data from the

sampling plots and extrapolated this to determine above ground carbon stocks per hectare. I also took soil samples to determine soil carbon levels in a subset of the area. Carbon stocks and flows in standing biomass and soil were determined.

The chapters detailing the field research and its results (chapters 4, 5 and 6) are in the form of articles, of which chapters 4 and 6 are already published in indexed scientific journals, while chapter 5 is under review. The first three chapters of the thesis provide the rationale, the context and the methodology of the study, while the final chapter pulls the results of the different articles together and attempts to provide answers to the research questions set in chapter 1. These were as follows:

1. How are above ground biomass patterns related to multiple biophysical factors, such as elevation, slope and insolation, in the region of Ayuquila, Mexico?
2. To what extent can spatial prediction of standing aboveground biomass (AGB) help to identify the locations within community territory that are most suited to the establishment of carbon enhancement projects using local topographic variables?
3. What is the impact of shifting cultivation on carbon stocks and how can cultivation cycles be optimized to promote carbon sequestration?
4. How could the findings of this study be used to help communities in SDTF areas to pursue carbon enhancement projects?

To summarize the findings of the three central studies: In Chapter 4 we investigated how different topographic variables were related to biomass levels in a SDTF landscape in Mexico, using a two dimensional approach (hill slope). Linear and nonlinear models showed relationships between regional and local topographical factors, and also human factors, and standing biomass. The significant regional topographical factors were altitude and diffuse insolation, while local topographic factors were slope, terrain curvature and a topographic humidity index. A generalized mixed linear model was the best model, accounting for 21% of the variation in biomass. This model shows a uni-modal increase in biomass with respect to elevation, slope, terrain curvature and topographic wetness index; in this model elevation had the greatest relative importance. The model also found two groups of rural communities with a differential response in biomass based on altitude, slope, terrain curvature and water availability in the soil. The communities in the higher areas of the study area with more humid in soils, greater concavity and steeper terrain, had higher levels of biomass; while those in the lower parts with convex terrain curvature, lower slopes and less water available in the soil had lower biomass levels. These results also support previous studies that relate biomass levels to the amount of water in the soil. In terms of human factors, the distance to roads showed a relationship which changes abruptly at 2,273 m. Sites with forest located closer to roads show a strong human effect that diminishes with distance, but after this threshold the human effect appears to increase again. Human activities that affect forest biomass more strongly also tend to occur more frequently on gently sloping sites with high convexity, in the lower lying lands. Using the method demonstrated in this chapter it is possible to identify typical areas along the hill slope which could most fruitfully be targeted under of Mexico's REDD+ programme, with a focus on reducing forest degradation processes and improving carbon stocks. All data on topographic variables was obtained from standard contour maps which are available at no cost in the public domain. This greatly reduces the investments needed for materials and technical training, compared to methods that are based on remote sensing. In developing countries this could make a very big difference in the feasibility of planning large numbers of REDD+ projects. This method could help to implement the landscape approach the Mexican government wants to take in its REDD+ national strategy.

Subsequently, I considering the results obtained in Chapter 4, to try to understand how local topographic variation within the rural communities can be used to predict biomass levels, using a three dimensional, fully spatial approach. Chapter 5 evaluates relationships between biomass and topographic variables using spatially explicit Bayesian regression models. We evaluated the extent to which elevation, terrain slope, terrain curvature and topographic wetness index, as well as the spatial relationships of these topographic conditions, determine biomass levels within the territory of four rural communities, and how this could help to obtain predictions of biomass levels in different areas within these communities. The error level of the models´ biomass predictions was evaluated out-of-the sample using the Root Mean Square Error, and the models with the least error were selected. The selected models use a combination of three local topographic variables; topographic wetness index, tangential curvature and slope. This combination of variables appears to determine the movement and accumulation of available water in the soil, which is very important in SDTFs. We found that of these three variables, the concavity and convexity of the terrain was the most important variable. We also found that the accuracy of my models for predicting biomass levels was between 65 to 80%. The results of this chapter are relevant for guiding REDD+ actions aimed at improving carbon stocks. The procedure carried out in this chapter makes it possible to make biomass estimates within the territory of a community and to identify sites in the forest whose biomass levels are well below the expected values, due to the use of forest resources by humans. Through this procedure it would be possible to identify sites within the territory of communities where forest degrading activities should be reduced and activities that promote natural or assisted regeneration should be promoted. Again, the data on topographic variables derived from topographical maps that are freely accessible, and remote sensing is not required.

Chapters 4 and 5 showed the relative contribution of topographic and human factors in determining biomass variation in SDTF landscapes. In order to increase the focus of analysis, we concentrated on one very important and widespread human activity: shifting cultivation (SC), otherwise known as ´slash and burn´. In Chapter 6 we assessed the differences in carbon stocks in aboveground biomass and soil in various land uses. The carbon stocks for the SC were divided into two management phases: cultivation and fallow, which in this area currently tend to be carried out for 2 and 8 years respectively. The fallow phase was divided into three age classes, allowing for a slightly more detailed idea of the increases in carbon levels as SC plots became older. We also identified landscape sites that had much earlier been used as SC plots, but had been abandoned (fallowed) for at least 20 years. We then simulated the impact of various modifications of the typical SC regime on carbon emissions through various management scenarios. The comparisons made on this last point were in terms of emissions derived from the production of one ton of maize. In this chapter we found that the carbon stocks at old SC sites were even higher than those in sites that had never been cut for SC. We also found that as we increased the length of the fallow in the SC cycle, carbon emission increased. Conversely, short fallow phases at the landscape level result in higher carbon stocks and lower carbon emissions. This indicates that the length of the SC cycle could be optimized to increase carbon sequestration within a land sharing approach. Our estimates indicate that emissions from a regular cycle of SC are higher than those in permanent agriculture, per ton of maize produced, although this does not take into account the carbon emissions associated with the inputs used in permanent agriculture.

In short, in this thesis I found that, as expected, there is evidence of the effect of topographical and anthropogenic factors on carbon ecosystem services in the SDTF of the study region in Jalisco, Mexico. The carbon ecosystem services evaluated in this thesis were carbon stocks in standing biomass levels (Chapter 4, 5 and 6) and soil (Chapter 6). We found that topographical factors related to water availability in the soil were the primary explanators of standing biomass volumes quantities in the SDTF. The study area has been modified by human activities since before colonial times, so it was not possible to assess the effect of topographic variables independently of human factors. The predictive models generated in this thesis made it possible to predict, with very good performance, the biomass levels present in the SDTF of the Ayuquila region of Jalisco, Mexico. These models can be used in planning of REDD+ projects in Mexico at the regional and local intervention scales: at the regional level, to select communities with the greatest potential for reducing degradation and enhancing forest stock and at the local level for selecting sites within communities where REDD+ actions should have a high probability of success. On either scale, these results provide an opportunity to target REDD+ actions to reduce forest degradation or improve carbon stocks in SDTF with a landscape approach, taking advantage of the tremendous potential that exists in the SDTF of Mexico for natural regeneration.

RESUMEN (IN SPANISH)

Los bosques tropicales son motivo de preocupación mundial en el contexto del cambio climático. Esto se debe a que los bosques pueden por una parte emitir dióxido de carbono (CO_2), el cual es un importante gas de efecto invernadero (GEI), por el otro lado secuestrarlo en la biomasa de los árboles. La capacidad de un determinado tipo de bosque para almacenar carbono está fuertemente influenciada tanto por la topografía del paisaje como por los usos humanos presentes. La topografía no sólo se indica en la literatura como un patrón dentro del paisaje que define los patrones de densidad de la biomasa, sino que también como un factor que determina los usos humanos. Mientras que la altitud, la pendiente y la convexidad del terreno, entre otras, muestran una relación con los patrones de biomasa, las actividades humanas como el la roza-tumba y quema (RTQ), el pastoreo y la extracción de productos leñosos, tienden a seguir la configuración topográfica del paisaje. Esto se debe a que las características topográficas proporcionan diferentes condiciones biofísicas que soportan diferentes actividades humanas. Sin embargo, la contribución relativa de los factores topográficos y humanos sobre los patrones de biomasa no está muy clara.

A los bosques se les ha dado un papel preponderante en la política de cambio climático porque si se reducen las actividades humanas dentro de los bosques, las emisiones disminuirán y los almacenes de carbono podrían aumentar. La política internacional que aborda esta cuestión, Reducción de las Emisiones de GEI derivadas de la Deforestación y la Degradación forestal en los países tropicales (REDD+), considera no sólo la reducción de la deforestación y la degradación forestal, sino también el manejo sostenible de los bosques, la conservación de los bosques y el aumento de las reservas forestales de sus almacenes de carbono. En México REDD+ está siendo implementada utilizando un enfoque territorial o de paisaje, aunque la definición de esto no está muy clara.

Esta tesis se llevó a cabo en la selva baja caducifolia (SBC), que es un tipo de bosque tropical caducifolio cuya estructura y funcionamiento están determinados por la disponibilidad de agua en el sistema durante todo el año. Aunque se sabe que históricamente en México este tipo de bosque tropical ha sufrido mucha deforestación y degradación como resultado de las actividades humanas, pocos estudios se han llevado a cabo en este bioma en comparación con los bosques húmedos tropicales, en parte porque tiene mucho menos valor comercial en términos de madera. Hay una necesidad de modelos predictivos de niveles de biomasa en este tipo de bosque tropical en México para apoyar el establecimiento de REDD+ y mejorar sus almacenes de carbono en la biomasa en pie.

Las estimaciones de biomasa en pie (arriba del suelo) para el área de estudio provienen de 144 parcelas de muestreo, distribuidas en seis comunidades rurales ubicadas en la región de Ayuquila en Jalisco, México, una de las áreas de acción temprana de REDD+. Estas áreas de acción temprana son laboratorios donde se están llevando a cabo diferentes actividades de demostración relacionadas con la implementación de REDD+. Como medida de los servicios ambientales de carbono utilicé datos de las parcelas de muestreo y extrapolé esto para determinar las reservas de carbono por hectárea. También tomé muestras de suelo para determinar los niveles de carbono en un subconjunto de comunidades del área. Se determinaron los almacenes los flujos de carbono en la biomasa en pie y en el suelo.

Los capítulos que detallan la investigación de campo y sus resultados (capítulos 4,5 y 6) se presentan en forma de artículos, de los cuales los capítulos 4 y 6 ya se publican en revistas científicas indexadas, mientras que el capítulo 5 se encuentra en revisión. Los tres primeros capítulos de la tesis proporcionan la justificación, el contexto y la metodología del estudio, mientras que el capítulo final reúne los resultados de los diferentes artículos e intenta dar respuestas a las preguntas de investigación planteadas en el capítulo 1. Las cuales fueron las siguientes:

1. ¿Cómo los patrones de biomasa sobre el suelo están relacionados con múltiples factores biofísicos, tales como la elevación, la pendiente y la insolación en la región de Ayuquila, México?
2. ¿Hasta qué punto la predicción espacial de la biomasa sobre el suelo (BSS) puede ayudar a identificar los lugares dentro del territorio comunitario que son más adecuados para el establecimiento de proyectos de mejora del carbono utilizando variables topográficas locales?
3. ¿Cuál es el de la roza-tumba y quema en los almacenes de carbono y cómo los ciclos de cultivo pueden ser optimizados para promover la captura de carbono?
4. ¿Cómo los resultados de este estudio podrían ser usados para ayudar a las comunidades en las áreas con SBC a llevar a cabo proyectos de mejora del carbono?

Para resumir los hallazgos de los tres estudios centrales: En el Capítulo 4 se investigó cómo las diferentes variables topográficas están relacionadas con los niveles de biomasa en un paisaje de SBC en México, utilizando un enfoque bidimensional (modelo de colina). Los modelos lineales y no lineales mostraron que existen relaciones entre los factores topográficos regionales y locales, así como los factores humanos y la biomasa en pie. Los factores topográficos regionales significativos fueron la altitud y la insolación difusa, mientras que los factores topográficos locales fueron la pendiente, la curvatura del terreno y un índice de humedad topográfica. El mejor modelo fue un modelo mixto lineal generalizado, que representó el 21% de la variación de la biomasa. Este modelo muestra un incremento uni-modal de la biomasa en cuanto a elevación, pendiente, curvatura del terreno e índice de humedad topográfica; en este modelo la elevación tuvo la mayor importancia relativa. El modelo también encontró dos grupos de comunidades rurales con una respuesta diferencial en biomasa basada en la altitud, pendiente, curvatura del terreno y disponibilidad de agua en el suelo. Las comunidades en las áreas más altas del área de estudio con mayor humedad en los suelos, mayor concavidad y terreno más escarpado, tenían mayores niveles de biomasa; mientras que las de las partes bajas con curvatura del terreno convexa, pendientes más bajas y menos agua disponible en el suelo tenían menores niveles de biomasa. Estos resultados apoyan también estudios previos que relacionan los niveles de biomasa con la cantidad de agua en el suelo. En cuanto a los factores humanos, la distancia a las carreteras mostró una relación que cambia abruptamente a 2,273 m. Los sitios con bosques situados más cerca de las carreteras muestran un fuerte efecto humano que disminuye con la distancia, pero después de este umbral el efecto humano parece volver a aumentar. Las actividades humanas que afectan más fuertemente a la biomasa forestal también tienden a ocurrir más frecuentemente en los sitios de pendiente suave con alta convexidad, en las tierras bajas. Usando el método demostrado en este capítulo es posible identificar áreas típicas a lo largo de la ladera de las colinas que podrían ser más fructíferas bajo el programa REDD+ de México, con el objetivo de reducir los procesos de degradación forestal y mejorar los almacenes de carbono. Todos los datos sobre variables topográficas se obtuvieron a partir de mapas topográficos estándar que están disponibles sin costo alguno y son de dominio público. Esto reduce en gran medida las inversiones necesarias para materiales y formación técnica, en comparación con los métodos basados en la teledetección. En los países en desarrollo, esto podría marcar una gran diferencia en la viabilidad de planificar un gran número de proyectos REDD+. Este método podría ayudar a implementar el enfoque de paisaje que el gobierno mexicano quiere adoptar en su estrategia nacional REDD+.

Posteriormente, consideraré los resultados obtenidos en el Capítulo 4, para tratar de entender cómo la variación topográfica local dentro de las comunidades rurales puede ser utilizada para predecir los niveles de biomasa, usando un enfoque tridimensional y completamente espacial. El capítulo 5 evalúa las relaciones entre biomasa y variables topográficas utilizando modelos de regresión bayesianos espacialmente explícitos. Evaluamos hasta qué punto la elevación, la pendiente del terreno, la curvatura del terreno y el índice de humedad topográfico, así como las relaciones espaciales de estas condiciones topográficas, determinan los niveles de biomasa dentro del territorio de cuatro comunidades rurales, y cómo esto podría ayudar a obtener predicciones de los niveles de biomasa en diferentes áreas dentro de estas comunidades. El nivel de error de las predicciones de biomasa de los modelos se evaluó fuera de la muestra utilizando el Error Medio Cuadrático, y los modelos con el menor error fueron seleccionados. Los modelos seleccionados utilizan una combinación de tres variables topográficas locales: índice de humedad topográfica, curvatura tangencial y pendiente. Esta combinación de variables parece determinar el movimiento y acumulación de agua disponible en el suelo, que es muy importante en los SBCs. Encontramos que de estas tres variables, la concavidad y convexidad del terreno fue la variable más importante. También encontramos que la precisión de mis modelos para predecir los niveles de biomasa era entre 65 y 80%. Los resultados de este capítulo son relevantes para orientar las acciones REDD+ dirigidas a mejorar los almacenes de carbono. El procedimiento llevado a cabo en este capítulo permite hacer estimaciones de biomasa dentro del territorio de una comunidad e identificar sitios en el bosque cuyos niveles de biomasa están muy por debajo de los valores esperados, debido al uso del bosque por parte de los seres humanos. A través de este procedimiento podría ser posible identificar los sitios dentro del territorio de las comunidades donde las actividades que promueven degradación forestal deberían ser reducidas y las actividades que promueven la regeneración natural o asistida deberían ser promovidas. Una vez más, los datos sobre variables topográficas derivados de mapas topográficos que son de libre acceso, y la teledetección no es necesaria.

Los capítulos 4 y 5 mostraron la contribución relativa de los factores topográficos y humanos para determinar la variación de la biomasa en los paisajes de SBC. Para aumentar el enfoque del análisis, nos concentramos en una actividad humana muy importante y generalizada: la roza-tumba y quema (RTQ). En el capítulo 6 se evaluaron las diferencias en los almacenes de carbono que se encuentra en la biomasa y el suelo en diversos usos de suelo. Los almacenes de carbono para el RTQ se dividieron en dos fases de manejo: cultivo y descanso, que en la zona de estudio tienden actualmente a realizarse durante 2 y 8 años, respectivamente. La fase de descanso se dividió en tres clases de edad, lo que permitió una idea ligeramente más detallada del incremento en los niveles de carbono a medida que las parcelas de RTQ envejecieron. También identificamos sitios en el paisaje que habían sido utilizados mucho antes como parcelas de RTQ, pero que habían sido abandonados (descansados) por lo menos durante 20 años. A continuación, se simuló el impacto de varias modificaciones del régimen típico de RTQ sobre las emisiones de carbono a través de diversos escenarios de manejo. Las comparaciones realizadas sobre este último punto se refieren a las emisiones derivadas de la producción de una tonelada de maíz. En este capítulo encontramos que en los sitios antiguos de RTQ los almacenes de carbono eran aún más elevados que en los sitios con SBC que nunca habían sido cortados para RTQ, y también encontramos que a medida que aumentamos la duración del descanso en el ciclo de RTQ, las emisiones de carbono aumentaron. Por el contrario, descansos cortos a nivel del paisaje dan lugar a mayores almacenes de carbono y menores emisiones de carbono. Esto indica que la duración del ciclo de RTQ podría ser optimizada para aumentar la captura de carbono dentro de un enfoque de land sharing. Nuestras estimaciones indican que, por tonelada de maíz producida, las emisiones de un ciclo regular de RTQ son superiores a las emitidas en la agricultura permanente, aunque esto no toma en cuenta las emisiones de carbono asociadas a los insumos utilizados en la agricultura permanente.

En resumen, en esta tesis encontré que, como se esperaba, hay evidencia del efecto de los factores topográficos y antropogénicos sobre los servicios de los ecosistemas de carbono en la SBC de la región estudiada en Jalisco, México. Los servicios ecosistémicos de carbono evaluados en esta tesis fueron los almacenes de carbono en la biomasa en pie (capítulos 4,5 y 6) y el suelo (capítulo 6). Encontramos que los factores topográficos relacionados con la disponibilidad de agua en el suelo fueron los principales factores que explican las cantidades de biomasa en pie en la SBC. El área de estudio ha sido modificada por las actividades humanas desde antes de la época colonial, por lo que no fue posible evaluar el efecto de las variables topográficas independientemente de los factores humanos. Los modelos predictivos generados en esta tesis permitieron predecir, con muy buen desempeño, los niveles de biomasa presentes en la SBC de la región de Ayuquila en Jalisco, México. Estos modelos pueden ser utilizados en la planificación de proyectos REDD+ en México a escala regional y local. A nivel regional, para seleccionar las comunidades con el mayor potencial para reducir la degradación forestal y mejorar los almacenes de carbono forestal y a nivel local para seleccionar los sitios dentro de las comunidades donde las acciones REDD+ deben tener una alta probabilidad de éxito. En cualquiera de las escalas, estos resultados proporcionan una oportunidad para enfocar las acciones REDD+ para reducir la degradación forestal o mejorar los almacenes de carbono en las SBCs con un enfoque de paisaje, aprovechando el enorme potencial que existe en el SBC de México para regenerar naturalmente.

SAMENVATTING (IN DUTCH)

In de context van klimaatverandering zijn tropische bossen een zorg van wereldwijde betekenis. Dit komt omdat bossen het belangrijke broeikasgas koolstofdioxide (CO_2) kunnen uitstoten maar juist in hun biomassa opvangen. Het vermogen van een bepaald type bos om koolstofvoorraden vast te houden wordt sterk beïnvloed door zowel de topografie van het landschap als door het menselijke gebruik. In de literatuur wordt de topografie niet alleen aangegeven als een landschap sjabloon dat de patronen van dichtheidsbiomassa definieert, maar ook als een factor die het menselijk gebruik beïnvloedt. Hoewel onder andere de hoogte, de hellingshoek en de concaafheid / convexiteit van het terrein (samen de terreinsvorm), een relatie met biomassapatronen vertonen, hebben menselijke activiteiten zoals zwerflandbouw, begrazing en extractie van houtachtige producten de neiging om de topografische configuratie van het landschap te volgen. Dit komt omdat verschillende topografische kenmerken verschillende biofysische omstandigheden bieden die verschillende menselijke activiteiten ondersteunen. De relatieve bijdrage van de topografische en de menselijke factoren aan de biomassapatronen is daardoor echter niet erg duidelijk.

Bossen hebben een prominente rol gekregen in het klimaatveranderingsbeleid, omdat als menselijke activiteiten in het bos worden verminderd, de emissies zullen afnemen en de koolstofvoorraden kunnen toenemen. Internationaal beleid ter bestrijding van klimaatverandering omvat daarom de vermindering van de uitstoot van broeikasgassen door ontbossing en degradatie in tropische landen. Het omvat niet alleen de vermindering van ontbossing en aantasting van bossen, maar ook duurzaam beheer, bosbehoud en verbetering van boskoolstofvoorraden (´Reduced Emissions from Deforestation and forest Degradation´, ofwel REDD+). In Mexico wordt REDD+ geïmplementeerd met behulp van een landschaps- of territoriale aanpak, hoewel de definitie hiervan niet erg duidelijk is.

Dit proefschrift is uitgevoerd in tropisch droog bos (SDTF), een soort loofbos, waarvan de structuur en functie wordt bepaald door de beschikbaarheid van water in het systeem gedurende het hele jaar. Hoewel bekend is dat dit type tropisch bos in Mexico historisch gezien te kampen heeft met veel ontbossing en degradatie als gevolg van menselijke activiteiten, zijn er weinig studies uitgevoerd in dit bioom in vergelijking met vochtige tropische regenwouden, deels omdat het veel minder commerciële waarde heeft in termen van hout. Er is behoefte aan modellen die het niveau van biomassa in dit type tropisch bos in Mexico kunnen voorspellen, ter ondersteuning van de oprichting van REDD+ projecten en ter versterking van de bestaande koolstofvoorraden in de bossen.

Schattingen van staande (bovengrondse) biomassa in het studiegebied zijn afkomstig van 144 bemonsteringspercelen, verdeeld over zes plattelandsgemeenschappen in de regio Ayuquila in Jalisco, Mexico, een van de REDD+ vroege actiegebieden (Early Action Areas). Deze vroege actiegebieden zijn laboratoria waar verschillende demonstratieactiviteiten met betrekking tot de implementatie van REDD+ worden uitgevoerd. Als maat voor de koolstofmilieudiensten heb ik gegevens uit de bemonsteringsplots gebruikt en geëxtrapoleerd om de bovengrondse koolstofvoorraden per hectare te bepalen. Ik nam ook bodemmonsters om de koolstofgehalten in de bodem te bepalen in een deel van het gebied. Koolstofvoorraden en -stromen in staande biomassa en bodem werden bepaald.

De hoofdstukken die het veldonderzoek en de resultaten ervan beschrijven (hoofdstukken 4, 5 en 6) hebben de vorm van artikelen, waarvan hoofdstukken 4 en 6 al zijn gepubliceerd in geïndexeerde wetenschappelijke tijdschriften, terwijl hoofdstuk 5 wordt herzien om opnieuw in te dienen bij een tijdschrift. De eerste drie hoofdstukken van het proefschrift geven de beweegreden, de context en beschrijven de methodologie van het onderzoek, terwijl het laatste hoofdstuk de resultaten van de verschillende artikelen bijeenbrengt en probeert antwoorden te vinden op de onderzoeksvragen die in hoofdstuk 1 zijn uiteengezet. Deze waren als volgt:

1. Hoe zijn bovengrondse biomassapatronen gerelateerd aan biofysische factoren, zoals hoogte, helling en bezonning in de regio van Ayuquila, Mexico?

2. In hoeverre kan ruimtelijke voorspelling van staande bovengrondse biomassa (AGB) helpen om de locaties binnen het gemeenschapsgebied te identificeren die het meest geschikt zijn voor het opzetten van projecten?

3. Wat is de impact van zwerflandbouw op koolstofvoorraden en hoe kunnen kweekcycli worden geoptimaliseerd om koolstofvastlegging te bevorderen?

4. Hoe kunnen de bevindingen van deze studie worden gebruikt om gemeenschappen in het SDTF gebied te helpen koolstofverbeteringsprojecten te implementeren?

Om de bevindingen van de drie centrale onderzoeken samen te vatten: in Hoofdstuk 4 hebben we onderzocht hoe verschillende topografische variabelen gerelateerd waren aan biomassaniveaus in een SDTF-landschap in Mexico, met behulp van een tweedimensionale benadering (heuvelhelling). Lineaire en niet-lineaire modellen toonden relaties tussen regionale en lokale topografische factoren, maar ook menselijke factoren, met niveaus van staande biomassa. De significante regionale topografische factoren waren hoogte en diffuse isolatie, terwijl de belangrijkste lokale topografische factoren helling, terreinsvorm en topografische vochtigheidsindex waren. Een gegeneraliseerd gemengd lineair model was het beste model, goed voor 21% van de variatie in biomassa. Dit model toont een unimodale toename van biomassa met betrekking tot hoogte, helling, terreinvorm en topografische natheidsindex; in dit model had elevatie het grootste relatieve belang. Het model vond ook twee groepen onder de zes landelijke gemeenschappen met een differentiële respons in biomassa op basis van hoogte, helling, terreinsvorm en beschikbaarheid van water in de bodem. De gemeenschappen in de hogere delen van het studiegebied met meer vocht in de bodem, grotere holheid en steiler terrein, hadden hogere niveaus van biomassa; terwijl die in de lagere delen met bolle terreinkromming, lagere hellingen en minder water beschikbaar in de bodem, lagere biomassaniveaus hadden. Deze resultaten ondersteunen ook eerdere studies die biomassaniveaus relateren aan de hoeveelheid water in de bodem. In termen van menselijke factoren vertoonde de afstand tot wegen een relatie die abrupt verandert op 2.273 m. Plaatsen met bossen die zich dichter bij wegen bevinden, vertonen een sterk menselijk effect dat afneemt met de afstand, maar na deze drempel lijkt het menselijk effect weer toe te nemen. Menselijke activiteiten die van invloed zijn op bosbiomassa komen ook vaker voor op zacht hellingen met hoge convexiteit, in de lagergelegen gebieden. Met behulp van de in dit hoofdstuk gedemonstreerde methode is het mogelijk om typische gebieden langs de berghelling te identificeren die het best onder het REDD+ -programma van Mexico kunnen vallen, met een focus op het verminderen van bosdegradatieprocessen en het toenemen van koolstofvoorraden. Alle gegevens over topografische variabelen zijn verkregen uit standaard contourkaarten die gratis beschikbaar zijn in het publieke domein. Dit verlaagt aanzienlijk de investeringen die nodig zijn voor materialen en technische training, in vergelijking met methoden die zijn gebaseerd op teledetectie. In ontwikkelingslanden zou dit een heel groot verschil kunnen maken in de haalbaarheid van het plannen van grote aantallen REDD+ projecten. Deze methode zou kunnen helpen bij het implementeren van de landschapsaanpak die de Mexicaanse overheid wil nemen in haar REDD+ nationale strategie.

Vervolgens, rekening houdend met de resultaten verkregen in hoofdstuk 4, probeer ik te begrijpen hoe lokale topografische variatie binnen de landelijke gemeenschappen kan worden gebruikt om biomassaniveaus te voorspellen, met behulp van een driedimensionale, volledig ruimtelijke benadering. Hoofdstuk 5 evalueert relaties tussen biomassa en topografische variabelen met behulp van ruimtelijk expliciete Bayesiaanse regressiemodellen. We evalueerden de mate waarin hoogte, terreinhelling, terreinsvorm en topografische vochtigheidsindex, evenals de ruimtelijke relaties tussen deze topografische factoren, biomassaniveaus bepalen binnen het territorium van vier landelijke gemeenschappen, en hoe dit zou kunnen helpen om voorspellingen van biomassa te verkrijgen. Het foutniveau van de biomassavoorspellingen van de modellen werd ´out-of-the-sample´ geëvalueerd met de Root Mean Square Error en de modellen met de minste fouten werden geselecteerd. De geselecteerde modellen gebruiken een combinatie van drie lokale topografische variabelen; topografische vochtigheidsindex, tangentiële kromming en helling. Deze combinatie van variabelen lijkt de verplaatsing en accumulatie van beschikbaar water in de bodem te bepalen, wat erg belangrijk is in SDTF's. We ontdekten dat van deze drie variabelen de concaafheid en convexiteit van het terrein de belangrijkste variabele was. We ontdekten ook dat de nauwkeurigheid van mijn modellen voor het voorspellen van biomassaniveaus tussen de 65 en 80% lag. De resultaten van dit hoofdstuk zijn relevant voor het begeleiden van REDD+ acties gericht op het toenemen van koolstofvoorraden. De procedure die in dit hoofdstuk wordt uitgevoerd, maakt het mogelijk biomassaschattingen te maken binnen het territorium van een landelijk gemeenschap en om locaties in het bos te identificeren waarvan de biomassaniveaus ver onder de verwachte waarden liggen vanwege het gebruik van bosbestanden door de mens. Via deze procedure zou het mogelijk zijn om locaties te identificeren binnen het grondgebied van gemeenschappen waar bosvernietigende activiteiten kunnen worden beperkt en activiteiten die natuurlijke of geassisteerde regeneratie kunnen bevorderen met het grootste effect. Nogmaals, de gegevens over topografische variabelen waren afgeleid van topografische kaarten die vrij toegankelijk zijn, en teledetectie was niet nodig.

Hoofdstukken 4 en 5 toonden de relatieve bijdrage van topografische en menselijke factoren aan het biomassavariatie in SDTF-landschappen. Om de focus van de analyse te vergroten, concentreerden we ons op een zeer belangrijke en wijdverspreide menselijke activiteit: zwerflandbouw of verschuivingskweek (SC), ook wel bekend als 'slash en burn'. In hoofdstuk 6 hebben we de verschillen in koolstofvoorraden in bovengrondse biomassa en bodem in verschillende landgebruiken beoordeeld. De koolstofvoorraden voor de SC waren onderverdeeld in twee managementfasen: teelt en braak, die in dit gebied momenteel meestal voor respectievelijk 2 en 8 jaar worden uitgevoerd. De braakliggende fase was verdeeld in drie leeftijdsklassen, waardoor een iets meer gedetailleerd beeld van de toename van koolstofgehalten mogelijk was naarmate SC-plots ouder werden. We identificeerden ook landschapssites die veel eerder werden gebruikt als SC-plots, maar al minstens 20 jaar braak werden gelaten. Vervolgens hebben we de impact van verschillende wijzigingen van het typische SC-regime op koolstofemissies gesimuleerd door middel van verschillende beheer scenario’s. De vergelijkingen op dit laatste punt waren in termen van emissies afkomstig van de productie van één ton maïs. In dit hoofdstuk ontdekten we dat de koolstofvoorraden op oude SC-sites zelfs hoger waren dan die op locaties die nog nooit voor SC waren gebuikt. We hebben ook vastgesteld dat naarmate we de lengte van het braakland in de SC-cyclus verhoogden, de koolstofemissie toenam. Omgekeerd resulteren korte braakliggende fasen op landschapsniveau in hogere koolstofvoorraden en lagere koolstofemissies. Dit geeft aan dat de lengte van de SC-cyclus kan worden geoptimaliseerd om de koolstofvastlegging te vergroten. Volgens onze schattingen zijn de emissies van een normale SC-cyclus hoger dan die van de permanente landbouw, per ton geproduceerde maïs, hoewel hierbij geen rekening wordt gehouden met de koolstofemissies die samenhangen met de inputs die in de permanente landbouw worden gebruikt.

In dit proefschrift concludeer ik dat er, zoals verwacht, aanwijzingen zijn voor het effect van topografische en antropogene factoren op koolstof ecosysteemdiensten in de SDTF van de studieregio in Jalisco, Mexico. De koolstof ecosysteemdiensten die in dit proefschrift worden beoordeeld, zijn koolstofvoorraden in staande biomassaniveaus (hoofdstuk 4, 5 en 6) en in de bodem (hoofdstuk 6). We vonden dat topografische factoren met betrekking tot de beschikbaarheid van water in de bodem de belangrijkste verklaringen waren voor de hoeveelheden biomassavolumes in de SDTF. Het studiegebied is sinds de koloniale tijd aangepast door menselijke activiteiten, dus het was niet mogelijk om het effect van topografische variabelen onafhankelijk van menselijke factoren te beoordelen. De voorspellingsmodellen die in dit proefschrift zijn gegenereerd, hebben het mogelijk gemaakt om met zeer goede prestaties de biomassaniveaus te voorspellen die aanwezig zijn in de SDTF van de regio Ayuquila in Jalisco, Mexico. Deze modellen kunnen worden gebruikt bij de planning van REDD+ projecten in Mexico op de regionale en lokale interventie niveaus. Op regionaal niveau, om gemeenschappen te selecteren met het grootste potentieel voor het verminderen van degradatie en het verbeteren van bosbestanden en op lokaal niveau voor het selecteren van sites binnen gemeenschappen waar REDD+ acties een grote kans hebben. Op beide schaalniveaus bieden deze resultaten de mogelijkheid om REDD+ acties te ondernemen om bosdegradatie te verminderen of de koolstofvoorraden in SDTF te verbeteren met een landschapsbenadering, gebruikmakend van het enorme potentieel voor natuurlijke regeneratie dat in de SDTFs bestaat.

Chapter 1

INTRODUCTION

1.1 CONTEXT

This thesis constitutes part of a larger research project entitled “Linking local action to international climate agreements in the seasonally dry tropical forests of Mexico”, supported by the Netherlands Organization for Scientific Research programme ´Science for Global Development (WOTRO)´. This project aimed to increase understanding of how systems for international marketing of ecosystem services (in particular, carbon) could function equitably at the local level, and to assess what the potential of seasonally dry tropical forest (SDTF) might be in providing such services through community management. At the heart of the overall research project, communities play a key role. On the side of biophysical factors, the project argues that communities themselves are able to quantify, record and transmit data on carbon and other environmental services and that in doing this, they will be in a stronger position to claim rewards from the payments system.

My research project covers the component to evaluate the potential of seasonally dry tropical forest landscape to provide carbon services under community management regimes. I identified not just the physical properties of terrain that determine to some extent the quantity of standing carbon, but also evaluated one community management regime that modifies this.

Tropical forest accounts for two-thirds of all terrestrial biomass, with more carbon present in biomass and soils than is contained in the atmosphere (Pan et al. 2013). Biomass carbon density varies between different forest ecotypes. Moreover, biomass density of forest stands varies spatially, within any forest ecotype (Pan et al. 2013). The variation at the regional and local scales could be related to soil type, topography, and other local environmental variables (Pan et al. 2013, Clark et al. 2017). A considerable and growing body of research in preserved forest has been done to identify the determinants of variation of forest standing biomass, and this supports this idea of multi-factorial dependence of forest biomass on biophysical factors and human uses within tropical landscapes. Some of these research studies argue that for SDTF, water availability poses the main constraint to plant growth (Allen et al. 2017). But constraints to plant growth in SDTF appear to be deeply related to physical conditions of environment, such as differences in curvature of the terrain along the hillslope, which in turn are an outcome of different topography conditions, manifesting themselves in different biomass levels (Murphy and Lugo 1986). These differences in topography not only define environmental conditions as mentioned, but as I shall show, may also define human uses of forest.

It is well known that in SDTF, human uses such as shifting cultivation, grazing and extraction of woody products affect the levels of biomass, therefore causing variation in patterns of biomass (Murphy and Lugo 1986, Bullock et al. 1995, Dirzo et al. 2011). It has been shown by other researchers, particularly some of those working with this Science for Global Development project (Borrego and Skutsch 2014, Morales-Barquero et al. 2014, Morales-Barquero et al. 2015, Skutsch et al. 2015, Salinas-Melgoza et al. 2017) that this tends to follow the logic of topography. A template is needed to split the relative contribution of the physical and human factors that underlie variation in forest biomass at different points within the landscape. A simple way to do this is to use a hillslope model with topographic variables.

1.2 TOPOGRAPHY AS A TEMPLATE

In the rural areas of Mexico an idealized model of hillslope and variation of biomass can be observed. This model goes from the high parts to the lower parts of the hillslope, with different effects on the biomass, arranged along the hillslope. This forms a gradient not only in elevation but also in a number of other topographic variables along the catena. The uppermost section of the hillslope is flat, and is the oldest in terms of soil development, and from these areas there is almost no runoff. In this area it is possible to find human activities that make use of small flat areas, but it is the farthest part of the hillslope in terms of accessibility; hence it is more likely not to find much human activity in this area. The next position below the summit is characterized by a convex slope, and is the youngest and least stable area of the slope, where runoff and erosion are maximal. Because of this instability and the convexivity of the area it is difficult to perform human activities here. Then follows the middle position, which is the steepest part in the hillslope. This position is unstable with a lot of erosion, all the sediments accumulate in the lower part of this area, which is concave. This area is characterized by shifting cultivation; gathering of fuelwood and fence poles, in these areas cattle are released to graze freely in forested areas. The lower position in the hillslope is between flat and concave, slope is not so steep, and this area receives the runoff. This area is the newest position in terms of soil development, and can have highly diverse sediment mantles, as it receives much of the deposited material from the upper positions in the hillslope. Vegetation in this area may have been removed to give rise to areas of permanent agriculture. The majority of the human activities are performed in this area and it is also where most of the human settlements are established. The entire catena could be described as: a) a uniform slope with the uppermost, middle and lower areas, arranged along the catena (this is a simple catena) or b) a subset of more than one catena that would be repeated several times (complex catena) (Fig. 1.1). In SDTF landscapes with altitudinal gradients ranging from the lower to the uppermost areas, it is possible to find contrasting slope conditions, variations in the ruggedness of the terrain, a large variability in aspect and elevation, all of which factors contribute to a large variability in water availability. However, ultimately, what is evident in the field is that the only portions of the landscape to remain intact are those that are too challenging for human activities; those that are too rugged in topography, too remote areas or too wet or too dry for agriculture and related activities. Studies that relate biomass and topography, in the context of the catena as explained above, tend to assume a continuous gradient of all topographic variables. In this study I have tried to treat the topographical variables separately to get a more nuanced understanding of their individual impacts on carbon stock.

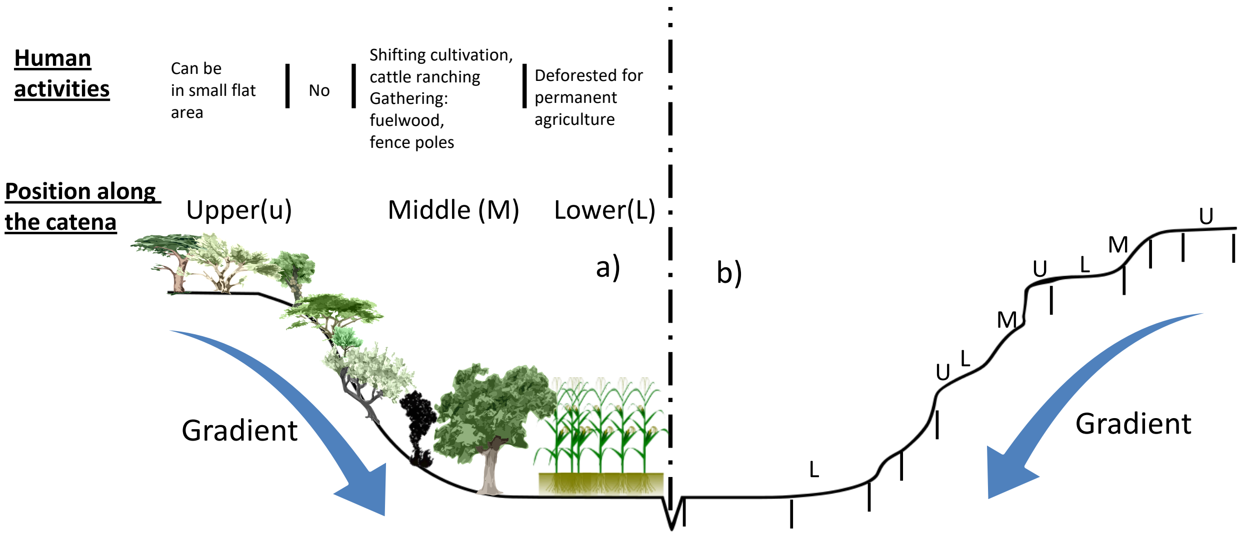

FIGURE 1.1 Representation of catena model with the three areas of the catena in the form of: a) Simple catena and b) complex catena. Human activities that follow the underling catena model are also mentioned. U, uppermost area, M, middle area and L, lower area. Modified from Schoeneberger et al. (2012).

1.3 WHY SEASONALLY DRY TROPICAL FOREST?

Seasonally dry tropical forest (SDTF) is widely distributed in the tropical areas of Africa, Asia and Centre and South America, within the tropics of Cancer and Capricorn. It is the second largest tropical forest worldwide with an estimated area of over 1.05 million square kilometres worldwide; this is about 40% of all tropical forest land mass (Murphy and Lugo 1986, Bullock et al. 1995, Miles et al. 2006, Dirzo et al. 2011). The extent of this tropical forest type in Latin

America is around 699,482 square kilometres, of which, 81% is in South America and the rest in Mesoamerica and the Caribbean (Miles et al. 2006). Originally, the coverage of SDTF was much greater, but most of the original area of this forest type has been converted to human uses (Hoekstra et al. 2005).

SDTF is found in areas which have three relevant climatic characteristics: a) pronounced seasonality in annual rainfall distribution, b) mean annual temperature higher than 17°C and c) mean annual rainfall between 250-2000 mm (Murphy and Lugo 1986, Bullock et al. 1995).

The loss (deforestation) of SDTF is related to conversion to grassland for extensive cattle raising, lands for permanent agriculture, both irrigated and rainfed (Maass 1995), while activities such as shifting cultivation (Maass 1995, Morales-Barquero et al. 2015), and gathering firewood (Masera et al. 1997) or poles for fences (Morales-Barquero et al. 2015) tend to result in degradation (i.e. having lowered biomass levels, although the area is still defined as forest). Around 97% of SDTF is said to be at risk globally as consequence of climate change, habitat fragmentation, fire, human population density and conversionto agricultural fields (Miles et al. 2006); in Mexico 80% of the remaining SDTF is degraded (Trejo and Dirzo 2000).

Mexican SDTFs have been disturbed even before the colonial times, but have been more drastically transformed after the beginning of this era (Louette et al. 2001, Gerritsen and van der Ploeg 2006). However, in some places they have recovered their structural characteristics (Chazdon 2014). This dynamic of loss and recovery of vegetation offers a window of potential opportunity for REDD+ projects for the improvement of forest carbon stocks, with carbon uptake rates which could be up to three times higher than those found in conserved forest (Pan et al. 2011, Chazdon et al. 2016, Poorter et al. 2016). In principle, degraded SDTFs have considerable room to grow though natural regeneration and improvement of management practices; but this requires first identifying and understanding drivers of deforestation and degradation of SDTF, in a way that helps to identify strategies to modify the management of the landscape. The approach I take is designed to indicate where, in the landscape, different the REDD + actions could be executed most effectively. Secondary SDTFs in Mexico offer great potential for activities aimed at increasing carbon stores, as well as reducing forest degradation (Herold and Skutsch 2011).

This forest type was selected for study in this thesis precisely because of this condition; for while SDTF is clearly vulnerable to deterioration as a result of human uses, it also offers the possibility of recuperation (regrowth, or enhancement of forest stock) if managed differently. It may therefore be a very suitable type of forest for treatment under policies such as Reduced

Emissions from Deforestation and forest Degradation (REDD+). Further, loss of biomass in SDTF has been under-researched compared to losses in rainforests. Rain forests have long been privileged in research because of their value in terms of timber and because of their iconic status in the public imagination. SDTFs may not be so beautiful to look at (especially in the dry season when they are is largely leafless), but they are at least as important in terms of biodiversity and in the provision of environmental services such as water to human populations (Bullock et al. 1985, Murphy and Lugo 1986, Trejo and Dirzo 2000, Maass et al. 2005, Skutsch et al. 2009, Dirzo et al. 2011). It is true that SDTFs in intact states hold less carbon than rainforests, but as I shall show, they offer considerable opportunity for regrowth and thus for increasing sequestration levels of carbon dioxide from the atmosphere.

To properly frame this study, the potential levels of AGB may be determined not only by the direct and indirect effects of physical factors at regional and local scale, but also as noted by dynamics of human activities in forest. Different studies have shed light on the complex interaction between forest and topographic attributes. However, almost all these studies have been carried out on undisturbed forests (Jaramillo et al. 2003, Xu et al. 2015, see Salinas-Melgoza et al. 2017 for more details), despite the fact that it is widely recognized that these tropical landscapes have been very disturbed by humans (Chazdon 2014). A small fraction of aboveground biomass is continuously removed by people at any given moment, for fence posts, firewood extraction and free-browsing in the forest cattle, and this results in degraded forest (Morales-Barquero et al. 2015, Vázquez and Givnish 1998). The problem to evaluate the potential biomass in a given location must be addressed as a whole; however splitting the relative contribution of the biophysical and the human factors that drive variations in forest biomass at different points in the hillslope is a hard task. To make such an analysis is important in a study whose aim is to assess the potential of SDTF in human modified landscapes (HML) to provide carbon environmental services. To understand what determines this potential in a given location is highly relevant for climate change policy in the forest sector (Fig. 1.2).

1.4 THE POLICY CONTEXT: REDD+

As will be described in more detail in chapter 2, Reduced Emissions from Deforestation and Degradation (REDD+) is an international policy which is considered by many to be a promising way of attaining more sustainable forest management as well as for providing carbon environment services for the global mitigation of climate change. Under REDD+, activities may be carried out that lead to five different outcomes: reduced deforestation, reduced degradation, sustainable management of forest, conservation and forest enhancement. This thesis focuses particularly on forest enhancement, for reasons that will be explained below.

1.5 RESEARCH QUESTIONS

The overarching question the research attempts to study is: what is the potential for SDTF to provide carbon environmental services? In order to respond to this large question, I broke it down into three main research questions, to which I added one more which asks how the information developed by the thesis could be used in practice to support policy. The outline of the logic of the research is shown in Fig. 1.2.

One of the most salient characteristics of much of the Mexican SDTF results from the impact of human activities which cause biomass degradation SDTF biomass levels in most places are well below those in the few more ´conserved´ areas with no human disturbance. Given this general condition of the SDTF, it is crucial to face this problem and propose strategies could help drive the existing levels of AGB to their maximum potential. One of the REDD+ activities previously mentioned would be particularly appropriate for this: forest carbon enhancement. This REDD+ activity will target interventions that would allow increase in carbon stocks within the forested areas of rural communities. I argue that the potential for forest carbon enhancement is determined by both physical and human factors in a complex interplay. The causes of AGB variation are complex and hidden and the links between AGB and topographic predictors are difficult to determine. On the one hand, this opens the opportunity to examine the ways in which AGB variation at landscape level could be modeled with regional topographic variables (Research Question 1). Local topographic factors show evidence of modulating spatial variation of AGB at a small scale. These relationships suggest that after obtaining spatial predictions of AGB within the communities territories, the most suitable places for carbon stocks enhancement projects could be identified (Research Question 2). On the other hand, human activities do modify the amount of biomass we can find in forest, but different management regimes yield different carbon levels. If management regimes compromise carbon levels, it would be possible to identify areas where carbon stocks are well below their potential levels and suggest improved management scenarios (Research Question 3). Since about 59% of all Mexico´s forests fall under community ownership (Madrid et al. 2009, targeting communities in this way could provide a major contribution to the national REDD+ strategy. There remains the question of how the study findings relating to Research Questions 1-3 could be used to help communities in SDTF to pursue carbon enhancement projects; this is encapsulated in (Research Question 4). As can be seen in the following diagram, the specific research questions that are raised in this thesis are the following:

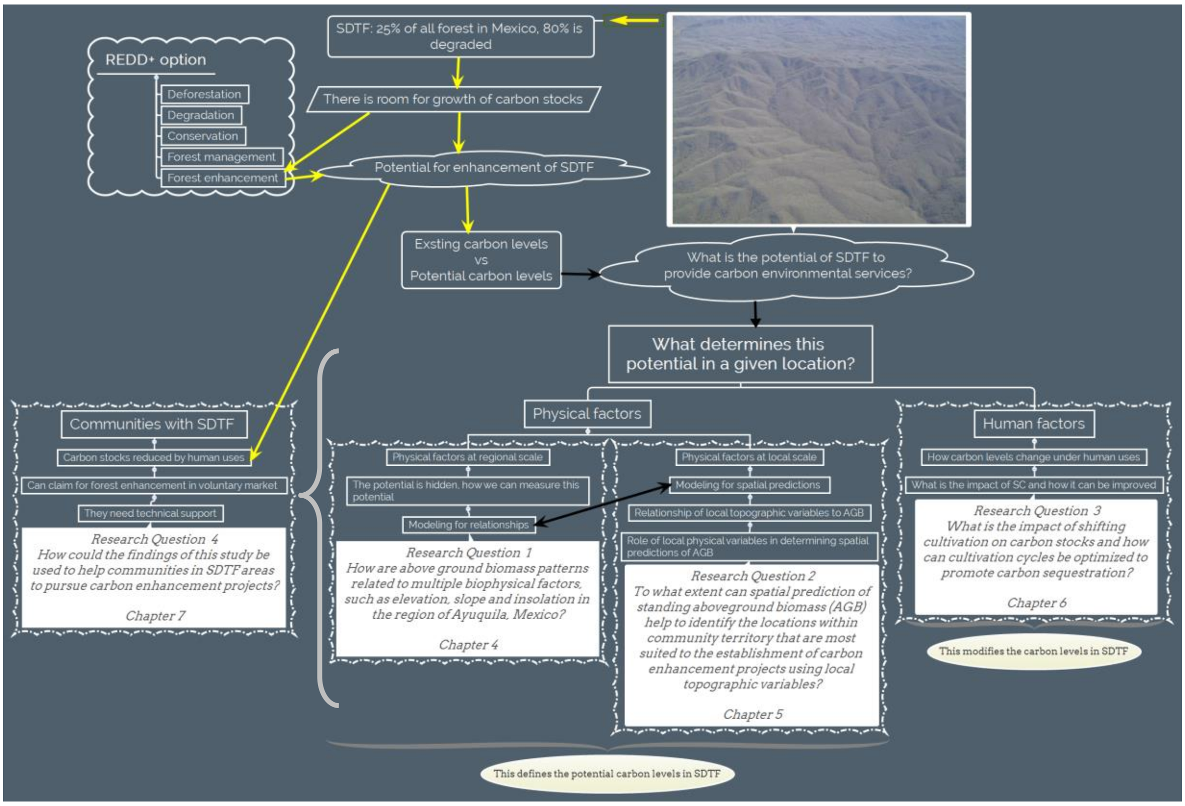

FIGURE 1.2 Conceptual frameworks that interrelate elements to determine the potential of SDTF to provide carbon environmental services, and what influences this potential in a given location.

1. How are above ground biomass patterns related to multiple biophysical factors, such as elevation, slope and insolation, in the region of Ayuquila, Mexico?
2. To what extent can spatial prediction of standing aboveground biomass (AGB) help to identify the locations within community territory that are most suited to the establishment of carbon enhancement projects using local topographic variables?
3. What is the impact of shifting cultivation on carbon stocks and how can cultivation cycles be optimized to promote carbon sequestration?
4. How could the findings of this study be used to help communities in SDTF areas to pursue carbon enhancement projects?

These are described and justified in more detail below.

RQ1: How are above ground biomass (AGB) patterns related to multiple biophysical factors, such as elevation, slope and insolation in the region of Ayuquila, Mexico?

Part of the variation of carbon stock levels in SDTF can be attributed to natural factors such as elevation (Alves et al. 2010, Pelletier et al. 2017), slope (Laurance et al. 1999), relative position on the slope (Jaramillo et al. 2003), convexity and concavity (Xu et al. 2015). However, the relative contribution of those topographic variables in human modified landscapes has been seldom studied because is hard to investigate. Regional and local biophysical factors may play a key role in explaining how AGB is distributed in the landscape, but also human factors must be considered. For example; at regional level, elevation and associated variables that vary jointly might impact AGB in different ways, but there are other possible confounding variables that may be playing determinant roles (Laurance et al. 1999). Human uses of forest may create permanent or temporary reductions in AGB levels in areas where human activities take place, which lessen or mask the natural effect, introducing confusion to the findings. This can be observed in results that show low correlations between AGB and regional variables (Unger et al. 2012).

Despite the low level of correlation between AGB and regional topographic variables, these results should be useful at least to identify which factors have an overall consistent association. In human modified landscapes, AGB tends to be lower at lower altitudes, strongly related to higher concentration of human activities in forest in these areas, than in areas in forest at higher elevation (Lovett et al. 2006). But if interventions are to be made to raise AGB levels and associated carbon stocks, it is important first to understand how above ground biomass patterns are related to multiple biophysical factors, such as elevation, slope and insolation in the region of study. (Fig. 1.2)

RQ2: To what extent can spatial prediction of standing aboveground biomass (AGB) help to identify the locations within community territory that are most suited to the establishment of carbon enhancement projects using local topographic variables?

To probe more deeply into the relationships between AGB and topographic variables, in order to support planning of REDD+ projects, it is necessary to identify locations with ideal conditions for targeting REDD+ interventions within the communities, that is to say, at the specific locations within the community territory where they will have the most scope. Studies performed in SDTF have been able to detect that biomass levels are determined by water availability (Jaramillo et al. 2003), which can be adversely affected by slope (Wilson and Gallant 2000). This suggests that if there were no human activities present, more biomass would be found in places with very favorable water conditions and these conditions can to some extent be pinpointed using local topographic variables.

Although the standard method to estimate spatially distributed carbon levels at large scales involves use of remote sensing (RS), this cannot be used to assess carbon levels at the community intervention level, because the spatial resolution of remote sensing images is too coarse (Mitchard et al. 2014, Ometto et al. 2014). Predictions of AGB levels at REDD+ community intervention locations needs to identify the small changes in forests that remain forests within any one land holding. Very high resolution images such as Rapid Eye still have to be tested to achieve this task; so far they do not appear to be very useful in this context. Although some studies have used high resolution RS technology to support communities to show results in carbon projects (Murthy et al. 2017), this is prohibitively expensive and agencies providing technical support have to cope not only with the expensive technology but also with a shortage of expertise. These drawbacks to use of remote sensing to predict carbon stocks at project level open an opportunity for other procedures to obtain accurate spatial predictions of AGB.

Several modeling procedures such as neural networks, ordination and classification methods, Bayesian models and locally weighted approaches have been developed over the last decades which with greater analytical development might be used to obtain spatial predictions of forest AGB (Guisana and Zimmermann 2000, Bell et al. 2017). Such modeling procedures are framed in a very flexible procedure that allows us to incorporate complications such as observer bias, missing data and non-standard error distributions, but at the same time makes use of previously available information to improve predictions without resorting to intensive ground level forest survey. Evaluation of local topographic variables that have been shown to impact AGB using such novel procedures would be helpful to identify to what extent spatial prediction of standing aboveground biomass (AGB) can identify the locations within community territory that are most suited to the establishment of carbon enhancement projects (Fig. 1.2).

RQ3: What is the impact of shifting cultivation on carbon stocks and how can cultivation cycles be optimized to promote carbon sequestration?

As mentioned several times already, another group of factors that determine carbon levels in the forest are those related to human uses. In SDTF many human uses of forest arise that do not result in complete forest loss (deforestation), but rather in small scale removals of AGB at any given moment, resulting in forest with lowered levels of biomass and carbon stock. Human activities like shifting cultivation (which in the study area is a traditional form of maize-based agriculture (*milpa*), performed on sloping and stony terrain, that involves no ploughing, but the use of a digging stick or coa) cause temporary destocking of forest but not permanent clearance of land as such (Morales-Barquero et al. 2015, Chazdon et al. 2016, Hobbs 2016, Ghazoul and Chazdon 2017). The landscape under shifting cultivation regime is a mosaic of forests of different ages in a continuum of forest succession, since these areas are used in the cyclical patterns. Shifting cultivation reduces carbon concentration in above ground vegetation (Lawrence and Foster 2002, Read and Lawrence 2003, Gehring et al. 2005, Eaton and Lawrence 2009, Lawrence et al. 2010, Antunes et al. 2013, Salinas-Melgoza et al. 2017, Fearnside 2000, Houghton and Goodale 2004, Houghton 2005, Detwiler and Hall 1988). It has been argued that improvement of these human management regimes would reduce overall greenhouse gases (GHG) emissions (Robinson et al. 2013).

However, before making any such recommendations under REDD+, it is essential to know what the impact of shifting cultivation on carbon stocks is and how cultivation cycles could be optimized to promote such GHG emission reduction; this has never, to my knowledge, been researched. In Mexico shifting cultivation cycles have been shortened and two scenarios may be considered in this regard; one in which shifting cultivation is replaced by permanent agriculture, sparing or conserving more forest land, and one in which cultivation cycles are lengthened to reduce the intensity of the production system. Both scenarios pose different circumstances, and it is interesting to study which option would be most effective to reduce emissions (Fig. 1.2).

RQ4: How could the findings of this study be used to help communities in SDTF areas to pursue carbon enhancement projects?

Under the REDD+ policy approach, country which are Parties of UNFCCC are requested to ensure the involvement of local communities in the implementation of REDD+. Around 60% of Mexico forested ecosystems belongs to rural agrarian communities, these are either ejidos or traditional indigenous communities (Skutsch et al. 2013). In Mexico the communities are mostly *ejidos* (Madrid et al. 2009). They are communities which form an agrarian nucleus with a communal land rights system. Originally each community member (*ejidatario*) was allocated an equal share of the total land available, for agriculture, and the remaining land was managed communally (this part was often dominated by forest). According to the Mexican legal framework communities own the biomass within their territory and logically they therefore own any increases in biomass that occur in this area. In principle, therefore, they may claim credits for forest enhancement through any voluntary market. However, they do not own, or have rights, to emission reductions on their territory (CONAFOR 2017), so that any such reductions achieved under the National REDD+ Strategy will be the property of the state (the rational for this somewhat confusing situation with regard to carbon credits is explained in more detail in chapter 2). What this means, in short, is that there is a direct incentive for communities to engage in projects which will result in increases in biomass rather than in those which result in decreases in emissions.

In the SDTFs in Mexico that have been degraded earlier as a result of human activities (Trejo and Dirzo 2000), there is considerable ‘room to grow’ and hence there is room for communities in SDTF to participate in such forest enhancement carbon projects, to increase carbon stocks in the forest by enabling natural regeneration to take place. This provides the context for the fourth question, whether the findings of this study can be used to help communities in SDTF areas to pursue carbon enhancement projects? (Fig. 1.2)

1.5 STRUCTURE OF THE THESIS

This thesis is an article-based thesis. The order of the chapters is overall in line with the order of the research questions and the conceptual frame work (Fig. 1.2). The thesis consists of seven chapters, including this Introduction (Chapter 1). Chapter 2 presents a review of the related, mainly empirical literature on the factors both physical and human that impact biomass levels in the case of seasonally dry tropical forests. It also explains the context of the thesis questions, and explains how REDD+ policy works in Mexico. Chapter 3 presents and justifies a set of methods which have been used in this thesis to answer the research questions formulated. Chapters 4, 5 and 6 are articles, two of which are already published while the third is under revision (Table 1.1). Chapter 4 addresses Research question 1. In this chapter I explore the extent to which aboveground levels in the SDTF could be predicted using linear and non-linear relationships at regional (that is to say, multi-community) scale with physical variables such as altitude, slope and insolation. More complex modeling approaches in which aboveground biomass levels are related to local topographic variables that are systematically replicated in the landscape, such as convexity/concavity of the terrain, link this to standing carbon biophysical potential of SDTF. These are presented in Chapter 5, which addresses Research question 2. Chapter 6 addresses research question 3. This chapter addresses the intensification of current shifting agricultural practices in the study area and evaluates the impact of shifting cultivation on carbon stocks. It considers how cultivation cycles can be optimized to promote reduction in carbon emission. Chapter 7 discusses the results of the three empirical chapters (articles), and addresses Research question 4, evaluating how the results of the thesis could be used to support carbon enhancement projects by communities. In this chapter I also highlight in general terms the original contributions of the thesis, the limitations of the study and directions for future research.

TABLE 1.1 Research questions in the papers of relevance to specific research questions.

RESEARCH QUESTIONS	Chapter	Publication
RQ1: How are above ground biomass patterns related to multiple biophysical factors, such as elevation, slope and insolation in the region of Ayuquila, Mexico?	**Chapter 4**	Salinas-Melgoza, M.A., Skutsch, M. and Lovett, J.C. (2018). Predicting aboveground forest biomass with topographic variables in human-impacted tropical dry forest landscapes. Ecosphere 9(1): 1-20 https://doi.org/10.1002/ecs2.2063
RQ2: To what extent can spatial prediction of standing aboveground biomass (AGB) help to identify the locations within community territory that are most suited to the establishment of carbon enhancement projects using local topographic variables?	**Chapter 5**	Salinas-Melgoza, M.A., Skutsch, M., Lovett, J.C. (2017). Spatial modeling of carbon in a local landscape using topographic variables: potential applications under REDD+. Manuscript submitted for publication to Ecology and Evolution
RQ3: What is the impact of shifting cultivation on carbon stocks and how can cultivation cycles be optimized to promote carbon sequestration?	**Chapter 6**	Salinas-Melgoza M. A., Skutsch, M., Lovett, J. C. and Borrego, A. (2017). Carbon emissions from shifting cultivation: a case study of Mexican tropical dry forest. Silva Fennica vol. 51 no. 1B https://doi.org/10.14214/sf.1553
RQ4: How could the findings of this study be used to help communities in SDTF areas to pursue carbon enhancement projects?	**Answered within the text of Chapter 7**	

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Chapter 2

CONTRIBUTING THEORIES AND LITERATURE REVIEW

2.1 INTRODUCTION

This chapter starts by reviewing the theoretical and empirical literature on the factors both physical and human which impact on biomass levels in the case of seasonally dry tropical forests (SDTF), explaining why certain physical variables have been used in this thesis in modeling carbon in the landscape and which human activities impact on carbon levels the study area. It then recalls the policy context (the UNFCCC initiative on Reduced Emissions from Deforestation and Degradation, REDD+) within which this thesis is framed and explains how communities in Mexico may be incorporated both in the national REDD+ plan, which deals with reducing deforestation, and in the voluntary carbon sector, where the possibilities for developing carbon credits for forest enhancement lie. Finally, I explore two relatively new policy concepts which may have bearing on how the results of this thesis could be used: the so—called ´landscape´ approach to climate change mitigation, and the ´land sparing-land sharing debate´.

2.2 TOPOGRAPHIC FACTORS WHICH EXPLAIN VARIATIONS IN BIOMASS

2.2.1 RELATIONSHIPS BETWEEN HILL SLOPE, WATER IN SOIL AND PLANTS GROWTH

In seasonally dry tropical forest, water availability is a constraining factor on forest biomass, as mentioned in the previous chapter. In this sense, the amount of water available in soil may limit different vital functions in plants. The amount of water in the soil is determined by multiple factors. Certain types of soil and topographic conditions are conducive to full water saturation; clayey soils, topographic curvature with greater concavity, and lower positions in the hillslope are some of these conditions. A wide range of combinations of these factors is possible and it is the combination that ultimately determines the water content in soil.

The effect of water in soil has a straightforward impact on plants. For example, too little soil water leads to water stress, resulting in poor water and low mineral uptake by roots, a reduction in litter decomposition, less photosynthesis and a rise in the relative respiration of the plants (Kirkham 2014). Oxygen in soil pore spaces is highly relevant for plant roots, because they use it to respire; if there is too much water in soil, it replaces the oxygen by resulting in anaerobic conditions in the root zone, which rots the roots (Kirkham 2014). Water soil saturation also promotes ideal conditions for the development of pathogenic organisms, such as fungus (Kirkham 2014).

2.2.2 PHYSICAL VARIABLES

There are two kind of topographic variables describing land-surface; primary-order and second-order. The former are geometric attributes of the topographic surface calculated directly from a digital elevation model (DEM) or contour map; these include slope, aspect, profile curvature, planar curvature, and others. Second-order variables are those that are computed using two or more primary variables, and are widely used because they describe pattern as a function of process (Wilson and Gallant 2000, Moore et al. 1991).

2.2.2.1 Slope

Slope is a primary-order geometric function describing the height below or above a plane. It has been used widely to link relations between landscape patterns and ecological processes and it is included in the calculation of other topographic variables and indexes (Wilson and Gallant 2000).

Water availability is usually understood to be the main determinant of biomass in the tropics (Borchert 1994, Hinckley et al. 1991, Jaramillo et al. 2003, Asbjornsen et al. 2011, Negusse and Garcia-Baquero 2014, Wagner et al. 2012, Mendivelso et al. 2013) and as this is strongly affected by slope, slope angle (inclination of a slope from a horizontal plane) it is often used as an indirect measure of water availability. Slope angle has been reported as one of the main explanatory variables of forest structure, particularly of biomass and canopy height (Yanagisawa and Fujita 1999, Segura et al. 2002, Linares-Palomino and Alvarez 2005, Sawada et al. 2015, Klein et al. 2015). Most studies do not look at the entire slope angle gradient but consider two or three contrasting slope angle conditions and relate this to biomass or other forest structure characteristics, (Yanagisawa and Fujita 1999, Sawada et al. 2015). Extreme slopes are more likely to promote movement of water and other materials by gravitational processes (Wilson and Gallant 2000). The middle part of the slope has little advantage to plants in water uptake from the soil due to shallow soils and the horizontal and vertical movement of water and other materials in this position (Lu and Godt 2013). The opposite happens in the lower and flatter parts of the hillslope; because due to accumulation of humidity and other materials in this area, no period of drying or nutrition restrictions are found even if soil is shallow (Lu and Godt 2013).

In theory, flat sites tend to have higher water availability, organic matter content and nutrient availability than sloping sites (Schaetzl and Anderson 2005), and as a result forest ecosystems on sites with small slope angles should show higher biodiversity, basal area, and annual net primary productivity than steeply sloping sites (Balvanera and Aguirre 2006, Jaramillo et al. 2003, Martínez-Yrízar et al. 1996).

This is on account of the significantly higher fertility and humidity in the level areas, which tend to be in the lower parts of the catena which receive nutrients displaced and transported downwards from more steeply angled terrain, in water solution. The effect has been reported as a general trend in many forests around the world (Martínez-Yrízar et al. 1996, Galicia et al. 1999, Tuomisto and Poulsen 1996, Laurance et al. 2010, Laurance et al. 2009, Guitet et al. 2016, Cielo-Filho et al. 2007). The relationship between slope and forest characteristics is however not universal. In some studies no correlation at all was found between slope and above ground biomass (Clark and Clark 2000).

Several other studies in subtropical forests have shown that flat summits harbor the highest levels of forest biomass (McEwan et al. 2011, Marshall et al. 2012, Xu et al. 2015), and that as angle slope increases, above ground carbon decreases (Marshall et al. 2012). Slope angle has been found to be an important determinant of biomass in central Amazonian Tropical Moist Forest where biomass changes by a factor of two between the summit and the foot of the slope (Laurance et al. 1999), and in the semi-arid southern region of Brazil where forests on steep slopes accumulate less biomass than they do on flat surfaces, due to wetness conditions. It is however difficult to separate out the different relief factors involved. Apart from differences in altitude, in this region the mountain slopes harbor unstable and shallow soils, that constrain root development (Arruda et al. 2011, Arruda 2015).

With respect to the study area (Jalisco, Mexico), water availability has been shown to be related to slope and to be the main factor affecting forest structure as well as biodiversity and species composition (Galicia et al. 1999, Segura et al. 2002, Balvanera et al. 2002). In another study it was found that total basal area of live stems was larger in relatively level sites at the ridge top and in sites at the bottom of the slope, and lower in the middle slope areas and at the summits (Morales-Barquero et al. 2015), indicating that it is indeed slope and not altitude per se that is the controlling factor. Segura et al. (2002) in a different area of Jalisco reported that mean stem basal area was halved between the extreme positions in the slope. The area at the bottom of the slope showed the lowest stand density, but had a higher frequency of larger trees, with a much higher basal area. However, perhaps the most relevant study in Jalisco state on this topic was carried out by Jaramillo et al. (2003). In this study the total aboveground biomass in floodplain forests and upland was assessed. They found that floodplain forests harbored the highest total above ground biomass with 416 Mg/ha, whereas the forests located on steep slopes showed the lowest, ranging from 94 to 126 Mg/ha.

Another study in Jalisco attempted to evaluate one of the most relevant factors that controls temporal and spatial distribution of seasonal soil water content within the landscape: solar radiation. Because solar radiation strongly affects soil water, it was used as proxy for seasonal water availability. It was found that areas with greater solar radiation interception had lower tree densities, and also lower average tree diametre at breast height (Galicia et al. 1999). This is in fact one of the very few studies that has used water availability to explain variation in biomass, although there are several which use water availability, or indeed slope, to explain biodiversity (Balvanera et al. 2002, Balvanera et al. 2011).

Although the effect of slope on water availability is clearly important, it also impacts on other physical and biological processes. Most obviously, it determines processes of soil formation along the hillslope, mainly because it is the means by which gravity induces movement of materials, modified to some extent by the velocity of both surface and subsurface flow (Wilson and Gallant 2000).

For the purposes of analysis, slope is one of the least sensitive terrain attributes with regard to resolution change (Deng et al. 2007). Its value can be obtained for each DEM cell, using the value of the cell centres of a three-by-three search window (Jones 1998). There are several algorithms to calculate slope, which are different in the ways in which surrounding values are selected to compute change in elevation (Jones 1998). The best algorithms are those which include the lowest local variability present in the original DEM without overestimating slopes (Dunn and Hickey 1998), including Morrison's test surface, and Fleming, Hoffer and Horn’s methods (Jones 1998).

2.2.2.2 Elevation

The role of elevation (height above sea level) on temperature is well known. As height increases, average temperature decreases at a rate of about 10 °C/km (Barry 2008). This affects biomass largely through evapo-transpiration rates, which decrease at lower temperatures (Goulden et al. 2012, Sundqvist et al. 2013). In tropical areas higher elevation is associated also with increases in wind speeds and rainfall, all of which can also have an impact on biomass levels. There is also a greater incidence of landslides (Lawton and Putz 1988), which may create temporary reductions in biomass levels in areas affected, although they may always not be related to altitude (Körner 2007).

The majority of studies evaluating the effect of elevation on biomass have been done over large elevation differences, covering several vegetation types and considerable variation in altitudinal gradients. However, studies at mesoscale (of a few square kilometres) or over short altitudinal gradients, which typify conditions in the area studied in this thesis, and particularly within one single vegetation type, have seldom been made.

Biomass responses to elevation may follow a monotonic decrease or increase, or have a unimodal pattern (Fig. 2.1). These three patterns can be observed over small changes in height (less than 300 metres, (Herbert and Fownes 1999)) as well as over large changes in altitude (more than 2,500 metres, (Lieberman et al. 1996)).

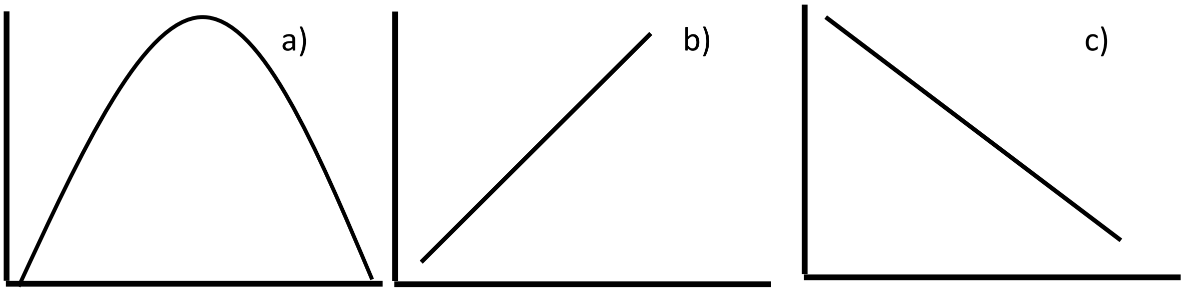

FIGURE 2.1 Hypothetical representation of biomass responses to elevation. a) U-shaped (increase followed by decrease with elevation); b) monotonic increase with elevation; c) monotonic decrease with elevation.

Studies that have evaluated the effect of large elevation differences on biomass in some tropical areas have shown both monotonic increases (Tanner 1980, Lieberman et al. 1996, Herbert and Fownes 1999, Culmsee et al. 2010, Alves et al. 2010, Moser et al. 2011, Marshall et al. 2012, Lovett et al. 2006) (Table 2.1) and monotonic decreases (Kitayama and Aiba 2002, Girardin et al. 2010, Moser et al. 2011, Weaver and Murphy 1990, Lieberman et al. 1996, Raich et al.1997, Aiba and Kitayama 1999, Kitayama and Aiba 2002, Girardin et al. 2010) (Table 2.1). Decreases of biomass with elevation would, other things being equal, be expected to be the norm. Increases in biomass with elevation can however occur in relation to limiting nutrient conditions, themselves due hydrologic situations that lead to decreases in mineralization rates. Such decreases have been related either to climatic factors (temperature decreasing) or to edaphic properties (e.g. soil waterlogging, excess or restriction of several key soil elements combined with decreasing temperatures), or to a combination of several of these factors, such as soil waterlogging and low temperatures at high elevations which promote incomplete decomposition of organic material, and tend to give rise to acid soils of low fertility.

U-shaped cases (with increases followed by decreases) have also been recorded (Table 2.1). In these cases, where biomass increases up to a certain elevation and then decreases, the explanation is that there exist constraints that co-vary with elevation (Raich et al. 1997, Marshall et al. 2012). This pattern is usually attributed to declining temperatures at high altitudes (Sundqvist et al. 2013). Non-directional responses of biomass to elevation have also been found. These are explained in terms of variation in other variables such as bedrock type, soil age and precipitation regime, which may have greater influence on biomass levels than elevation (Sundqvist et al. 2013).

In those studies which have investigated forest biomass levels over relatively small differences in altitude, the comparison is usually between sites at the lowest altitude and at the highest altitude, rather than continuously along a gradient. The majority of these studies show that sites located in the lowest elevation have higher forest biomass or basal area than those at higher elevations (Raich et al. 1997, Jaramillo et al. 2003, Segura et al. 2002) (i.e. following the monotonic decreasing mode). However some of the studies carried out along short elevation transects have found that as elevation increases, basal area generally increases (Tanner 1980, Herbert and Fownes 1999, Aiba and Kitayama 1999, Takyu 2003).

TABLE 2.1 Types of relationships between biomass and elevation.

Relationship	References	Location	Explanation
Monotonic decreasing with elevation	Homeier et al. 2010 Kitayama and Aiba 2002 Raich et al. 1997 Weaver and Murphy 1990 Jaramillo et al. 2003 Segura et al. 2002 Girardin et al. 2010	Ecuador Malaysia Hawaii Puerto Rico Mexico Mexico Peruvian Andes	- Temperature -Drought periods -Reduced radiation -High wind speeds
Monotonic increasing with elevation	Tanner 1980 Lieberman et al. 1996 Moser et al. 2011 Alves et al. 2010	Jamaica Costa Rica Ecuador Brazil	-Reduction in forest canopy height -Limiting nutrients -Large numbers of small

	Herbert and Fownes 1999 Unger et al. 2012 Aiba and Kitayama 1999 Basnet 1992 Takyu 2003 Weaver 1990 Lovett et al. 2006	Ecuador Puerto Rico Tanzania	trees per unit area -Land form -Decrees of mineralization rates -Rainfall -Soil drainage -Human uses
Bi-modal	Ensslin et al. 2015 Brown and Lugo 1982 Marshall et al. 2012	Mount Kilimanjaro Tropical area	- Soil nutrient relations -Biotic interactions - Biomass pattern linked to precipitation patterns -Slope -Potential Evapotranspiration -Human disturbance

2.2.2.3 Aspect

The effect of aspect (the direction a slope faces in relation to the sun’s rays) on forest structure has been discussed for a long time with regard to temperate forest in the mid and high latitudes (Holland and Steyn 1975). In the northern parts of the globe, slopes facing north tend to receive less sun light (Fig. 2.2) and are consequently colder and wetter than the ones facing south, which provide more favorably sheltered areas for tree development (Holland and Steyn 1975).

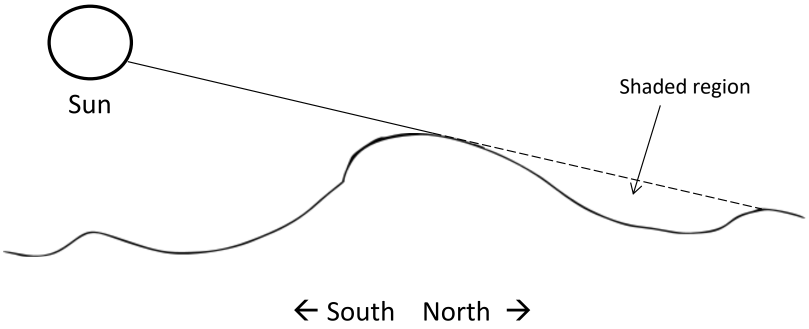

FIGURE 2.2 Hypothetical representation of shading effect by aspect in relation to slope orientation.

In tropical areas aspect does not usually play a key role in structuring vegetation (Sarmiento 1986, Williams-Linera and Lorea 2009) because during the entire year solar radiation is received from angles both north and south. North-facing slopes have a weaker effect on soil water retention than south-facing slopes, followed by west-facing and east-facing slopes, favoring lower evapotranspiration. Flat areas do not receive the effect of aspect. Several studies in tropical latitudes have shown no correlation between aspect and basal area, such that areas with differing aspect have the same basal area (Basnet 1992, Burnett et al. 1998, Bellingham and Tanner 2000, Gallardo-Cruz et al. 2009, Lee et al. 2015). In all probability, a variety of other environmental factors lessen or mask the effect of aspect (Kirkpatrick et al. 1988), so that its effect cannot always be clearly observed. However results from some studies have shown northern-facing slopes having higher basal area than southern-facing ones (Segura et al. 2002) or higher biomass gain (Kariuki et al. 2006, Le Bec et al. 2015). What is not in doubt is that vegetation attributes are modified primarily by patterns of water availability, and this is indirectly impacted by slope orientation, via the effect of differential solar radiation.

2.2.2.4 Soil

The fundamental nature of soil will be determined by underling geology and climate, but as regards its relation to topography two factors are important: transport and deposition, the former from the top and the later at the base of the slope. Soil characteristics are often related to the position along a soil catena (Chauvel et al. 1987). The upper positions in the hillslope lose material, which moves down the slope and gets deposited on the lowest positions of the catena, leading to two contrasting conditions as regards soil properties. There is also a loss of nutrients by downslope leaching and runoff which enriches the soils at the valley bottom.

Because finer sediments move more easily to lower hillslope positions, coarser materials are generally left behind on upper hillslope positions. Under this model, the soils at the top would be expected to be shallowest and sandy, soils at the lowest position would tend to be deepest and made up of clay or silty particles (Schaetzl and Anderson 2005). While summit positions are expected to be the driest, positions downslope are more humid.

Many studies about impacts of soil fertility on forest biomass have, not surprisingly, found higher biomass in nutrient-rich soils than in nutrient-poor soils (Clark and Clark 2000, White and Hood 2004, Laumonier et al. 2010, Paoli et al. 2008, De Walt and Chave 2004, Laurance et al. 1999), but in other studies no differences in aboveground biomass were found between the rich and poor soil condition (Gonzalez and Zak 1996, Clark and Clark 2000). This is because topographic characteristics control the soil chemical and physical properties (Quesada et al. 2009, Oliveira-Filho et al. 2001). Also one single nutrient may play a crucial role on forest biomass; Quesada et al. (2009) found that while total phosphorus concentration has a positive effect on biomass, soil exchangeable potassium shows a negative effect.

2.3 HUMAN ACTIVITIES WHICH IMPACT CARBON LEVELS IN THE STUDY AREA

Human activities are common in rural landscapes, but are scattered unevenly throughout them. Some parts of the tropics, and some ecosystems, have relatively high human population densities, while others are very low (Murphy and Lugo 1986, Miles et al. 2006, Malhi et al. 2014) with figures ranging from less than 10 people per km^2 (in the Amazonia and Guyana Shield) to around 350 (Western Ghats and Sri Lanka) (Cincotta et al. 2000). In Mexico, seasonally dry tropical forests in general tend to have higher densities of population than humid tropical forests (Murphy and Lugo 1986). Density matters, since the livelihoods of most rural populations depend in part on resources from forest lands (Sunderlin et al. 2008), and where pressure is greater there is obviously more likelihood of direct or indirect impact on natural vegetation (Cincotta et al. 2000, Malhi et al. 2014). However studies evaluating the impact of human activities on biomass do not usually put this in the context of their position in the hillslope. This is in some ways surprising, given that agriculture (permanent or shifting cultivation), forest management, cattle raising and collection forest products (such as firewood), all follow, to some extent, the logic of topography.

2.3.1 SHIFTING CULTIVATION

In the area of study, low–lying flat terrains with nutrient rich soils are suited to permanent, and particularly to irrigated agriculture, which is more profitable than shifting agriculture (Ryan et al. 2003, Flores-Díaz et al. 2014, Morales-Barquero et al. 2015, Salinas-Melgoza et al. 2017).

In permanent agriculture plots, forest is permanently cleared, removing the aboveground biomass, and soil carbon is rapidly depleted by tillage which leads to oxidation (Salinas-Melgoza et al. 2017). The carbon in both aboveground biomass and in soil never recovers its original levels because the soils are in constant use for production of crops (Detwiler and Hall 1988, Salinas-Melgoza et al. 2017).

Shifting cultivation, which is a traditional low-input and non-mechanized agriculture, is performed in hilly and stony areas or in flatter lands at higher altitudes as these are not suitable for permanent cropping.

Shifting cultivation is characterized by a cyclical process. Untouched forest or secondary vegetation is cut, the debris is burned, and the land is then used to plant crops, usually in a cyclical system alternating between cropping and fallow/forest regeneration, in a continuing agricultural system. The cultivation phase involves clearing small plots of primary or secondary forest and growing crops for one to three years, taking advantage of the nutrients in the ashes of the burnt plants until these are depleted and weeds become a problem. There follows a fallow phase, during which crop production is suspended to allow recovery of soil fertility. Cultivation then moves on to another plot, while the nutrient depleted plot is allowed to recovery naturally, often being used as a grazing area as the trees re–grow. The details of the practice and factors involved vary greatly from place to place and from one group of people to another, for example as regards the cropping pattern, length of fallow, crop mixture, type of vegetation and canopy cover, rainfall, soil quality, method of production and migration systems. The length of the cycle can vary from 3 years to over 20.

Shifting cultivation has been a stable and popular cultivation system throughout agricultural history and in many parts of the world. This is because it gives relatively high returns to labour (Raintree and Warner 1986, Seidenberg et al. 2003) and is therefore an efficient form of production, provided population densities are low and the potential cultivation area abundant, so that the fallow period matches or exceeds the time necessary for recovery of the sites. However, in some places, as rural populations have increased, fallow periods have been shortening, from two to three decades, down to 0–5 years (Grogan et al. 2012 citing cases in S.E. Asia), resulting in lowered soil fertility, increased soil erosion losses, and reduced annual crop yields. During the colonial period, shifting cultivation was generally considered ´wasteful´ and ´primitive´ (Geertz 1963, Spencer 1966), and other such attitudes are mentioned in Dove 1983, and Jarosz 1993. The term ´slash and burn´ originates from this period and the choice of words has a clear negative connotation. Despite the fact that during the last 25 years a large number of scientific articles have vigorously contested the negative effect of shifting cultivation (Rambo 1990, Angelsen 1995, Fox et al. 2000, Ickowitz 2006, but see also earlier re–assessments such as Schultz 1964), this negative point of view is still very common. Shifting cultivation is widely blamed as a leading cause of tropical deforestation (Geist and Lambin 2001, Geist and Lambin 2002) and for the associated carbon emissions (Houghton et al. 2003, Houghton and Goodale 2004, Nigh and Diemont 2013).

There is evidence of the effect of time on various forest attributes where shifting cultivation is performed, but the time needed for carbon levels to recover to the levels found in old-growth forest is highly variable. This variation is influenced by several variables, such as the original condition of forest when it was felled, the vegetation left behind in the remnant patches (Velázquez and Gómez-Sal 2007, 2008, Maza-Villalobos et al. 2011), intensity and frequency of management practices (number of slash-and-burn cycles, and length of fallow period (Eaton and Lawrence 2009, Dalle and Blois 2006), type of soil, changes in environmental conditions and resource availability (Lebrija-Trejos et al. 2011) all of them playing a key role in how fast the succession on fallowed shifting cultivation plots rolls out over time. Lowering of carbon concentration in above ground vegetation has been reported for tropical forests where shifting cultivation is performed (Lawrence and Foster 2002, Read and Lawrence 2003, Gehring et al. 2005, Eaton and Lawrence 2009, Lawrence et al. 2010, Antunes et al. 2013, Salinas-Melgoza et al. 2017), but since shifting cultivation involves a fallow period, the natural vegetation recovers and builds up stocks of aboveground carbon, albeit that the stocks of carbon in these fallowed forests are lower than those in undisturbed forests (Fearnside 2000, Houghton and Goodale, 2004 Houghton 2005, Detwiler and Hall 1988). The extent to which recovery reaches carbon concentration levels similar to preserved forest is highly variable (Lawrence and Foster 2002).

2.3.2 CATTLE MANAGEMENT

In the study area two general types of cattle ranching are found, both of which modify forest to some extent; clearing of forested areas for creation of pastures, and the practice of putting free-ranging cattle in the forest for grazing (Sánchez-Velásquez et al. 2002, Montaño et al. 2003, Vargas et al. 2000, Skutsch et al. 2015). The former involves man-made or induced grasslands replacing seasonally dry tropical forest. The later does not involve direct tree removal; in this case the forest remains as forest in which the cattle browse freely. This tends to reduce understory growth rates as the cattle eat the accessible woody twigs and leaves from trees and shrubs and woody seedlings. It has the effect of negatively impacting tree regeneration or compromising the establishment of future trees (Sánchez-Velásquez et al.

2002, Adams 1975, Adler et al. 2001, Stern et al. 2002, Buffum et al. 2009, Álvarez-Yépiz et al. 2008, Vargas et al. 2000, Trilleras et al. 2015), partly as a result of trampling.

Studies considering the relationship of cattle with different slope conditions have shown that slopes between 0 and 9° are reported as the most in demand for pasture development, with less interest by farmers in terrain with slopes between 10% and 19%, and even less in areas with slopes higher than 20° (Hart et al. 1991, Holechek 1988, Ganskopp and Vavra 1987, Ganskopp et al. 2000, Bailey et al. 2015). This corroborates national studies in Mexico which have examined land use cover change, and which show that grassland area has increased (Mas et al. 2004, Rosete-Vergés et al. 2014), at the expense of forested areas (Mas et al. 2004, Trejo and Dirzo 2000), and that most of this has occurred in areas with relatively gentle slopes.

Free-ranging cattle grazing distribution patterns are more variable however. They may be influenced not only by steepness of slope, but also by roughness of terrain, distance from water, distance from their home base and type of vegetation (Vallentine 1990, Bailey et al. 1996). Free range cattle are found in all positions along the hillslope (Mueggler 1965, Cook 1966, Pinchak et al. 1991), although the topography itself affects cattle behavior, eg. by concentrating the animals for longer periods in resting and watering sites (Senft et al. 1985, Ganskopp and Vavra 1987). What grazing animals primarily look for however is nutritional value of the vegetation. Studies investigating cattle preferences on slopes have reported reduction in grazing capacity as slope increases (Holechek 1988, Vallentine 1990, Phillips 2002, Bailey 2005, Bailey et al. 2015), which as I have shown above in most cases reflects lower levels of biomass and reduced biodiversity. Thus, all other things being equal, it would be expected that the cattle would concentrate themselves in less steep locations.

The one factor which may disrupt this relationship is water (Vallentine 1990, Phillips 2002). Poor water availability modifies cattle movement patterns and grazing activity. With increasing distance to water sources, a clear decrease in grazing activity has been registered (Owens et al. 1991, Bailey 2005, Harris et al. 2002).

In general therefore, when considering the relationship of carbon to landscape and topography in areas with high human population densities, such as is the case in the study area: if I were to disregard the physical factors described in the previous section, I would expect to find lower densities of carbon in the less steep slopes and on the flatter areas within the landscape, than on the slopes and hill tops, as a result of these farming practices. In reality, of course, biomass and carbon levels will the determined by both physical and human factors.

2.4 REDD+ POLICY

Climate change is one of the biggest challenges facing human kind. The Paris Agreement signed in 2015 at the 21st Conference of the Parties (CoP) of the United Nations Framework Convention on Climate Change (UNFCCC), was a landmark accord and set ambitious goals to limit global temperature rise to less than 2°C. Under this accord, each individual country should take action to conserve and enhance sinks and reservoirs of greenhouse gases in order to achieve the worldwide goal. Country contributions are expressed in terms of mitigation targets, called Intended Nationally Determined Contributions.

Reducing Emissions from Deforestation and forest Degradation in developing countries (REDD+) is a policy which was developed under the United Nations Framework Convention on Climate Change (UNFCCC) between 2005 and 2015. It uses market and other financial incentives to national governments in order to promote the reduction of emissions of greenhouse gases (GHG) from forest sources. Originally conceived of in terms just of avoided deforestation (`RED´) in 2005 at CoP11 in Montreal, the policy was first broadened to include reductions in forest degradation (`REDD`), and then, at CoP13 in Bali to include also conservation of forests, sustainable management of forests and forest carbon enhancement (´REDD+´; UNFCCC 2010, Agrawal et al. 2011). Degradation was introduced partly to avoid leakage from reduced deforestation into losses of biomass from forests which remain forests, but also because it was recognized that degradation itself is a major source of emissions in some forest ecosystems (Skutsch and Bressers 2007). Conservation was added to deal with the fact that some countries (such as India) had already curbed their rate of forest loss but would need incentives to retain their forests (Skutsch and Bressers 2007), and the remaining elements were added because Parties to the UNFCCC recognized that many forests are ´working forests´, forming part of the livelihood base of rural communities, and that it is important to avoid such forests being put under strict conservation regimes with associated negative social impacts.

Nevertheless, most of the discourse on REDD+, and the majority of publications on this topic, address the issue in binary terms, expressing it in the form of change between forest and non-forest. In other words, the focus is implicitly on deforestation, avoiding much discussion of the other four REDD+ activities, which are often treated essentially as footnotes to the main theme. First generation REDD+ projects operated on spaces that had well-defined forest boundaries, where it was relatively straightforward to quantify changes in forest carbon stocks following the IPCC or other accepted guidelines (Sills et al. 2009).

In reality, however, many forests are highly complex systems, presenting a continuum of diverse conditions and natural dynamic processes with spatial heterogeneity. Human interactions result in the situation that within forests there are cycles of loss and gain of biomass stocks, and this is particularly the case where the forests form part of the livelihood resources of rural communities. In many rural productive systems there is a constant movement of land between different land use categories, and the impact on forest is often not deforestation as such but degradation or temporary clearance which is then followed by forest recovery and enhancement. A typical mosaic landscape results, with patches of forest and patches of agriculture and pasture, and these are not fixed patches but change from year to year. If REDD+ is to deal with emissions from such systems, and to promote management practices that reduce the emissions, then it is clear that the simplistic binary thinking of ´forest/non-forest´ has to be replaced with more holistic approach which reflects this reality.

2.4.1 REDD+ ACTIVITIES

Formally, developing country Parties should contribute to mitigation actions through REDD+ in the forest sector by undertaking activities in the categories: a) reducing emissions from deforestation, b) reducing emissions from forest degradation c) conservation of forest carbon stocks, d) sustainable management of forest and e) enhancement of forest carbon stocks, but the potential of these mitigation actions depends very much on bio-physical and spatial characteristics of the landscape, and on the drivers that have caused deforestation and degradation in a given area. In reality, the five mitigation actions are of just two types (Herold and Skutsch 2011). Reduction of deforestation implies lowering the rate of loss of area of forest, which can be achieved in various ways including conservation activities. Reduction of degradation and enhancement of forest are essentially two sides of the same coin, implying changes in carbon density within forest, and can be achieved in a variety of ways including sustainable management of forest.

Deforestation is caused by a complex of causes, not least the spatial distribution of population and population growth (Geist and Lambin 2002), of tenure types (Sunderlin et al. 2009), and of roads (Helmut and Lambin 2002), but is relatively easy to detect and measure using remote sensing techniques. Forest degradation, which implies a reduction of stocks of carbon in forest which remains forest (and often, temporary losses of stock), is in contrast difficult both to detect and to measure. However like deforestation, degradation is a place-dependent activity, often resulting from subsistence-based extractive processes, such as selective extraction of timber for poles, fuel wood and other raw materials and shifting cultivation. If these practices are intensive and are carried out for prolonged periods they may have negative environmental impacts of the forest, and in particular they may inhibit its regeneration capacity (Kozlowski 2002, Pearce et al. 2003), entailing long run or permanent reduction of average forest carbon stock. However more commonly these activities are part of a forest transition process through time which also involves forest enhancement; and they are widely spread in the terrain; each stage of transition creates the conditions for the next stage and a temporary plant community is replaced by another, until a sort of equilibrium may be reached between the plants and the environment. The future return of forest to original conditions through natural regeneration after a certain time is often assumed by the forest owners (Bowles et al. 1988), and may occur in practice. The length of time before the forest returns to its original condition will vary with the ecosystem and with the intensity of the degradation activities that have been carried out.

2.4.2 EJIDOS AS COMMUNITIES IN REDD+

Under REDD+ policy, countries which are Parties to the UNFCCC are requested to ensure the involvement of local communities in the implementation of REDD+. Around 60% of Mexico forested ecosystems belongs to rural agrarian communities, these are either ejidos or traditional indigenous communities (Skutsch et al. 2013). In Mexico an ejido is an agrarian nucleus with a communal land right system. Originally each member (ejidatario) was allocated an equal share of the total land available for agriculture, but part of the area was managed communally (this part was often dominated by forest). Recent changes in the legal system have resulted in semi-privatization of land in many ejidos, and while this is not supposed to happen in the forested areas, in practice many ejidos have *de facto* parcelised/individualized the forest areas. The system in indigenous communities is similar but there has been less privatization and in general communities have much larger land areas per head.

The Mexican approach to REDD+ is described in its ¨Vision for REDD+ (SEMARNAT 2010), in its Emission Reductions Strategy (ENAREDD+; CONAFOR 2017) and in its Emissions Reductions Initiative, a proposal to the World Bank for finance for pilot projects in the so-called Early Action Areas of REDD+ (CONAFOR 2017). These make clear that communities (i.e. ejidos and comunidades indigenas) are the focus of the approach, which will aim not just at reducing carbon emissions, but also at a land use management approach which is sustainable in other ways. Crucially, the national REDD+ plan, in terms of its claims for finance from international sources, is based solely on reduction of deforestation, since the National Emissions Reductions baseline (NREL), as submitted to the UNFCCC, is cast only in these terms. According to Mexican law, any carbon credits that result from reductions in rates of deforestation, are the property of the state, not of the land or forest owner (CONAFOR 2017, Skutsch et al. 2017), although the state has pledged to invest the financial value of any such credits to stimulate activities for sustainable land management. Ejidos participating in REDD+ may receive investment in the forms of grants from government in this respect, but will not receive rewards for the carbon they save as a result of their efforts in reducing deforestation. This is based on various legal arguments, including the fact that reduced rates of deforestation cannot be considered legal entities as they are always measured against a counterfactual baseline, that is to say, a baseline that is an extrapolation of past and current forest losses to the future. If REDD+ activities are undertaken, it will be impossible to know whether the losses predicted in the baseline would in fact have happened. Moreover deforestation is in principle illegal, and the government cannot therefore reward those who do not deforest since this would be tantamount to paying people not to commit a criminal act. On the other hand, Mexican law recognizes that any growth in woody biomass levels (i.e. forest enhancement) belongs in principle to the owners of the trees. Hence credits relating to forest enhancement can be claimed by ejidos, and in principle could be sold by them on a voluntary carbon market, independently of the government´s REDD+ scheme. This may open major opportunities for ejidos in terms of income generation, apart from investments they might receive under the government REDD+ programme to promote sustainable land management and reduce deforestation.

2.5 BROADER THEORIES WHICH COULD PROVIDE CONTEXT FOR THE RESULTS OF THIS THESIS

2.5.1 LANDSCAPE APPROACHES TO REDD+

Alongside the developing discourse on REDD+, there is a debate on-going on Land Use, Land Use Change and Forestry (LULUCF), a sector recognized e.g. in the context of national greenhouse gas inventories. This is an accounting sector that covers the entire land area of a country which is in some way ´managed´ (i.e. touched by human activities) including all human management of vegetation and soils. It categorizes management activity in terms of forest management, afforestation, deforestation, reforestation, re-vegetation, cropland and grazing land management, and wetland rewetting and drainage (IPCC 2006). Some voices have been raised suggesting that REDD+ should be embedded in a LULUCF-type policy which deals with all land use, not just forests (Minang et al. 2014). This has resulted in the presentation of a new term, REALU: Reducing Emissions from All Land Uses (Minang et al. 2014), which takes as its starting point the idea that land-based sources of GHGs are not limited to forest loss, and suggests that all the activities undertaken in the terrain should be included both in accounting and in policies to deal with emissions (Bernard et al. 2013). In this, the multifunctionality of land uses in the landscape and the associated dynamics, as I have sketched above, are central concepts (Mander et al. 2007, Bernard et al. 2013, Kissinger et al. 2013).

At CoP18 in Doha, there were strong calls for ´a landscape approach to REDD+´ both in the UNFCCC sponsored discussions and at Forest Day, the annual event devoted to REDD+ which is organized by the International Centre for Forestry Research, CIFOR. Leading international institutions and partnerships are focusing on integrated landscape approaches because they are concerned about the role played by land outside the forest in storing carbon and in reducing GHG emissions. These institutions argue that problems related to land-based sources of GHGs and how to deal with them have not been sufficiently addressed, and they are introducing the concept of a ´landscape approach´ to cope with this. The most voiced approaches regarding carbon sequestration and reducing GHG emissions are those framed by CIFOR, ICRAF and their brother institutions included in CGIAR. These approaches try to include forests, agroforestry and agriculture in one climate change mitigation instrument; their research efforts are aimed to try to end the agriculture versus forests debate, and they are pushing for forestry to come out of the forest. However, while recognizing that such conceptions may well have value, I also note that the term is becoming broader and broader, and increasingly less meaningful as a result. For example, a recent addition to the literature on the ´landscape approach´ states that a landscape is ´a place where governance is in place` (Holmgren 2013) - which in my view, while clearly recognizing the importance of the human element in landscapes, does little to help operationalize a `landscape approach` in REDD+ in practice.

At CoP19 in Warsaw, a two-day event, “The Global Landscapes Forum”, was undertaken to appraise expectations of a “landscape approach”, in particular as regards how to manage the interlinkages between different land uses and different stakeholders. As stated at that event, the approach aims to be cross-cutting and holistic, and to engage agriculture, forestry and environmental policy sector for multiple problems at the same time (Reed et al. 2015). The results of this discussion have been proposed as a deliverable to the international community, especially to UNFCCC, as a contribution to the climate change negotiations. The potential of the landscape approach has also been addressed from the point of view of Sustainable Development Goals (SDG), where is has been suggested that it could be included in the analysis of different place-based activities. In this context, it is expected to be redefined to 1) provide necessary livelihood for people living in the landscape, 2) improve the ecosystem services provided 3) increase commodities supply and 4) reduce GHG emissions from landscape activities through resource efficiency. It is because the `landscape approach´ is seen to necessitate working across the agriculture and forestry boundaries that it is being introduced to the SDG and UNFCCC agendas.

However, what was really meant by a ´landscape approach´ was still not clearly defined at this important gathering. In that it seems mainly to refer to inclusion of agriculture as well as forestry, it appears to be similar to a LULUCF, REALU approach in which forest land use is just one of many to be accounted for. Given that agriculture is acknowledged to be the main driver of deforestation in the tropics (Geist and Lambin 2002 or any other), the approach needs to include all the forestry and agricultural problems embedded in a matrix of conditions which form a continuum from relatively undisturbed forest to intensively farmed agricultural lands. In other words, in a landscape-based approach to REDD+, monitoring systems would not simply measure changing stock of carbon in forests, but also the agricultural drivers of deforestation and forest degradation and the effects of REDD+ policy on these. According to the discussions held at the Global Landscapes Forum, the idea is to manage land and tackle climate change while trying to meet the full range of human needs for food, feed, water, and energy. It should contribute more broadly to controlling trends in deforestation, forest degradation and biodiversity loss, by promoting policies directed at the full landscape of agriculture, land uses, and the people who depend on them.

This would seem to require a full wall-to-wall assessment of all land uses in a country, with activity rates and emission factors for every category. It is questionable whether such an approach is a practicable at the moment. First of all it would require a huge technical effort to provide the baseline data and to set up the monitoring systems required, and secondly it would require the political will on the part of the participating countries to bring agriculture – which is a much bigger and more important sector than forestry – under control and under the purview of the UNFCCC. Although the logic is clear and the objective laudable, I feel that attempts to expand REDD+ policy in this way could set back the start of effective emission reductions by years. I therefore take the more pragmatic line that REDD+ should at least in the short term focus on forest land uses, but that this must include the dynamics of interchange in typical mosaic landscapes in which there is continuous shift between agriculture and forest as a result of shifting cultivation and other uses. In these areas it is clear that both assessment of emission and planning of management measures to reduce emissions require a landscape approach.

In this much more limited sense, the most recent attempt to develop a landscape approach which could be useful in the context of REDD+ perspective is that of Hett et al. (2012), in which a quantitative landscape mosaics analysis was formulated. In this study, swidden agricultural plots are distinguished from permanent agriculture and the model is based on temporal vegetation dynamics of different cultivation cycles. The authors argue that this approach could play a key role in monitoring REDD+ climate change mitigation programs. But questions regarding how to monitor, report and verify carbon emissions in the context of a multifunctional landscape cannot be entirely resolved using this landscape scheme. For this, a wider spatial coverage of REDD+ activities would be needed (McCall 2016).

2.5.2 LAND SHARING/ LAND SPARING

Several policies have been proposed from the forestry sector to address both reducing clearance of forest and forest degradation (Meyfroidt and Lambin 2007). In this context arises the idea of land sharing and land sparing, in which duality there is a trade-off between production of commodities (agricultural products) and protection of nature. Land sparing argues for setting aside some land for complete conservation, and raising the intensity of production of the rest to meet demand, rather than allowing demand for agricultural land to spill over into ´natural areas´. Land sharing implies that the two functions can be mixed, without the need for strong boundaries and segregation. The main criticism of land sharing is that it is thought that its agriculture will produce less food than a system of land-sparing, and that it will result in ´loss of nature´ (i.e. untouched, intact, nature) in the long run. Criticism of land sparing centres around the industrialized approach to agriculture which may be unsustainable in other ways, and which might well dispossess smallholder farmers, losing genetic and cultural biodiversity. Land sparing in theory reduces the need for further expansion into the forests for conversion to other land uses, thus among other things reducing forest carbon emissions (Carter et al. 2015, Salvini et al. 2014). Mexico has been identified as one of the six priority countries with the potential to mitigate agriculture-driven deforestation emissions through such land sparing (Carter et al. 2015). Land sharing has been presented in contrast as a ´wildlife-friendly´ or ´biodiversity-friendly´ strategy (Meyfroidt and Lambin 2007). This strategy follows a multifunctional approach, by which several objectives are covered on a given allotment of land, but at the potential cost of low crop-yields. In the context of climate change land sharing is idealized as a ´carbon-friendly´ strategy that might integrate provision of several commodities such as food and building material, while preserving ´good´ carbon levels throughout the farmed landscape. Shifting cultivation is a subsistence agricultural system, carried out by smallholder farmers around the world. This agricultural system has been blamed as a leading cause of tropical forest cover loss (Geist and Lambin 2001, 2002) and thus, in the context of climate change, for the associated carbon emissions (Houghton 2012, Nigh and Diemont 2013) (see above text). However, shifting cultivation is idealized by proponents of land sharing as having a multifunctional role, which means that shifting cultivation plots are spatially and temporally integrated to cover both objectives; produce food staples while preserving forest in the long run. The dynamic allows for a diversified agricultural landscapes with in a land sharing context.

The debate is about whether landscapes should be used in a more intensive way separating conservation and production functions, or in a more mixed way with overlapping functions. The choice between these options depends however on the objective one has in mind. REDD+ policy could be applied in both of these land management strategies to reduce GHG emissions and improve carbon stocks: land can be extensively farmed, with more ecosystem services dispersed in the landscape, but producing less food per hectare, or it can be intensively farmed over a smaller area and the remaining land help to maximise ecosystem services and biodiversity. As will be seen, I will discuss the impact of shifting cultivation and permanent agriculture on carbon emission in the light of this interesting debate.

2.6 RESEARCH GAPS

The bibliographical review presented above has allowed me to recognize that there is a wide discussion in the literature about the factors that determine variation in the forest biomass. As reported in the literature, both natural and anthropogenic factors determine field biomass levels. Many of the studies previously conducted to evaluate those factors include physical factors that determine the conditions promoting establishment and growth of seedlings, which in turn become adult individuals.

The standing biomass levels we observe in the field are quite variable, and differ between forest types, and even within the same forest type. What is persistent, when comparing the studies, is how biomass relates to the topographic factors that guide water movement and accumulation. This is even more remarkable in tropical forests with marked seasonality such as SDTF, because topography plays a crucial role in defining water availability in the landscape. The biomass variation becomes more complex and more relevant to study in tropical forests that have been modified by humans, if we consider that the great majority of SDTFs in Mexico are in some state of degradation or have been completely converted to another type of land use. However, the relative importance of those factors for determining biomass variation in the SDTF landscape, modified by human activity, has not been studied. That is why it is necessary to carry out research that can contribute to the understanding of the factors that determine the variation of standing biomass levels in SDTF modified by human activities. Advancing this understanding will enable us at the same time to make predictive models of biomass levels in the field.

Shifting cultivation, as mentioned above, is frequently considered to be a major cause of GHG emissions, despite the fact that it known that the cultivation phase is always followed by a fallow phase in which secondary forest grows, such that carbon stocks recuperate. Studies indicate that secondary forest absorbs carbon much faster than primary forest (Detwiler and Hall 1988, Fukushima et al. 2008, Lawrence et al. 2010). However few studies have been done to actually measure the carbon absorption rates of fallow and hence the overall effect of shifting cultivation on carbon emissions. This study tries to make a contribution to the literature in this sense.

By increasing understanding of how biomass levels vary in the landscape of tropical forests impacted by human activity, it is possible to contribute to addressing certain problems we face. The review I presented in this chapter shows climate change as one of the greatest problems facing humanity, which is intimately related to greenhouse gas (GHG) emissions from deforestation and forest degradation. The international policy to address this problem from the forest sector; Reducing GHG emissions from Deforestation and Forest Degradation in tropical countries (REDD+) is just starting to operate and the need to use a landscape approach in this policy has been increasingly acknowledged, but each country is adopting its own way of making it operational. The Mexican government's REDD+ landscape approach seeks to promote the sustainable use of forests and improve forest governance at the community territorial levels, making REDD+ an issue that takes a multisectoral/cross-cutting perspective based on a coherent, community-level spatial plan for sustainable development. To make this approach operational, it is necessary to have good, cost-effective methods to obtain field biomass estimates. In Mexico's REDD+ initiative, it is clear that communities will be able to claim for carbon increases, but how this would operate is not yet clear yet. Low cost methods that produce good estimates of biomass potential could be used to select communities within the REDD+ project area and also to locate areas within the territory of the communities where REDD+ activities could be most effectively carried out.

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Chapter 3

METHODOLOGY

3.1 INTRODUCTION

This chapter presents and justifies the use of a set of methods which have been used in this thesis to answer the research questions formulated in the introduction section. The fundamental aim of the research is to determine to what extent biomass levels in different parts of the landscape can be ´predicted´ from a set of physiographic and human management variables. If it is possible to model carbon stocks from a relatively simple set of independent variables, it would enable estimates of biomass and hence carbon stocks over whole landscape areas to be made. This would be very significant for developing management scenarios and hence for planning interventions under policies such as REDD+.

3.2 RESEARCH APPROACH

This thesis takes a quantitative, inductive approach (Goddard and Melville 2004); it starts with empirical data and uses this to build theory, drawing conclusions from the discernment of patterns in the data that may lead to the identification of underlying causes. Above ground biomass (AGB) levels were measured in the field and the effect of a set of topographic variables (data for which was taken from maps) on the AGB levels was estimated using statistical methods. As I established in Chapter 1, the causes of ABG variation are hidden and direct relationships between AGB and independent variables are difficult to determine.

3.2.1 CHARACTERISTICS OF SDTF

The trees of SDTF tend to be multiple-stemmed; such trees account for 58% of total basal area (Murphy and Lugo 1986). The majority of stems tend to be of small diameter, less than 10 cm at diameter at breath height (DBH) (Segura et al. 2002, Ferreira-Nunes et al. 2013, Sabogal 1992). The appearance of the forest is therefore unlike that of humid tropical forests, which are characterized by large trees with big girths. SDTF in contrast looks like a woodland, with many bushy species.

SDTF is widely distributed in Mexico (Fig. 3.1); it is present along the coast of the Pacific Ocean and in some regions of the coast of the Gulf of Mexico (Miranda and Hernández-Xolocotzi 1963, Rzedowski 1978). SDTF prefers hills and mountains, in sites with moderate to strong slopes (Jaramillo et al. 2010). Recent estimates suggest that 27% of the original area of SDTF remains intact, while 27% has been somewhat altered by human uses. Another 23% of the original area is considered heavily degraded, and the remaining 23% has been completely replaced by other land uses, mainly agriculture and pastures (Trejo and Dirzo, 2000).

FIGURE 3.1 Geographical distribution of seasonally dry tropical forest in Mexico. Data: INEGI 2013.

3.2.2 SELECTION OF STUDY SITES

The study area was selected in collaboration with other researchers working on the WOTRO project “Linking local action to international climate agreements in the seasonally dry tropical forests of Mexico”, to represent typical SDTF with heavy human impacts in the past, but also potential for better management in the future. The Mexican government is working towards REDD+ and selected (parts of) five states in so-called ´REDD+ Early Action Areas´ for the purposes of pilot projects with finance from the World Bank´s Forest Carbon Partnership Facility. These early action areas are regions in the country where demonstration activities are being carried out during the preparation process for REDD+ to encourage early involvement and broad participation of stakeholders (UNFCCC 2007: Decision 2/CP. 13, CONAFOR 2010, CONAFOR 2017). These areas are conceptualized as laboratories where the REDD+ intervention model is to be tested and evaluated. This intervention model includes building capacities and evaluation of methods and tools in monitoring, reporting and verification (MRV), including estimating changes of carbon stocks with an acceptable level of certainty (CONAFOR 2017). This model of intervention in Mexico aims to promote sustainable use of forests and enhancing forest governance at community and landscape levels (CONAFOR 2015, CONAFOR 2017).

The four so-called ´Cuencas Costeras´ of Jalisco are included in the Early Action Areas, and my study focused on sites within one of the cuencas, in the area the of the lower Ayuquila River Basin, which has a surface area of 417,554 hectares. This area pertains to an inter-municipal environmental organization, the ´Junta Intermunicipal del Rio Ayuquila´ (JIRA) and includes the territory of 10 municipalities; Autlan de Navarro, Ejutla, El Grullo, El Grullo, El Limón, San Gabriel, Tolimán, Tonaya, Tuxcacuesco, Unión de Tula and Zapotitlán de Vadillo.

JIRA has been carrying out activities for sustainable use of natural resources in the study area since 2007 (JIRA 2015), and has built up extensive experience and knowledge of the different characteristics of the communities in the study area. The study sites within the JIRA area were selected to focus on communities with major SDTF coverage and which were reasonably secure[1]; the selection was made in discussion with JIRA in the study area, who knew the territory very well and whom community members trusted. This trust and confidence of the communities in the JIRA allowed me to establish a dialogue with the majority of the inhabitants of the communities. JIRA accompaniment on first field trips was very important, but despite this support from JIRA, sometimes this process was not easy, so in some communities a greater investment of time was made to build confidence.

The first field trips were to: 1) present the study to the inhabitants of the communities and 2) have a first impression of the conditions in which the SDTF was located within the territory of the communities. This helped me to understand that contiguous communities may carry out their activities within the forest in very different ways. For example, Fig. 3.2 shows how the boundary between two communities defines an area of forest cover in the community of San Buenaventura (not included in this study) and the community of El Temazcal (which was included). Secondly, I realized that the patterns of collection of woody biomass can be very different between communities; for example, the collection of fence posts (Fig. 3.3a and 3.3b) may be more active in some communities than in others. Some communities had more shifting cultivation activity; the white circle in Figure 3.3 shows an area that is used for shifting cultivation in the El Temazcal community, a small portion of the area was burned on April 12,

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[1] The security situation in rural Mexico is not good in some communities due to operations of narcotics gangs

2017. Co-workers (Morales-Barquero et al. 2015) showed among the various human activities that use forest resources, livestock and the extraction of poles to build fences have a significant negative impact on the amount of standing biomass present in the forest, but this effect also changes between communities. Considering the aforementioned, the selection of the communities that would be used in this thesis started with a group of communities suggested by the JIRA that could serve to fulfill the objectives of the study. Secondly, from the communities suggested by JIRA, I started carbon pool measurements in those that gave me permission to carry out the study in their territory, which was given at different times in each community. The villages selected are shown in Fig. 3.4.

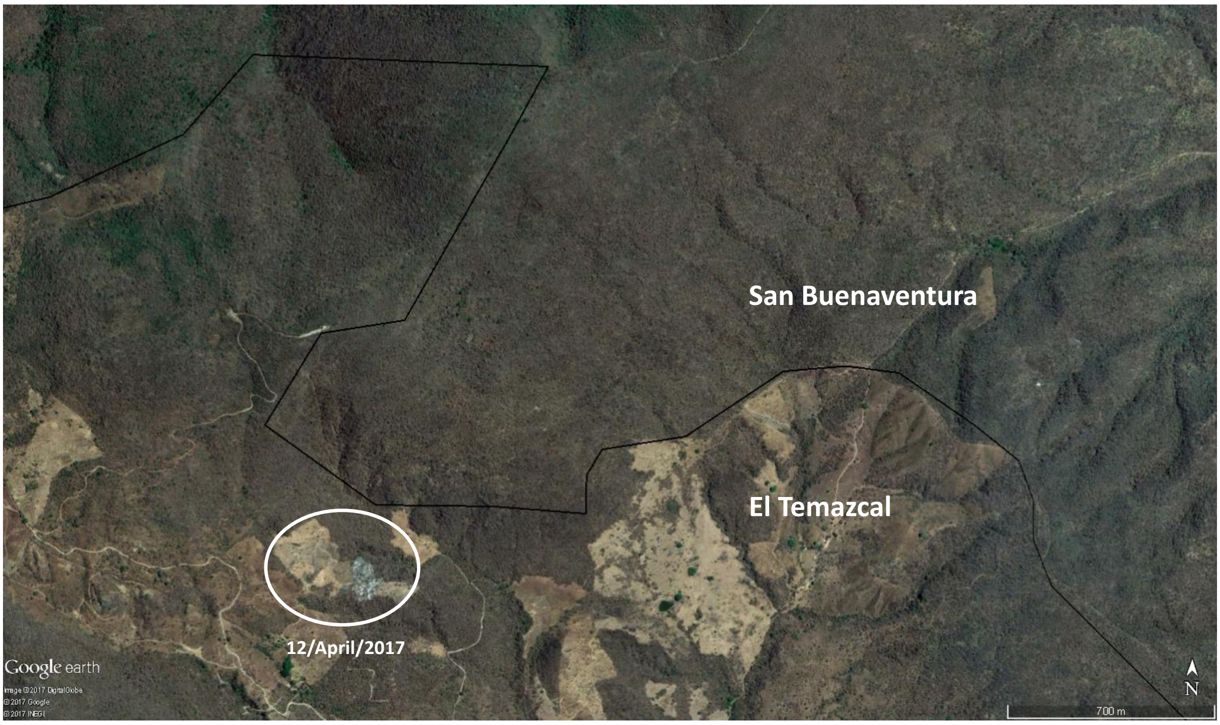

FIGURE 3.2 Image showing boundaries (black line) of the El Temazcal (one of the communities where the study was conducted) and an area within this community used for shifting cultivation (white circle).

FIGURE 3.3 Fence within community forest, delimiting individualized forest areas.

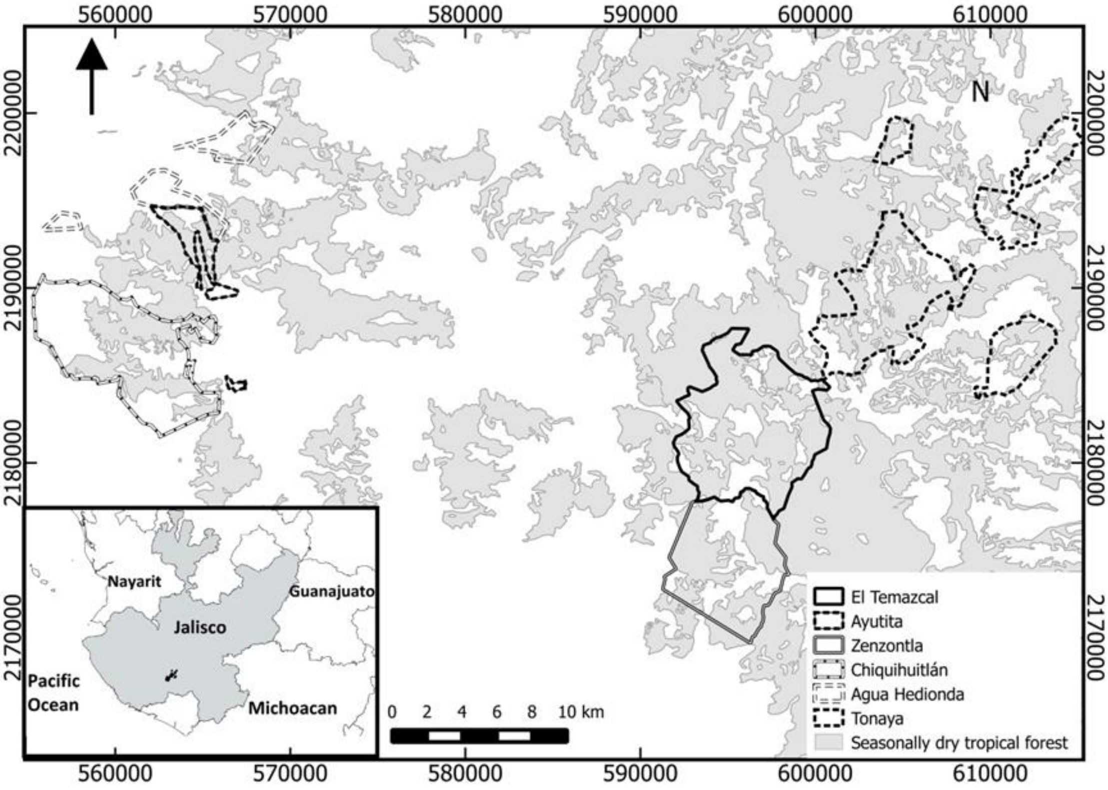

FIGURE 3.4 Study area and the six communities included in this study. Grey areas indicate SDTF in the study area obtained from Jardel et al. (2012)

3.2.3 SELECTION OF CARBON POOLS TO MEASURE

In the global context, tropical forests constitute a large carbon pool, containing roughly 40 ~50% of all carbon in the form of terrestrial biomass (Houghton 2005), in only 7–10% of the world´s land area. The main carbon pools in tropical forest ecosystems are the living biomass of trees and understory vegetation and the dead mass of litter, woody debris and soil organic matter. Estimating the aboveground living biomass is usually the most critical task in determining carbon stocks and carbon fluxes, because this carbon pool is typically the largest pool and the most directly impacted by deforestation and degradation (Gibbs et al. 2007). However both above ground and below ground biomass levels are highly variable in SDTF can be seen in Table 3.1. In this study I measured AGB, and in some sites also soil carbon, as these are the largest pools in the study area.

TABLE 3.1 Biomass estimates for Latin American seasonally dry tropical forests.

Country/Site	Type	AGB	BGB
Mexico			
San Javier, Sonora			
San Juan 2	D	81.5 a	n. d.
Alamos, Sonora			
Vara Blanca	D	60.3a	n. d.
Tempisque	D	44.8 a	n. d.
La Luna	D	117.5 a	n. d.
Isleta	D	46.6 a	n. d.
Sahuria	D	34.8 a	n. d.
Cieneguilla	D	72.6 a	n. d.
Chamela, Jalisco			
Biol. Reserve	D	85 b	35.7c
Biol. Reserve	D	73.6 a	30.9b
Baja plot	D	105.6 a, b	—
Alta plot	D	121.4 a, b	—
Ridgeline	D	59.9 a,b	n. d.
Middle slope	D	68.5 a, b	18.0b
Lower slope	D	80.7 a, b	16.0b
Garrapata	SD	390.2 a, b	32.0b
Buho	SD	247.5 a, b	32.0b
Yucatán Peninsula			
El Edén, Q. Roo	SE	130.9 a, b	26.1b
Q. Roo & Yucatán	SE	191.0 a	n. d.
La Pantera, Q. Roo	SE	225 b	n. d.
La Pantera, Q. Roo	SE	191.5 b	n. d.
El Refugio	SE	128 a, b	n. d.
Nicolás Bravo	SE	150 a, b	n. d.

Aroyo Negro	SE	125 a, b	n. d.
Puerto Rico			
Guánica	D	44.9 b	45b
Sites 16, 17, 18	SE	163 a	n. d.
Venezuela			
Cerro El Coco	D	140 a	66.8

Notes: Methods for calculation: a, allometric equations; b, harvest; c, root:shoot ratio; d, forests ≥ 50–60 years old. Forest type: D, deciduous; SD, semideciduous; SE, semi-evergreen; BA, basal area (m^2/ha); AGB, aboveground biomass (Mg/Ha of dry weight); DBH, minimum steam diameter at 1.3 m included in measurement; BGB, belowground biomass (Mg/ha of dry weight); n.d., not determined. Source: Jaramillo et al. (2011).

3.3 FOREST SURVEY

3.3.1 SELECTION OF PLOT SHAPE AND SIZE

As communities were at the heart of the proposed project, I needed an AGB measuring system that is both representative and easy to implement by communities. I employed people from the communities to help me with plot measurements and experimented to find a reliable measurement protocol for them. The standard way to gather information from a forest area is by using sample plots. In evaluating how communities may best perform in lying out sampling plots, I formed a sampling crew with members of community and we did a number of samplings, using square plots and circular plots. The plot size used in this evaluation was of three sizes, 400, 500 and 1,000 m^2. After we finished the sampling, we discussed the most suitable size and shape for sampling, everybody in the sampling crew agreed that the best plot shape for sampling was the circle, because these were substantially easier to lay out per effort invested. With regard to the plot size, there were agreement that a plot of 1,000 m^2 was more time consuming and harder to layout. Members of the community team agreed that it can take a great deal of time to measure trees in large plot, under certain forest conditions.

In this thesis work, a final decision to use circular plot of 400-500 m^2 was taken on the basis of the community feedback and because: 1) defining the perimeter of the plot is done just with the radius, 2) there is no specific orientation of the plot, 3) bias in area due to slope may be corrected, 4) boundaries of circular plots are much easier to delineate accurately than are those of square plots, 5) this minimizes the area-to-perimeter ratio, decreasing the probability of failures in including in sample trees at border line, by measuring distance of trees to circle center (this is particularly useful in SDTF, where vegetation is characterized by many individuals of small diameters), 6) plots with this shape can be relatively easily established and it requires much less effort (Kershaw et al. 2017). Although sampling plot sizes may range from 10 to 10,000 m^2 (Kershaw et al. 2017), I finally decided to use plots between 400 and 500 m^2 for three reasons: a) this plot size is widely used, b) smaller circular plots are more efficient than large ones (Kershaw et al. 2017) and c) in order to make my findings further comparable with data from National Forest Inventory (Inventario Nacional Forestal y de Suelos (INFyS)), because sampling units used in INFyS for SDTF were of 400m^2 (CONAFOR 2004).

Generally, a subplot is nested within a larger plot, and the smaller trees are recorded only in the smaller one (Kershaw et al. 2017). The minimum Diameter at Breast Height (DBH) used in this study was 2.5 cm. Two concentric circular plots of different sizes were used in a nested design to survey different components of the vegetation. Different size classes of trees were sampled in those circles; 1) in plots of 400 m2, with a radius of 11.28 m, the subplot was of 3 m radius, 2) in plots of 500 m^2 with radius of 12.62 m, the subplots were 4 m radius. Within the plots of 400 and 500 m^2 all individuals of DBH greater than 10 cm were measured, while in the subplots individuals between 2.5 and 10 cm DBH were also included.

3.3.2 ESTIMATION OF ABOVEGROUND BIOMASS

The aboveground biomass was considered as an adequate proxy of standing carbon measurement in field (Brown and Lugo 1982, IPCC 2006). Aboveground biomass was obtained with the use of an allometric equation. I recognize that choosing the right allometric equation to get the best estimations of biomass is difficult, because there are a number of different sources of variation (Chave et al. 2014). Although the use of locally developed equations is suggested (Chave et al. 2014), no allometric equation specific to my study area was available. The estimated AGB for each sample plot was done by using an allometric equations widely used for Mexican SDTF (Equation 1). This equation was originally obtained using a destructive sampling procedure, and was specifically calibrated on data from a Mexican SDTF which is located no more than 60 km from my study area, with forest structure quite similar to my area, i.e. with a large number of small stemmed trees (Martínez-Yrízar et al. 1992). This equation uses the diameter at breast height (DBH) as predictor of AGB.

Equation 1 $$log_{10}B = -0.5352 + 0.9996 \log BA$$

Although there is considerable variation of carbon content in wood tissue (Thomas and Martin 2012), I followed IPCC guidelines (IPCC 2006) in assuming that 50% of AGB was carbon and estimated carbon stock densities in each site. This is a pragmatic way to estimate carbon content, widely used in estimating carbon content (Thomas and Martin 2012).

3.4 STATISTICAL ANALYSIS

The statistical methods used in this thesis look for relations between the independent or explanatory variables (quantitative descriptors of topography and human use) and AGB (the dependent or response variable); they aim to find a direct relationship between response variable and explanatory variables. Classification and regression trees (CART), as well as generalized linear models (GLM) and generalized linear mixed models (GLMM) are able to capture relationships between the response variable and explanatory variables; CART evaluates the behavior of response variables in a non-linear fashion and GLM and GLMM in a linear fashion. The statistical methods used in this thesis were interesting in four ways: 1) they are designed to obtain the simplest function that explains the highest proportion of variance, 2) when possible, they show what proportion of AGB is explained by the independent variables, 3) they can develop spatially distributed predictions of AGB and 4) they can obtain the best predictions of AGB using the selected model.

When I used the linear relationship, I faced the problem of finding more than one solution to each problem. There is a principle that argues that the simpler, the better (Crawley 2013), this principle is known as “Occam’s razor”. When the simpler solution was not a linear relationship, non-linear relationships were evaluated, but still the principle was to find the simplest one. In order to respond to the research questions; in Chapter 4 of this thesis I used the first and the second group of methods (see Figure 3.5), either to find linear and non-linear relationships between dependent variables and AGB, in a non-spatial context. The fifth chapter used the first, the second and the third group of methods. Chapter 6 uses the first group of statistical methods plus a set of calculations on emissions (Fig. 3.5). More detail on the methods used to answer the different research question can be found in each chapter.

I addressed the issue of the non-normal distribution of AGB by using a generalized linear model with an error structure that does not require the dependent variable to be normally distributed. I used the Generalized Mixed Effect Models because when I grouped my biomass data by community, I assumed that observations were not independent and that there was a correlation structure in the structure of the error.

In this thesis, one problem when evaluating and modelling the impact of multiple factors on forest biomass is multi-collinearity among the topographic predictors. This is another type of a correlation structure in the structure of the error.

I used geostatistical methods because these methods are aimed at analyzing continuous spatial phenomenona, in a set of discrete data (sampling points), referenced to a specific location, within a spatial region of interest. These methods allowed me to model spatial variations of AGB within the community territory at any location, that is, between any two sample locations.

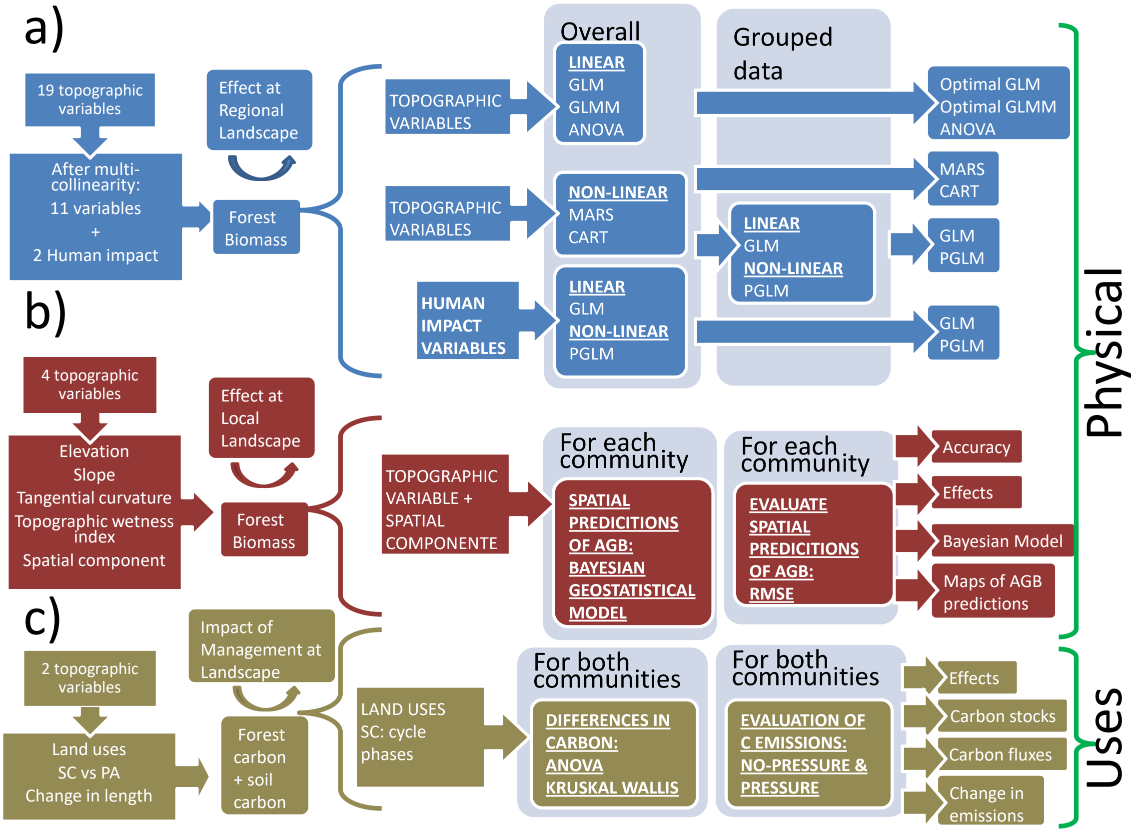

FIGURE 3.5 Schematic representation of the three analysis strategies used in the thesis. a) analysis steps used in Chapter 4, b) analysis steps used in Chapter 5 and c) analysis steps used in Chapter 6.

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Chapter 4

PREDICTING ABOVEGROUND FOREST BIOMASS WITH TOPOGRAPHIC VARIABLES IN HUMAN-IMPACTED TROPICAL DRY FOREST LANDSCAPES

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ABSTRACT

Topographic variables such as slope and elevation partially explain spatial variations in aboveground biomass (AGB) within landscapes. Human activities which impact vegetation, such as cattle grazing and shifting cultivation, often follow topographic features and also play a key role in determining AGB patterns, although these effects may be moderated by accessibility. In this study we evaluated the potential to predict AGB in a rural landscape, using a set of topographical variables in combination with indicators of accessibility. We modeled linear and non-linear relationships between AGB, topographic variables within the territorial boundaries of six rural communities, and distance to roads. Linear models showed that elevation, slope, topographic wetness index and tangential curvature could explain up to 21% of AGB. Non-linear models found thresholds values for the relationship of AGB and diffuse insolation, topographic position index at 19×19 pixels scale and differentiated between groups of communities, improving AGB predictions to 33%. We also found a continuous and positive effect on AGB with increased with distance from roads, but also a piecewise relationship that improves the understanding of intensity of human activities. These findings could help in the design of REDD+ projects under the international policy Reducing Emissions from Deforestation and Forest Degradation (REDD+), by identifying locations where actual biomass is well below its potential and thus where forest enhancement activities could be targeted.

Keywords: aboveground biomass, topographic variables, rural communities, REDD+, landscape approach

4.1 INTRODUCTION

Above ground biomass (AGB) patterns, and hence carbon stocks, are unevenly distributed in the space, even within the same forest ecotype (Houghton 2005). These uneven patterns are determined by multiple biophysical factors, such as elevation, slope and insolation, but also by human factors (Toledo-Garibaldi and Williams-Linera 2014, Lovett et al. 2006, Alves et al. 2010, Marshall et al. 2012, Jaramillo et al. 2003, Galicia et al. 1999). Often referred to as ´perturbations´, the effects of human uses on forest which remains forest include changes in the overall amount of standing stock (AGB) and changes in structure, through selective removal of certain species, while others find the opportunity to regenerate. The changes may be small, but they may also be considerable, to the point where the ecosystem may be considered secondary forest (although this term is often also used to refer to regrowth of forest following clearance). The magnitude and the impact of human uses on forest structure depend primarily on the particular type of use: grazing, shifting cultivation, and harvesting for firewood or for charcoal will all leave distinctly different footprints on the forest (Chazdon et al. 2016).

Human factors may however be partially dependent on the biophysical determinants (Méndez-Toribio et al. 2016), or independent of them, as in the case of accessibility from roads or human settlements (Mon et al. 2012). While the influence of human factors on AGB may be fluid, varying over time and space as a result of different human activities (Toledo-Garibaldi and Williams-Linera 2014, Lovett et al. 2006, Alves et al. 2010), biophysical factors such as water availability are strongly influenced by relatively permanent topographic variables such as elevation, slope and aspect (Marshall et al. 2012, Laurance et al. 1999, Lovett et al. 2006). The aim of this paper is to explore the possibilities of modeling the impacts of topographic and human variables on vegetation structure and particularly on carbon stocks. One purpose of such modeling may be to provide technical support to governments in their planning for Reductions in Emissions from Deforestation and forest Degradation (REDD+), which involves reducing losses of biomass and enhancing forest carbon stocks whilst ensuring biodiversity conservation and sustainable development. If biomass and carbon stocks can be predicted using a set of topographical variables in combination with indicators of accessibility, locally realistic targets for improvement carbon stock can be constructed.

4.1.1 ENVIRONMENTAL FACTORS THAT INFLUENCE FOREST BIOMASS

Many studies have related variation of forest structure and density to topographic variables, which are used as proxies for the factors that are believed to cause the variation. Water availability is one of the main such factors in seasonally dry tropical forest (SDTF) (Galicia et al. 1999, Maass and Burgos 2011, Jaramillo et al. 2011, Brienen et al. 2010). For example, strong differences in biomass associated with relative position and water availability have been reported in deciduous upland and the semi-deciduous floodplain forests in Chamela (Jaramillo et al. 2003). Since water availability is strongly affected by elevation above sea level, aspect, slope angle and terrain convexity, these variables are often used as indirect measures (Pachepsky et al. 2001), usually in combination, since water availability may be substantially modified over short distances in response to the interplay of such topographical factors (Leij et al. 2004).

Elevation and slope are the most commonly considered topographic variables in relation to forest structure (Appendix 1: Table S1). Elevation or factors related to it such as air temperature and solar radiation affect forest biomass through evapotranspiration rates (Homeier et al. 2010, Sundqvist et al. 2013). Forest biomass may relate to elevation to it both in a monotonic (Lieberman et al. 1996) and in a hump-shaped (Marshall et al. 2012) pattern. While the former trend suggests that temperature decreases and stress increases with elevation, the latter suggest that there exist constraints that co-vary with elevation. Slope angle has also been reported as an explanatory variable of forest structure, particularly of biomass and canopy height (Yanagisawa et al. 1999, Laurance et al. 1999, Sawada et al. 2015) (Appendix 1: Table S1).

The effect of aspect on forest structure has been well recognized, but in tropical areas this does not usually play a key role in structuring vegetation (Gallardo-Cruz et al. 2009). However results from some studies performed in the northern hemisphere have shown northern-facing slopes having higher biomass levels (Kariuki et al. 2006) than southern-facing ones. This is probably linked to a number of other environmental factors which lessen or mask the effect of aspect (Kirkpatrick et al. 1988). Solar radiation, that is, the amount of radiant energy received at certain location, varies not only with the amount of sunshine but with slopes, aspect and adjacent relief (Wilson and Gallant 2000).

4.1.2 HUMAN FACTORS THAT AFFECT FOREST BIOMASS

It is important to note, however, that almost all studies that evaluate topographic variables as determinants of forest biomass and forest structure have been carried out in preserved forests (Appendix 1: Table S1), that is, in forests which are hardly affected by human factors. In many tropical forests, natural forest cover is being reduced and forests are being modified by human uses (FAO 2016), and it is precisely in these forests that the potential for REDD+ is greatest. Clearly, the addition of anthropogenic factors complicates the relationships between environmental variables and biomass and makes prediction of biomass levels over space even more challenging. However, while human intervention is an extra factor modifying carbon stocks, these effects may not be random. They may well follow a topographic template, since human uses of forest such as shifting cultivation and grazing tend to occur at specific elevations and on specific types of slopes and may therefore have relatively predictable effects (Vázquez and Givnish 1998, Morales-Barquero et al. 2015, Méndez-Toribio et al. 2016). For example, common uses of seasonally dry tropical forest (SDTF) in Mexico include temporary clearing of patches of trees for shifting cultivation on the lower slopes and on the shoulders of hilly terrain (Morales-Barquero et al. 2015, Borrego and Skutsch 2014), which is followed by regrowth, resulting in a spatial mosaic of varying biomass densities across these zones. Wet season grazing by small farmers, which takes place largely on the steeper slopes between these two zones, has the effect of lowering biomass stocks slightly across these areas (Morales-Barquero et al. 2015, Jardel et al. 2012). However, where pressure is greater as a result of accessibility to roads and human settlements, there is obviously more likelihood of direct or indirect impact on natural vegetation (Mon et al. 2012, Luoga et al. 2002, Cincotta et al. 2000, Malhi et al. 2014, Morales-Barquero et al. 2015). The effects of firewood gathering also depend on the intensity of this activity, and may be very limited if much of it dead wood. It is therefore to be expected that there will be a response in forest structure due to human activities, and that this may be partly related to topography but to the gradient of intensity, which may expressed in terms of accessibility (Mon et al. 2012, Luoga et al. 2002).

4.1.3 POLICY CONTEXT AND SETTING OF THE STUDY

This study has been carried out in the context of Reducing Emissions from Deforestation and forest Degradation in developing countries (REDD+) and recent calls for this to follow a ´landscape´ approach. REDD+ is a policy framework under the United Nations Framework Convention on Climate Change (UNFCCC). It proposes a performance-based payment mechanism to reduce the emissions of greenhouse gases (GHG) from tropical forest sources (Pelletier et al. 2016). Although popularly considered a mechanism to slow down the rate of deforestation, REDD+ also aims to reduce forest degradation and promote forest enhancement and in this context it is logical to target secondary forests. Strategies to promote natural regeneration by removing the human factors that cause degradation may in some countries result in greater carbon savings than reductions in deforestation, given the fact that so much of the forest is degraded (for example, Trejo and Dirzo (2000) estimate that 80% of SDTF in Mexico is degraded, while the rate of deforestation of SDTF was less than 0.4% per annum from 2002 to 2007, and has since been decreased even further (CONAFOR

2010). The rate of uptake of carbon when secondary forest is allowed to recover naturally may be substantial. For example, Pan et al. (2011) explored the differences in sink activity between intact and re-growth forests and found the absorption rates in anthropogenically and naturally modified (i.e. degraded but regenerating) forests are more than three time higher than those in intact forests across the tropics. Poorter et al. (2016) have provided evidence of carbon uptake rates in secondary forests across the neotropics which are up to 11 times higher than those in intact forests, at around 3 t C per ha per year. Chazdon et al. (2016) have estimated that secondary growth forests in Latin America and the Caribbean have the potential over the next 40 years to absorb carbon equivalent to that emitted by the region from all fossil fuel and industrial sources between 1993 and 2014.

To deal effectively with the potential of secondary forests under REDD+, it is necessary to better understand the drivers which cause degradation and stand in the way of enhancement. For this reason, a ´landscape approach´ has been proposed with the idea that improved forest management will depend on managing entire rural production systems in more sustainable ways (GLF 2013a, 2013b, Minang et al. 2015). Particularly in Mexico, REDD+ policy is moving towards a landscape approach in which territorial plans at community level will be the basis for financial support for management activities (CONAFOR 2016, Madrid and Deschamps 2014, Rantala et al. 2014).

Our study focused on SDTF, which is widely distributed throughout Mexico (Trejo and Dirzo 2000) in areas with strongly marked seasonal rainfall (Bullock et al.1995, Murphy and Lugo 1986, Dirzo et al. 2011). AGB in this forest type ranges from 45 to 390 Mg/ha and below ground biomass from 26 to 66 Mg/ha (Jaramillo et al. 2011). SDTF is generally water, rather than nutrient, limited (Murphy and Lugo 1986), so biomass in sites with high soil water storage capacity may be high (Jaramillo et al. 2003). This is thought to be the primary explanation for the wide range of AGB figures that has been observed within Mexico (Jaramillo et al. 2011).

Almost all SDTF in Mexico has been affected by anthropogenic activity. About half of the original area covered by this tropical forest type was cleared in the 20th century and the majority of the remaining part is used by rural populations for shifting cultivation, grazing and collection of a variety of forest products including firewood and fencing posts (Maass et al. 2005). AGB in majority of Mexican SDTF is well below that in the intact forest (Morales-Barquero et al. 2015), which offers opportunities for reversal under programs such as REDD+.

The paper explores the possibilities of modeling the impacts of topographic and human variables on AGB. Standing forest biomass levels will be related to variables which describe the physical form of landscape, such as elevation, slope, curvature, etc., based on empirical evidence gathered in a case study site in a SDTF zone. If forest biomass levels can be statistically explained by combinations of such factors, this could be used to estimate the carbon potential of a given landscape and assist in the identification of areas where levels are well below this, pointing to areas most appropriate for REDD+ interventions at local level and thus filling an important role for the implementation of this policy at the local level. These relationships would be expected to differ under different topographic landscape configurations, due more to regional topographic controls on forest structure than local ones.

4.2 METHODS

4.2.1 STUDY AREA

The study was conducted in the central part of the basin of the Rio Ayuquila, in Jalisco, a state in west-central Mexico (Fig. 4.1), within an area which falls under the Inter-municipal Association of the Ayuquila River Basin (JIRA). This is a group of 10 municipalities, which aims to coordinate environmental management and has been selected as an Early Action Area for REDD+. The area is surrounded by uplands such as Sierra de Manantlan, Sierra de la Amula, Sierra de Cacoma y and Sierra de Tapalpa and includes three distinct plains areas: Autlán, El Grullo and el Llano en Llamas.

The study area is dominated by undulating hills grading to steep slopes and narrow river valleys with elevations ranging from 515 to 1,711 m above sea level. The slopes range from 0 to 87%. Elevation and slope generate a gradient in micro-climatic conditions, particularly with regard to humidity and temperature. Mean rainfall is between 400 and 1, 600 mm (Vidal-Zepeda 1990), with a dry season from mid-November through May; summer rains occur between June and September (Jardel et al. 2012). Temperature range is between 20° and 24° (García 1998). The eastern section of study area is warmer and drier than the western.

Several forest types are found in the study area (Jardel et al. 2012), but this study focused on Seasonally Dry Tropical Forests (SDTF). In the study area, this type of tropical forest is used for a number of productive activities, including extensive cattle ranching (Jardel et al. 2012) and shifting cultivation, which is locally called *coamil* (Salinas-Melgoza et al. 2017, Borrego and Skutsch 2014).

Six rural communities (*ejidos*) were included: Agua Hedionda, Ayutita, Chiquihuitan, El Temazcal, Tonaya and Zenzontla (Fig. 4.1). These communities show a wide range of topographical characteristics within the SDTF zone, enabling relationships between forest structure and topographical variables tested in this study (Table 4.1).

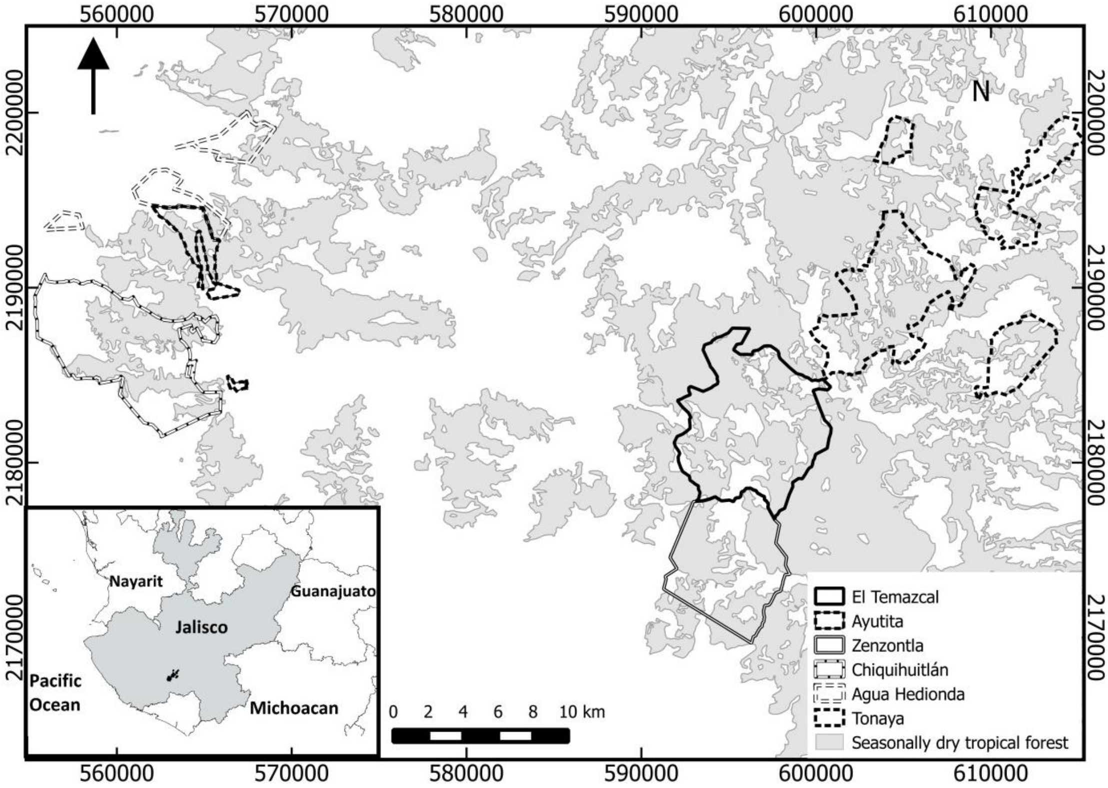

FIGURE 4.1 Geographical distribution of seasonally dry tropical forest (data: Jardel et al. (2012) and location of agrarian communities in study area in Jalisco state, western Mexico (EPSG projection: 32613-wgs84/utm zone 13N). Note that some communities are made up of several polygons.

Vegetation in the study area has been modified by humans at least since Mexico's colonial era for productive purposes such as cattle, sugar cane, etc. (Louette et al. 2001, Gerritsen and van der Ploeg 2006). Clear evidence of human disturbances has been reported close to human settlements (Vázquez and Givnish 1998, Morales-Barquero et al. 2015). The agrarian communities in the study area were set up between 1920 and 1950 in a land reform process, which allocated land to groups of landless people on a communal basis. After land rights were decreed, forest was cleared for farming in communities, but agriculture cannot be practiced on steep areas; such areas were therefore allocated to forest-based uses. Generally, the flatter areas are used for permanent agricultural systems (*yuntas*), some of which are irrigated; crops grown in these systems include maize, sorghum and agave. The lower slope areas are used for small plots of shifting agriculture. These areas, like the *yuntas*, are considered to belong to individual farmers. In addition there are common areas in many communities that may be used by all members as unplanned silvo-pastoral systems, where livestock graze freely. These common forest areas are also the source of building materials, poles for fences and fuel wood (Morales-Barquero et al. 2015).

TABLE 4.1 Characteristics of forest inventory datasets used in the study.

Parcel characteristics	1stdataset†	2nddataset‡	3rddataset§
Number of sites	34	106	23
Shape plot	Circular	Circular	Circular
Plots per site	4	1	1
Nested designee (radius)	Yes (11.28 m and 3 m)	Yes (12.62 m and 4 m)	No
Plot size	400 m^2	500 m^2	400 m^2
Minimum DBH included	2.5	2.5	2.5
Range of elevation (m a.s.l.)	515–1,144	899–1,711	778–1,048
Range of slope angle (°)	8–76	8–87	1–33

Notes: † Salinas-Melgoza et al. unpublished data. ‡ Jardel et al. (2012). § Salinas-Melgoza et al. (2017). dbh, diameter at breast height.

4.2.2 DATA SOURCES

Two different sources of information were used in this study. A forest survey was used to obtain AGB levels while data on physical conditions of the sites was obtained by physical measurements in the sampling sites and from Digital Elevation Models (DEM), i.e. from existing topographic maps.

Forest inventory data from 144 sampling sites was obtained from three different datasets from different sources; sites in these datasets cover a wide range of topographical conditions. The combination of these three datasets increased the size of the sample used in analyses. Although some of the communities are duplicated in different datasets, plots are unique by community and by dataset. All plots are circular. Plots in two of the datasets used two concentric circles. Diameter at breast height from each tree registered in each dataset was used to infer dry AGB (Table 4.1).

Different allometric equations give different results (Návar 2010) and it is difficult to know which one is most reliable. In order to improve the accuracy of biomass estimates, Chave et al. (2014) suggest using locally developed equations. No allometry specific to my sites was available, but we used an equation which had been developed using destructive tree sampling in a SDTF site characterized, like my study area, by having a large number of small stems; this site was only about 60 km from my study area (Martínez-Yrízar et al. 1992), see equation (1). Biomass of multi–stemmed trees was calculated separately for each stem and summed. Identification of individual trees was done at the species, genera or morpho–

species level. Aboveground biomass and total basal area measurements are not independent, because both are calculated from stem diameters (Brown 1996).

Equation (1)

$$log_{10}B = -0.5352 + 0.9996 \log BA$$

where B is aboveground dry biomass in kg, BA is basal area (cm).

Information by site includes basal area, which was measured using diameter tapes, biomass (calculated using equation 1) and total number of stems. Slope was measured using a clinometer, elevation estimates were taken using an altimeter, and aspect was obtained with a compass; geographic location was obtained with a handheld Global Positioning System (GPS).

4.2.3 DATA ANALYSIS

It is often difficult to obtain a strong signal from complex non-linear relationships and the methods of data analysis were designed to explore a wide range of possible interactions before focusing on those with the most influence. An initial selection of 19 topographic explanatory variables was made, based on current knowledge of determinants of AGB (topographic variables related to ecological processes) (Appendix 2: A1). An analysis of multi-collinearity reduced these to a set of 11 variables to analyze overall patterns (further details in Appendix 2: A2). Two variables that relate to potential human impact on vegetation were added to the topographical variables; distance to roads and distance to human settlements (Appendix 1: Table S2). Details of selection and calculation of all variables are in Appendix 2: A1 and A2.

The use of different scales for the topographic position index (TPI) calculation is to provide a measurement of plot level topographic exposure to shade, due to nearby hills. As TPI is determined by the neighborhood scale used in the analysis, TPI with significant change (Appendix 1: Table S2; Appendix 2: Table S1, A2) with regards to change in scale of analysis would indicate more favorably sheltered areas for tree development (Fig. 4.2).

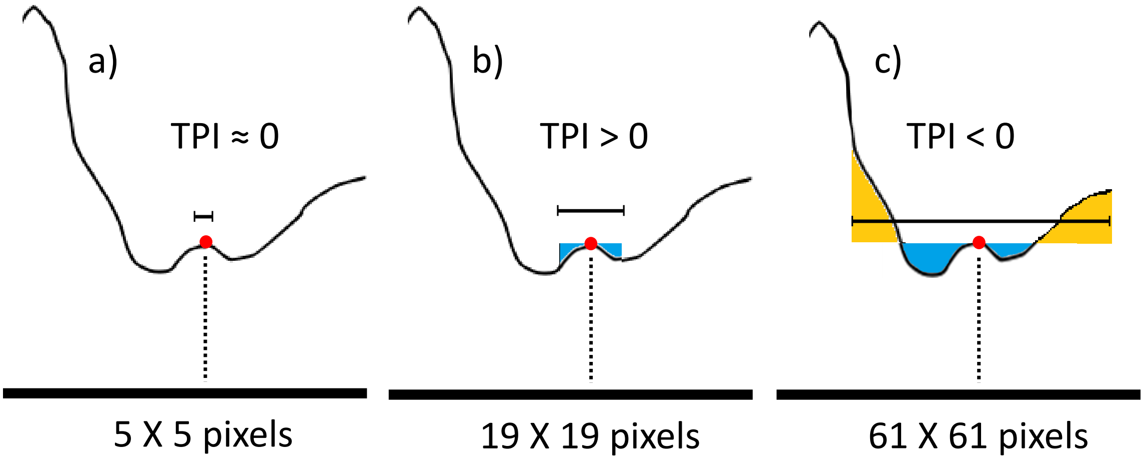

FIGURE 4.2 Representation of topographic position index (TPI) for the same point (red point) at 3 different scales (horizontal line above red point). a) TPI is around zero because point elevation is about the same as the whole analysis region, b) TPI higher than zero means that point elevation is above analysis region mean elevation and c) TPI lower than zero means that point elevation is above analysis region mean elevation.

4.2.4 DATA ANALYSIS STRATEGY

The data analysis strategy to relate biomass to the topographic variables encompassed two approaches (Fig. 4.3). Firstly, in order to investigate overall patterns, a number of linear models were constructed using Generalized Linear Models (GLM) and Generalized Linear Mixed Models (GLMM). Non-linear relationships were evaluated with Multivariate Adaptive Regression Splines analysis (MARS) and Classification and Regression Tree analyses (CART). Secondly, non-linear relationships were used to identify breakpoint or threshold values where patterns change dramatically between subgroups of data of AGB; to this end CART analysis and Piecewise-Generalized Linear Models (PGLM) were used. Furthermore, GLM and PGLMs were used to investigate overall linear and non-linear relationships between human factors and AGB.

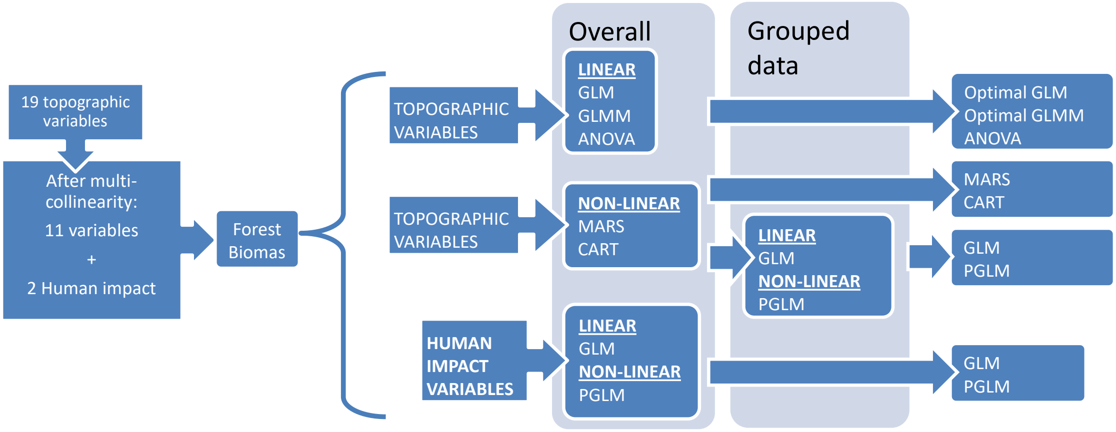

FIGURE 4.3 Schematic representation of the analysis steps used in the study.

4.2.4.1 GLM, PGLM AND GLMM ANALYSIS

In order to evaluate linear and nonlinear relationships between AGB and the independent variables, several linear models were estimated using Generalized Linear Models (GLM), Generalized Linear Mixed Models (GLMM) and Piecewise-Generalized Linear Models (PGLM). The independent variables used in these analyses were the topographic and human factors. We obtained a full model that included the 11 selected variables. Then, we obtained optimal GLM and GLMM models that statistically explain the relationship between independent topographic variables and AGB using a simplification procedure suggested by Crawley (2013). GLM and GLMM for AGB were fitted for the entire data set. Furthermore, GLM and PGLM were used to evaluate the effect of distance to roads and settlements on AGB.

GLMM random intercepts and random slope models were constructed to investigate whether differences in any of the significant explanatory topographic variables within the territory of communities explain AGB. This analysis identifies at the same time a nested hierarchy of sites within communities (Bates et al. 2014). This type of model allows fitting a regression model to the individual communities, while accounting for systematic unexplained variation among the six communities with regard to topographic variables. In the model, topographic variables were used as fixed factors, and two random structures were used, one with communities as the grouping variable (random intercept variable) and another with topographic variables as the random slope variables. The former allows the intercept to deviate from the mean intercept for each community, the latter allows slope of the linear regression to vary for each community. In this way, the consistencies of resulting effects were tested across both communities and topographic variables. The significance of the random intercept was evaluated at the 95% confidence interval. Statistical differences would imply that variation in biomass patterns comes from more than one source, in this case, the character of the different rural communities (Bates et al. 2014, Faraway 2016).

Two different proportions of variance generated by the GLMM were calculated using the method explained in Nakagawa et al. (2017); the proportion of variance explained by the model as a whole and the proportion of variance explained by topographic variables (fixed factor). Following the procedure developed by these authors, the proportion of variance explained by communities (as grouping factor) was quantified, obtaining the intra-class correlation coefficient (ICC). The best model was selected on the basis of the proportion of variance explained (pseudo R^2).

Further, GLM was used to investigate the relationship between topographic variables and a subgroup of data on AGB obtained from a CART analysis, as explained in more detail below.

In order to specify the appropriate error distribution to be used and the associated link in performing GLM, PGLM and GLMM for AGB, several potential distributions were consider, and eventually a Gamma error distribution with log link was selected (Faraway 2016). For GLMM, all numerical predictors were standardized (so that they have a mean equal to zero and variance equal to one) by centering them and dividing by two standard deviations (Faraway 2016). This procedure alleviates computational challenges of numerical stability of the GLMM algorithm (Faraway 2016). Relative importance (%) of each variable in the optimal GLM and GLMM models was obtained through a randomization approach. These values then were normalized to 100; the stronger the influence on the response variable, the higher the value.

PGLM evaluates thresholds iteratively along the extent of variation of the independent variables, but a starting threshold most be provided. In order to provide this, changes in the slope of the GLM were performed using the Davies' test. This test chooses a number of fixed thresholds along the X-axis and looks for statistically significant differences in regression slopes on each side of the threshold. Piecewise models are statistically significant when threshold estimates do not overlap the 95% confidence intervals (Muggeo 2008) (further details in Appendix 2: A3).

4.2.4.2 MARS ANALYSIS

MARS analysis was conducted to evaluate whether AGB follows more complex non-linear functions of topographic predictable variables, and was used to unravel high-dimensional data patterns. This is a non-parametric analysis that produces simpler and easier-to-interpret piecewise models. They are fitted by several piecewise linear basis functions (BFs) using a threshold value called a knot (Friedman 1991). This technique allows for the use of multiple variables that may not have common effects across the sample (Faraway 2016) (further details in Appendix 2: A3).

4.2.4.3 CART ANALYSIS

CART analysis is a nonparametric approach for constructing classification and regression tree models based on rules (Faraway 2016). CART was used as an exploratory procedure to find subgroups in the data, which were then used to perform further parametric linear regression models, as mentioned above. This type of procedure uses a partitioning approach on single variables to perform a binary split in a recursive manner that continues until a terminal node and a constant estimate of Y is obtained (Faraway 2016) (Appendix 2: A3). CART first splits the data set into homogeneous subsets based on relationships between the dependent and predictor variables, identifying breakpoint or threshold values on the splitting variable to form a tree structure (Faraway 2016). It then looks for the relative importance of each of the variables within different parts of the tree (Faraway 2016). As we will show, this analysis first divided the data into two distinct groups, four of the communities making up group A and two communities making up group B (further details in Appendix 2: A3).

4.2.4.4 ANOVA

A one-way analysis of variance (ANOVA) was also run to evaluate whether mean biomass was equal across all the communities. AGB values were log transformed to meet ANOVA assumptions regarding homogeneity of error variances and distribution of residuals. AGB was considered the dependent variable, with ´rural community´ as the independent variable. Tukey HSD tests were used to identify differences between communities (Faraway 2016).

All the analysis was carried out in R 3.3.2 (R Core Team 2016) using different packages for specific analysis. GLMM modelling was performed with lme4 (Bates et al. 2014). PGLM was obtained with Segmented package (Muggeo 2008). MARS analysis was performed using earth package (Milborrow 2017), while CART analysis was conducted using the rpart package (Therneau et al. 2015). The potential distribution and associated link for AGB was checked with fitdistrplus package (Delignette-Muller and Dutang 2015). To graph GLMM the sjPlot package was used (Lüdecke 2017). The relative variable importance was calculated with the function varImpBiomod (Thuiller et al. 2009).

4.3 RESULTS

4.3.1 ABOVEGROUND BIOMASS VARIATION WITHIN COMMUNITIES

Analysis of variance indicates that there is significant variation within groups of communities (F (5, 138) = 15.08, $p<0.0005$). Tukey post hoc tests showed that pairwise comparisons were significantly different at $p < 0.05$ for the group of communities that included Chiqihuitlán, Temazcal and Tonaya and the group that included Ayutita and Zenztontla. It was also found that the former group has lower mean biomass than the latter. Agua Hedionda does not differ significantly from the other communities ($p > 0.05$) (Fig. 4.4).

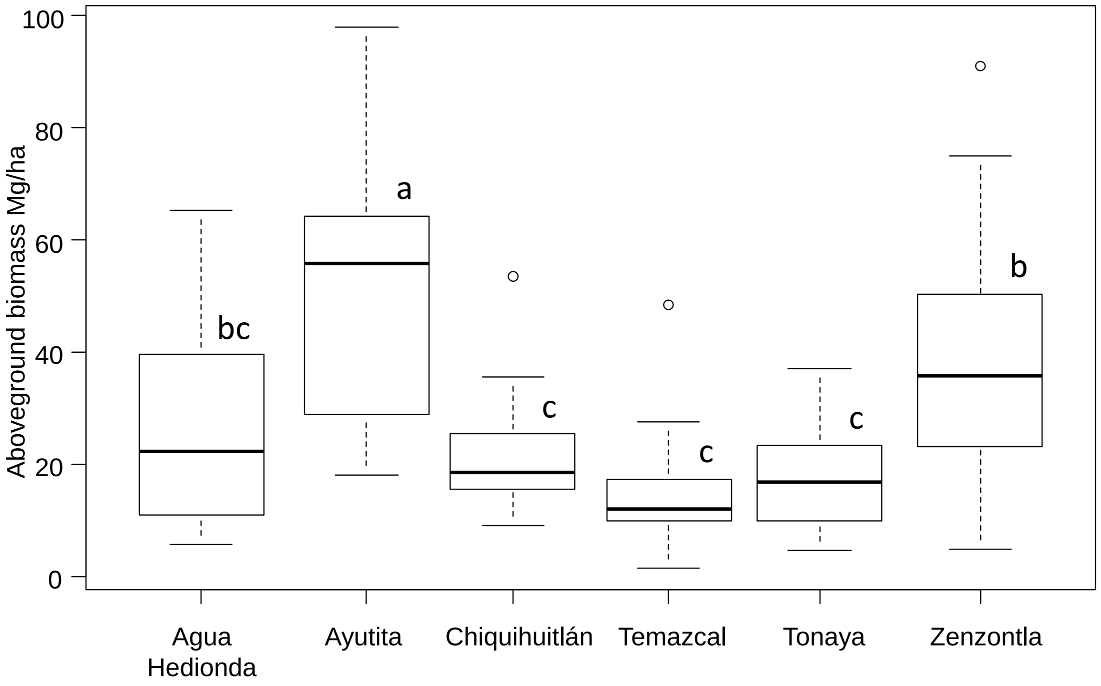

FIGURE 4.4 Aboveground biomass variation by community. Boxes show the 25th and 75th percentiles. The whiskers of each plot extend to ± 1.5 of the interquartile range to detect very extreme outlying data points, which are represented by dots. Letters above the whiskers indicate the communities, which are significantly different from each other according to Tukey HSD test.

4.3.2 LINEAR EFFECTS OF TOPOGRAPHIC FACTORS ON BIOMASS

The optimal GLM and generalized linear mixed model (GLMM) for the entire dataset showed evidence for the effect of elevation on AGB (Table 4.2). Optimal GLM was positively statistically significant (F= 6.40, df=141, p<0.05), explaining 19% of the variation in biomass (Table 4.2, column 1). For this GLM optimal model, elevation above sea level was the variable with the highest relative importance, followed by slope (Table 4.2, column 1, Fig. 4.5). The piecewise form of this model (Table 4.3) was statistically significant and slightly improved the proportion of biomass variation explained by the GLM model (Table 4.2).

TABLE 4.2 Results of different models for topographic factors: GLM, generalized linear model; GLMM, generalized linear mixed model.

Model	**GLM**	**GLMM**
(Intercept)	7.711**(1.766)	3.216***(0.006)
Elevation	1.001***(0.0003)[73%]	0.138***(0.006)[33%]
Slope	1.001**(0.0038)[27%]	0.135***(0.006)[25%]
TWI	NA	0.112***(0.006)[13%]
ctan	NA	0.135***(0.006)[29%]
Pseudo-R^2	$R^2_{N1} = 0.19$	$R^2_{N2(m)} = 0.10$ $R^2_{N2(c)} = 0.21$ $ICC_{N2(Community)} =0.13$
AIC	1199	1170.84
∆AIC	22.3	50.5
Log-Likelihood	-595.51 (df=4)	-578.42 (df=7)
RD	56.83	41.48

Notes: Each cell indicates the estimate. R^2_N, Pseudo-R^2, indicates the proportion of the variation explained: $R2_{N1}$, using Nagelkerke (1991); $R^2_{N2(m)}$, by topographic variables (fixed factor); $R^2_{N2(c)}$, for model as a whole; $ICC_{N2(Community)}$, intra-class correlation coefficient community (grouping factor), using Nakagawa and Schielzeth (2017). RD, residual deviance; ∆AIC, change in AIC; ctan, tangential curvature, TWI; topographic wetness index; NA, not applicable. In parenthesis, standard error. In square brackets, relative importance (%) of variables in models. Probability values: ** p<.01 *** p<.001.

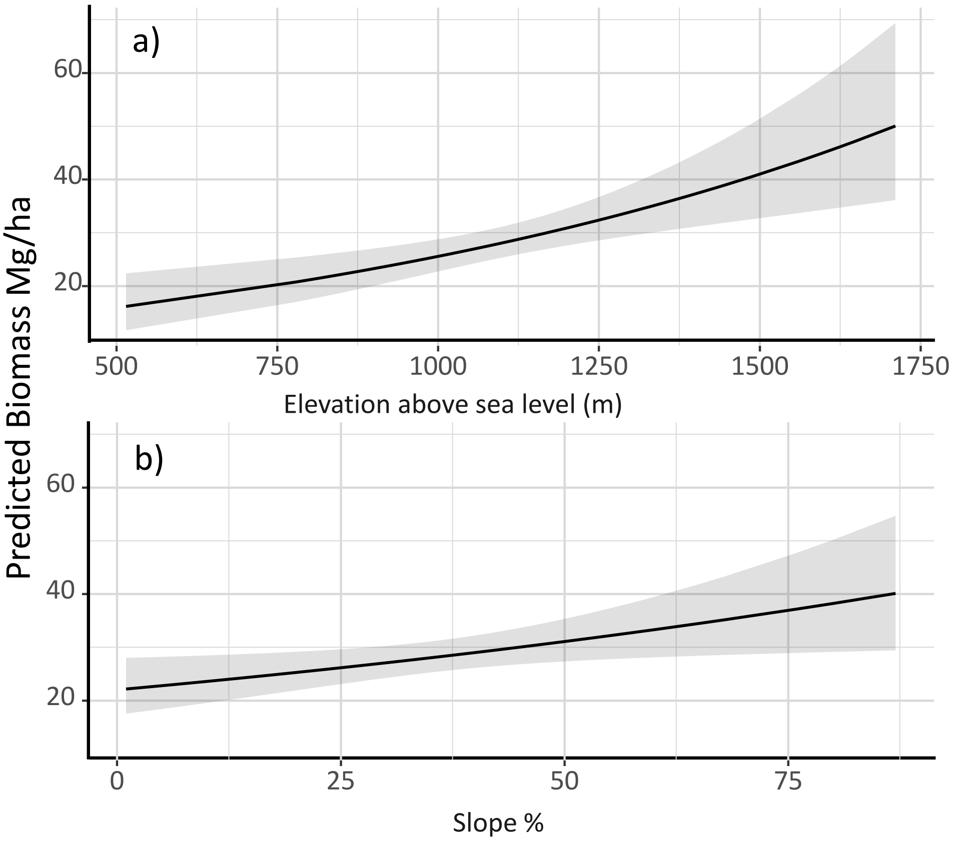

FIGURE 4.5 Mean predicted aboveground biomass variation over the observed range of each of the topographic variables: a) elevation above sea level and b) slope, for communities together. The fitted lines are generalized linear model estimates. Gray area around the black line shows confidence region.

TABLE 4.3 Results of PGLM model for elevation and slope.

Parameter	PGLM Model	
Breakpoints	Elevation=1400 (1078–1722)	Slope=47.28 (35.02–59.55)
β0a	1.79	1.791
β0b	4.35	0.43
β1a	0.0013 (0.0005–0.0021)	-0.0009 (-0.0104–0.0085)
β1b	-0.0004 (-0.0037–0.0028)	0.0276 (0.0068–0.0483)

Notes: Breakpoints refer to sudden and sharp change in directionality of the linear relationships. β0a, estimate of the intercept for first piece; β0b, intercept for second piece; β1a, estimate of the slopes for first piece; β1b, estimate of the slopes for second piece. The 95% confidence intervals are shown in parentheses for breakpoints and slope. Pseudo-R^2 =24, (indicates the proportion of the variation explained using Nagelkerke (1991)); AIC = 1198.7; Log-Likelihood = -591.35; Residual deviance = 53.82.

Four variables were significant (elevation, tangential curvature, slope and topographic wetness index) in the optimal GLMM model, which accounted for the random effect of rural communities while testing for the fixed effect of topographic variables (X^2=4.14, df=1, p<0.05, Table 4.2). There is a positive effect on predicted AGB of each of the four significant variables, after adjusting for the other three variables. That is, AGB will be higher at sites with the steeper terrain, with convergent flow of water (higher values of tangential curvature), with relatively more runoff (higher values of topographic wetness index) and at higher elevations (Fig. 4.6). These positive linear trends did not differ among communities. The predicted random intercept effect (±95% confidence intervals) for this GLMM was statistically significant for Ayutita = 0.36 (0.12–0.59), Temazcal = -0.24 (-0.46–-0.03) and Zenzontla = 0.37 (0.23–0.51), while it was not significant for Agua Hedionda =-0.11 (-0.34–0.11), Chiquihuitlán =-0.13(-0.34–0.06) and Tonaya =-0.16 (-0.34–0.01). This means that AGB follows two similar trends (Fig. 4.6). Overall, elevation above sea level, tangential curvature, slope and topographic wetness index accounted for most AGB variability. This model has the lowest residual deviance, better performance (the best log-likelihood and AIC scores) and the highest proportion of the explained variation (Table 4.2, column 2). Elevation has the highest relative importance in this GLMM optimal model, followed by tangential curvature. The proportion of variation explained by ´community´ was higher than the proportion explained by topographic variables (Table 4.2, column 2).

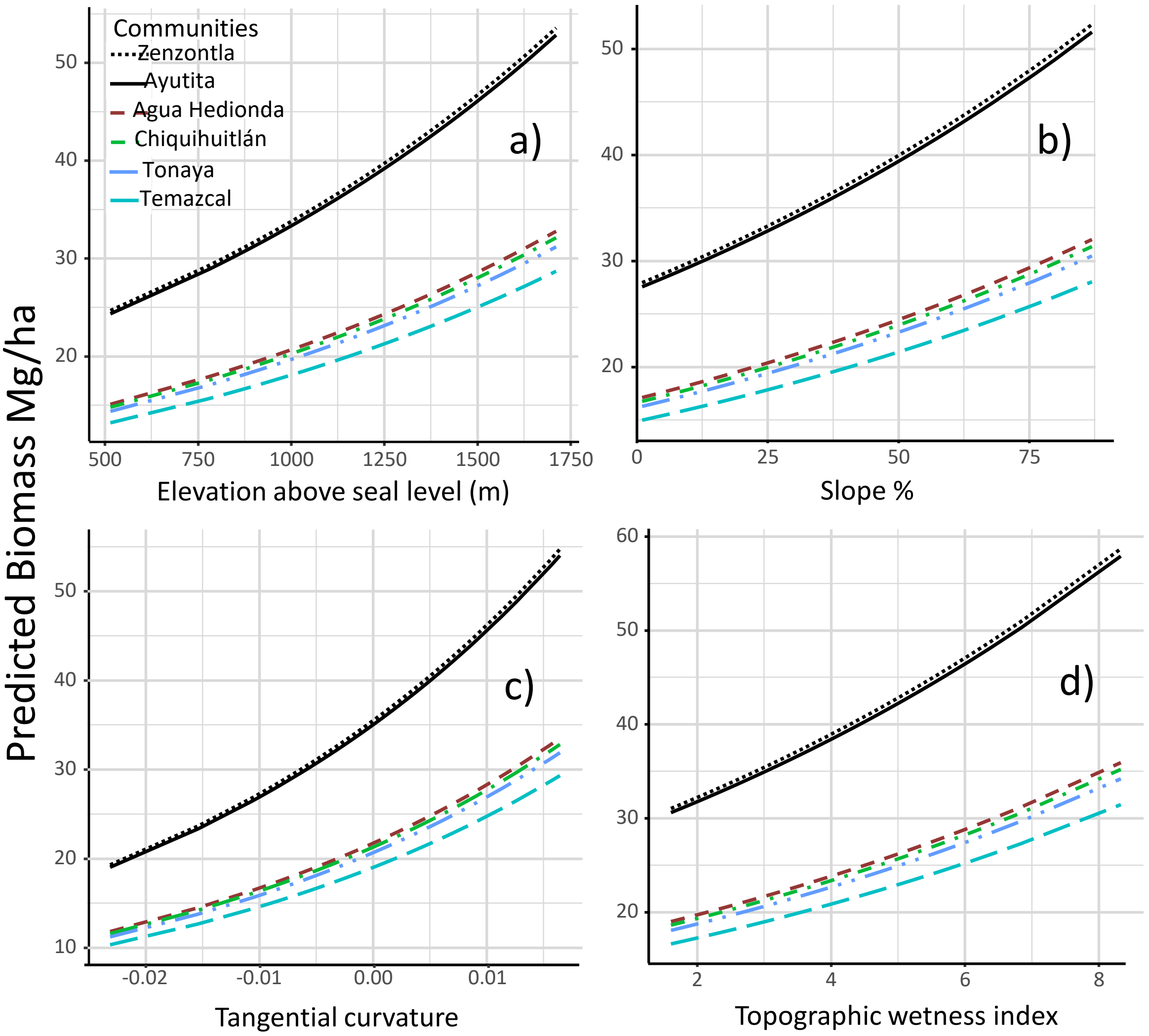

FIGURE 4.6 Relationships between mean predicted aboveground biomass and each topographic variable within the rural community's territory: a) elevation above sea level, b) slope, c) tangential curvature and d) topographic wetness index. The fitted lines are generalized linear mixed model estimates for each community. Gray area around the black line shows confidence region.

4.3.3 NON-LINEAR EFFECTS OF TOPOGRAPHIC FACTORS ON BIOMASS

The MARS interactions model performed for the entire dataset showed more complex non-linear relationships that best fit AGB. This model is composed of three basis functions and interactions that were found statistically significant (BF1, BF2, BF3, Table 4.4). These basis functions combine diffuse insolation and two rural communities, plus one function that relates to knot threshold values. Function BF1 decreases overall AGB (Table 4.4), this means that in general, sites with diffuse insolation lower than 320 kWh/m^2 have lower biomass. Functions BF2 and BF3 increase overall AGB, which is to say, biomass at sites in Ayutita with diffuse insolation of less than 320 kWh/m^2 would be higher but not as high as in sites in Zenzontla.

Basis function BF1 is used in basis function (BF2) to express the interactions between Ayutita community and diffuse insolation (Table 4.4). The performance of this model was 33%.

TABLE 4.4 Basis functions (BF) of the MARS for aboveground biomass, including their knot threshold value (h) and their corresponding magnitude of effect of the basis function.

Id	Basis function	Estimate	SE	T
Int.	(Intercept)***	3.28	0.087	37.52
BF1	h(difinsol-320.62) ***	-0.01	0.004	-3.80
BF2	Ayutita × h(320.62-difinsol) ***	0.07	0.021	3.75
BF3	Zenzontla ***	0.52	0.104	5.06

Notes: SE, standard error; t, t value; df, degrees of freedom; difinsol; diffuse insolation. Null deviance = 67.40, df = 143; Residual deviance = 46.37, df = 140; R-squared of the mode = 0.33; probability value: *** = <0.0005.

The CART analysis for the entire dataset that includes the relationships between AGB and each of the 11 topographic variables together found six of these variables to be significantly non-linearly related to biomass (Appendix 1: Table S3, column 2). The most important variable explaining variation in biomass was ´community´, since biomass levels varied more between individual rural communities than with any of the biophysical variables individually. This analysis created two groups of communities, as suggested by the GLMM, group A (four communities) and group B (two communities). Using just this as the breakpoint, more than 30% of the variation in AGB of the root node error is explained. This CART analysis then split the A and B branches on the basis of variables relative importance (Appendix 1: Table S3, columns 3 and 4), resulting in a tree with two terminal nodes each group (Fig. 4.7).

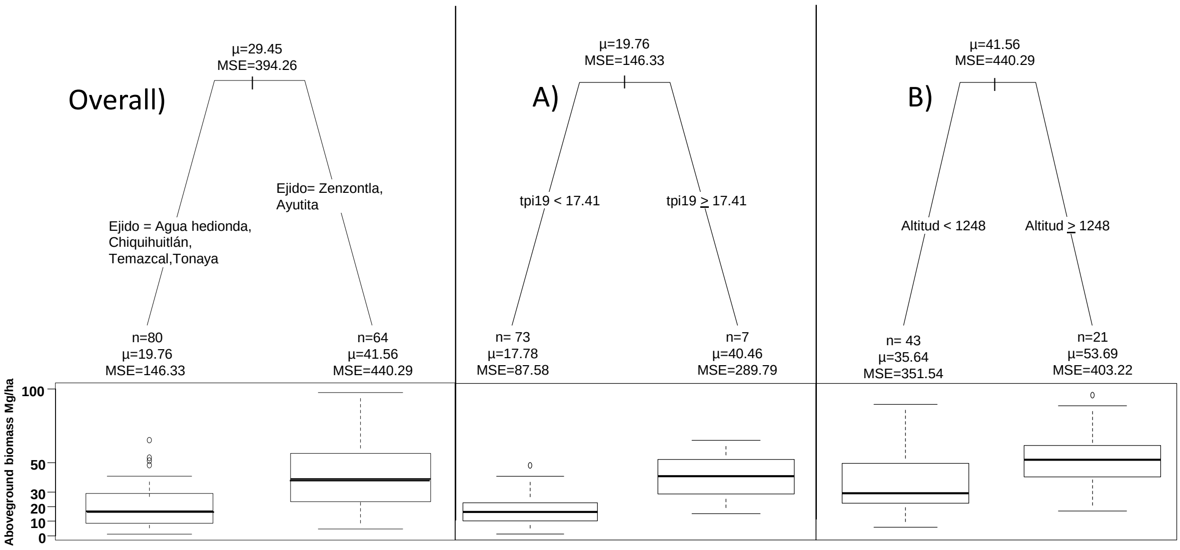

FIGURE 4.7 Regression tree for biomass for total dataset and for community groups A and B. MSE, mean squared error; µ, mean aboveground biomass (Mg/ha); n, number of plots in that particular terminal node. The boxplots at bottom section show the biomass variability in each of the terminal nodes. Boxes show the 25th and 75th percentiles. The whiskers of each plot extend to ± 1.5 of the interquartile range to detect very extreme outlying data point, which are represented by dots.

The tree for group A accounts for about 28% of the variance in overall biomass, and the breakpoint variable in this branch of the tree was tpi19 at 17.41 (Fig. 4.7). This variable together with topographic wetness index contributed with 60% of the explanatory value within this branch (Appendix 1: Table S3, column 3). The tree for group B accounts for about 17% of the overall biomass variance. The breakpoint variable for group B was elevation, with a threshold at 1,248 m a.s.l. (Fig. 4.7). Together with two other variables (diffuse insolation and planar curvature) this accounts for 82% of the explanatory value within this branch.

After identifying the complex non-linear relationships for the entire dataset, rather than binary splitting, the two splitting explanatory variables identified as having most influence within each of the groups (tpi19 and elevation) were assessed to determine their relative linear and non-linear influence on biomass by means of a GLM and a PGLM.

For group A of communities, both linear ($F(1,78)=9.58$, $p< 0.005$) and non-linear (Davies test $p= 0.003$) relationships were found between biomass and tpi19 (Fig. 4.8). PGLM found a significant negative trend at values of tpi19 lower than 11.8, and positive above this breakpoint (Table 4.5) (Fig. 4.8). This indicates that biomass decreases slowly at sites which are lower than the average elevations within the immediate neighborhood; above this threshold, biomass increases rapidly. The PGLM analysis explains 27% of the variation in biomass, while GLM explained only 12% (Table 4.5). This result matches the AIC values, which indicate that PGLM using tpi19 has the best trade-off between the goodness of fit and the complexity of the model (Table 4.5).

For the communities in group B, there is also a statistically significant linear relationship between AGB and elevation ($F(1,62)= 9.93$, $p>0.005$), explaining around 14% of the variation of AGB in this group of communities (Appendix 1: Fig. S1). The slope of the non-linear relationship was not statistically significantly different from zero (Davies test $p>0.05$).

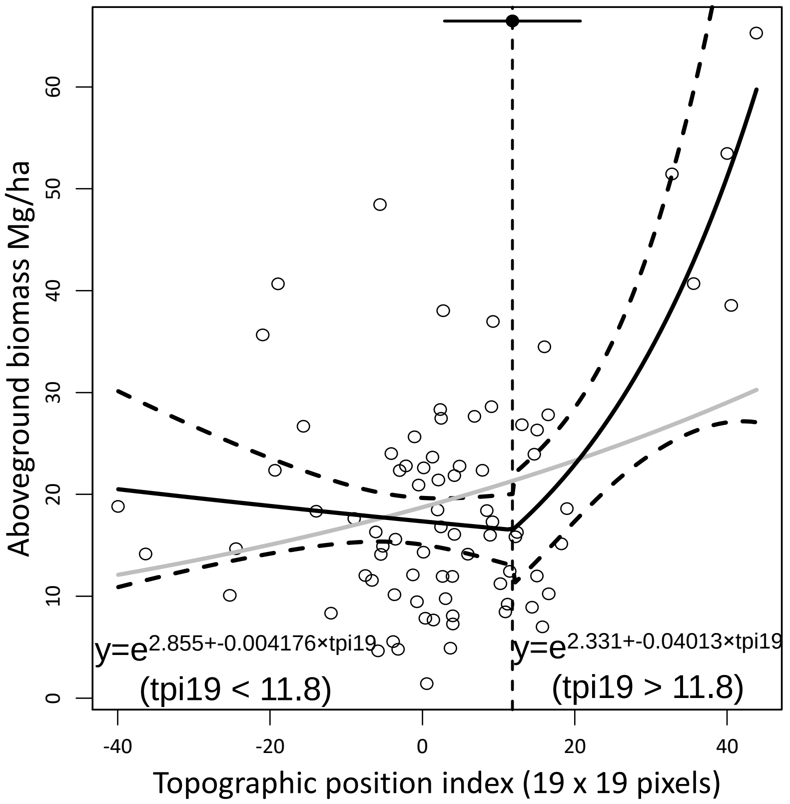

FIGURE 4.8 GLM and PGLM for biomass in Group A as a function of tpi19. GLM, gray solid line; PGLM, solid black lines. Vertical dashed line shows threshold for PGLM. Continuous dashed line, PGLM confidence intervals for tpi19 at 95%. Equations shown in the graph for each segment in base of the threshold from PGLM.

TABLE 4.5 Results of GLM and Piecewise GLM models for the relationship between tpi19 and aboveground biomass GLM for group A of communities.

Parameter	PGLM Model	GLM Model
Breakpoints	tpi19=11.81 (2.88–20.74)	NA
Intercept	NA	***2.931318
β0a	2.855	NA
β0b	2.331	NA
Slope	NA	*0.010921
β1a	-0.004 (-0.016–0.007)	NA
β1b	0.045 (0.012–0.063)	NA
R^2_N	27	12
AIC	588.01	597.31
LL	-289.00	-295.65
RD	22.75	26.65

Notes: Breakpoints refer to sudden and sharp change in directionality of the linear relationships. β0a, estimate of the intercept for first piece; β0b, intercept for second piece; β1a, estimate of the slopes for first piece; β1b, estimate of the slopes for second piece. The 95% confidence intervals are shown in parentheses for breakpoints and slope. R^2_N, Pseudo-R^2, that is, the proportion of the variation explained using Nagelkerke (1991); AIC, Akaike Information Criteria; LL, Log-Likelihood; RD, residual deviance. NA, not applicable. * <0.0005; *<0.05.

In short; five models were constructed and their results compared to determine which topographic factors best explain variation in AGB. The overall optimal linear model was the GLMM which allowed the individual weighting of variables to be applied in the different communities; this performed better than the other linear models including GLM, in which such weighting was not applied. GLMM also performed better than the non-linear models (PGLM, CART, MARS) in this sense. However, the MARS model achieved higher levels of explanation (33%) but only under particular conditions, for example in specific sites in specific communities, which experience higher levels of diffuse insolation.

4.3.4 EFFECT OF ACCESSIBILITY ON BIOMASS

No statistically significant linear (F(1, 142)=0.40, p>0.05) nor non-linear (Davies test p-value = 0.19) relationship between biomass and distance from settlements was found. There is a statistically significant linear (F(1, 142)=18.92, p< 0.0005) and non-linear (Davies test p-value = 0.023) relationship between biomass and distance from roads. The slope of this nonlinear relationship was statistically significant; positive at low distances from road and negative after breakpoint (2,273 m) (Fig. 4.9) (Table 4.6). The threshold also provides an empirical means of separating signals of human impact into two pieces. That is, between 0 and 2,273 m there is great human impact; this means sites closer to roads have less AGB. The second part of the line shows higher biomass figures at distance to roads greater than 2,273, which subsequently steeply decreases (Fig. 4.9). We also found that PGLM have a better fit than GLM; it attributed 20% of variation in biomass to road accessibility, compared to 13% in the GLM model (Table 4.6).

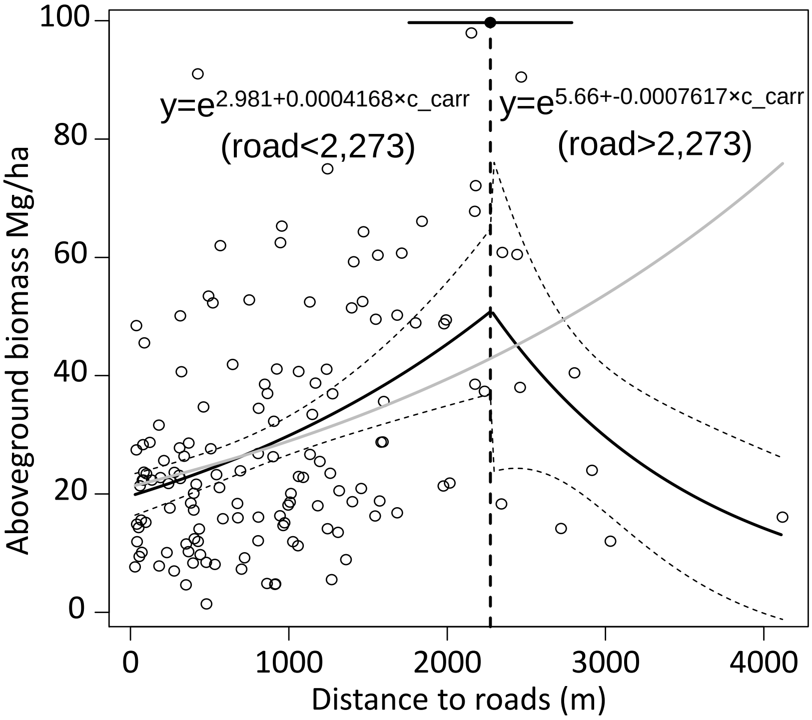

FIGURE 4.9 Linear and non-linear relationship for aboveground biomass as function of distance from roads. GLM, gray solid line; PGLM, solid black lines. Vertical dashed line shows threshold for PGLM. Continuous dashed line shows PGLM confidence intervals for tpi19 at 95%. Equations shown in the graph for each segment on basis of the threshold derived from the PGLM.

TABLE 4.6 Results of GLM and Piecewise GLM for the relationship between distance to roads and AGB.

Parameter	PGLM Model	GLM Model
Breakpoints	2273 (1758–2787)	NA
Intercept	NA	*** 21.29 (1.7940)
β0a	2.98	NA
β0b	5.66	NA
Slope	NA	*** 1.0003 (0.0001)
β1a	0.0004 (0.0002–0.0005)	NA
β1b	-0.0007 (-0.0015–0.000002)	NA
R^2_N	0.20	0.13
AIC	1199.49	1205.17
LL	-594.74	-599.58
RD	56.26	59.92

Notes: Breakpoints, refers to sudden and sharp change in directionality of the linear relationships. β0a, estimate of the intercept for first piece; β0b, intercept for second piece;

β1a, estimate of the slopes for first piece; β1b, estimate of the slopes for second piece. The 95% confidence intervals are shown in parentheses for breakpoints and slope. R^2_N, Pseudo-R^2, that is, the proportion of the variation explained using Nagelkerke (1991); AIC, Akaike Information Criteria; LL, Log-Likelihood; RD, residual deviance. NA, not applicable. ***, <0.0005.

4.4 DISCUSSION

This study differs from others in that it focuses on the explanators of biomass variation in *human modified* seasonally dry tropical forest landscapes rather than in natural, undisturbed SDTF. This is highly relevant in the context of REDD+ policy. Overall, the results suggest that in these modified landscapes, AGB is correlated not only with a number of regional and local topographic variables including elevation, slope, topographic wetness index, tangential curvature, diffuse insolation and the topographic position on the slope, but also with human factors. While GLM models place primary importance on regional topographic variables such as elevation, mixed GLM, CART and MARS models show that elevation and the details of micro-topography in different communities may have important effects in explaining differences in biomass density. This was shown in particular by the MARS model for the sites with scattered sun radiation, at the highest elevations. This was also revealed by piecewise regression where AGB of communities at lower elevations was shown to be affected by shading from nearby hills. We expected that human factors in the landscape would impact biomass levels, and analysis performed in this study supports this. We found that AGB increases not just in a linear monotonic relation with increasing distance to roads, but also in a non-linear way. The monotonically increasing density of biomass with elevation may also in part be explained in terms of human uses such as shifting cultivation, grazing and poles extraction, which are themselves highly selective as regards elevation.

4.4.1 Effects of specific indicators on biomass

In this study, four topographic variables were shown to be potential predictors of AGB when combined; elevation, slope, topographic wetness index and tangential curvature. On one hand, the first two variables together using a GLM approach enabled the inference of biomass over the entire study area. On the other hand, my best model that includes all the four variables together in a generalized linear mixed model (GLMM) enabled the inference within each community individually. Elevation had the greatest relative importance in both models, while tangential curvature was indicated as a second major expanator in the GLMM. It was possible to obtain 21% predictive power using GLMM models to improve our understanding of how environmental and human-based variables affect standing carbon.

GLMM was also able to show that different AGB/topography patterns exist in lower lying communities compared to communities at higher elevations.

No differences in slope of the regression equation but marked differences in the interceptor (y axis) between two groups of communities were found, so that the monotonic positive trend of biomass with elevation for each community is similar. A possible reason for the difference in interceptors is that terrain Ayutita, Zenzontla and Temazcal have a distinctly different topographic form from that of Agua Hedionda, Chiquihuitlán and Tonaya with regard to elevation, terrain curvature and the amount of diffuse insolation received, as indicated by CART analysis. As noted in the results section already, the MARS model enables us to explain 33% of the AGB levels variation relating to diffuse insolation values in sites above average elevations and particularly at the highest elevations.

This finding suggests that diffuse insolation may modify the effect of topography on soil water availability (corroborating Galicia et al. 1999), which impacts positively on aboveground biomass. Moreover, in Ayutita and Zenzontla the plot level topographic exposure to shade from nearby hills would be more favorable to biomass growth (see Appendix 1: Table S3). The average aboveground biomass for the four remaining communities (Agua Hedionda, Chiquihuitlán, Tonaya and Temazcal) is lower, with water availability related simply to elevation. The findings reported here support general trends concerning the link between soil water availability and aboveground biomass (Jaramillo et al. 2003, D'Odorico and Porporato 2006, Bullock et al. 1995, Jaramillo et al. 2011), and concur with those of studies from within the same region of Mexico (Maass 1995, Maass and Burgos 2011), which indicate the importance of inter- and intra-annual rainfall distribution on biomass.

Our findings are in complete contrast, however, to many studies which show a unimodal decrease in biomass with elevation in tropical forests (Raich et al. 1997, Marshall et al. 2012, Sundqvist et al. 2013). This negative relationship is usually explained in terms of limited soil nutrient/slower litter decomposition and lower water availability at higher elevations (Galicia et al. 1999, Maass and Burgos 2011, Jaramillo et al. 2011, Brienen et al. 2010). However these studies have almost all been carried out on undisturbed forests (Homeier et al. 2010, Leuschner et al. 2007, Aiba and Kitayama 1999), where there are no human factors at play. Human perturbation is markedly stronger in low lying areas (Toledo-Garibaldi and Williams-Linera 2014, Lovett et al. 2006, Alves et al. 2010). These areas have the best production potential (Maass 1995) and are where the majority of the human productive activities take place (Maass et al. 2005). Large scale human disturbance (deforestation) characterizes these areas, where the forest coverage may be almost completely removed. Extractive practices which have less impact, as well as cyclical shifting cultivation, are normally performed on slopes with less fertile soils (Morales-Barquero et al. 2015, Salinas-Melgoza et al. 2017). Human disturbance in these areas is mainly on a small scale with continuous removal of a small fraction of aboveground biomass for e.g. posts and firewood (Morales-Barquero et al. 2015), and vegetation changes may also be caused by grazing cattle in the forests (Vázquez and Givnish 1998, Méndez-Toribio et al. 2016).

As expected, human activities have a continuous and negative effect on aboveground biomass, which increased with distance from roads. This finding is in agreement with Mon et al. (2012) and Luoga et al. (2002). This trend can be explained in part by the human tendency to utilize the more accessible areas in preference to those that are more difficult to reach, as the remaining patches of SDTF are in remote places (Trejo and Dirzo 2000). One unanticipated finding was the threshold at which the negative effect reverses. A possible explanation for this might be a dual relation between the extractive activities and the distance to roads; some activities are carried out between the road and the threshold of 2,273 m, but beyond that, other activities may be implicated. It is possible, for example, that illegal activities such as charcoal production might be deliberately ´hidden from view´. More studies are needed to address and understand this interesting pattern.

These findings add another dimension to the so-called REDD+ ‘landscape’ approach to emission reduction (GLF 2013a, 2013b, Minang et al. 2015). The method we present could enable the identification of areas which are well below their potential biomass levels, for targeting REDD+ activities designed to halt further degradation and promote forest enhancement through natural regrowth, increasing overall carbon stocks. This could be done across the entire landscape of communities using only data from DEM (i.e. from existing topographic maps that are freely available from the national statistical institute of Mexico, INEGI (2017)), without the need for extensive ground forest surveys or for high resolution remote sensing images, which are costly. The differential forest biomass response along environmental gradients will be a critical information input for the design of locally appropriate REDD+ interventions. Although the models presented in this study explain only part (19-33%) of the variation in AGB, their level of accuracy is similar to that of other exercises based on expensive remote sensing inputs (Solórzano et al. 2017). For this reason, this approach could be an attractive and cost-effective alternative.

4.5 CONCLUSIONS

The main goal of the current study was to determine causal relationships between the geometry of the landscape and standing AGB in order to model AGB based on a quantitative description of the form of the land surface, which can be derived simply from topographical maps. As explained in the discussion, we found that the GLMM model is the most effective overall in explaining variations in AGB, and that four topographical variables (elevation, tangential curvature, slope and wetness index) together explain 21% of the variation. One of the more significant findings to emerge is that elevation was the most important variable among these, and that in SDTFs which are subject to human disturbance, this relationship is positive (higher biomass levels at higher elevations), which is contrary to patterns found in undisturbed forests. The second major finding was that topographic configuration (i.e. all four variables) of rural communities *as a whole* defined average aboveground biomass, in such a way that Ayutita and Zenzontla have more biomass than Agua Hedionda, Chiquihuitlán, Temazcal and Tonaya, although elevation still plays the greatest role. It was also shown that human activities affect AGB and that the intensity of human activities is related to distance from roads in a non-linear way.

The study has implications in terms of REDD+. It indicates the possibility of estimating AGB levels in similar areas of SDTF without the need for a forest survey or high resolution remote sensing, using just quantitative land surface information, derived cheaply from topographic maps. This may be particularly useful in the context of the so-called ‘landscape’ approach to REDD+, which aims at treating emission reductions not merely in full forest areas but across landscapes in which agricultural and other human activities are integrated within forests, where they form dynamic mosaic patterns and shifting locations of carbon stocks. REDD+ policy in Mexico is moving towards a landscape approach in which territorial plans at community level will be the basis for financial support for landscape management activities which will hopefully result in reduced emissions and increased sequestration (CONAFOR 2016). In this context, my study provides a feasible tool by which it is possible predict from 19% to 34% of current biomass levels in rural communities with SDTF landscapes within the study area, just from the DEM data. This information could be used to set targets for potential carbon stocks in different parts of the landscape, that is, to suggest where in the landscape REDD+ activities should best be targeted. While the calibration of these models is specific to this region and vegetation type, the method itself could be extended for use in other areas and other types of forest.

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APPENDIX 1

Table S1 Overview of studies that have analyzed the relationship between tropical forest structure variables and topography. AGB, aboveground biomass, BA= Basal area; DBH, diameter at breath height; SD=stem density; TH, Tree height; Ref, reference; P, preserved forest, D, disturbed forest.

Ref	Topographic variable related to	Forest structure variable used	Forest type and location	P/D
1	Slope	TH and DBH	Mixed Dipterocarp forest, Borneo	P
2	Relative position on the slope	AGB, BA and SD	Wet tropical forest, Puerto Rico	P
3	Slope	AGB	Terra firme wet forest, Central Amazon, Brazil	D
4	Elevation and slope	AGB	Wet tropical forest, Costa Rica	P
5	Relative position on the slope	AGB	Lowland moist tropical forest, Central Panama	P
6	Relative position on the slope	AGB and TH	Lower montane forest, Borneo	P
7	Elevation and slope	AGB	Terra firme moist tropical forest, Amazon	P
8	Relative position on the slope	AGB and SD	Wet tropical forest, Ecuador	P
9	Elevation	AGB	Tropical forest, Hawaii	P
10	Relative position on the slope	AGB	Lowland tropical forest, French Guiana	P
11	Elevation and Slope	AGB	Tropical moist forest, Atlantic coast, SE Brazil	P
12	Slope	AGB	Lowland moist tropical forest, Central Panama	P
13	Relative position on the slope	AGB, SD and BA	Hill dipterocarp forest, Sumatra	P
14	Elevation and slope	AGC	Tropical montane cloud forest, puna, and transition zone, Peru	D

15	Elevation, slope and aspect	AGC	inhumbane lowland forest, transitional/submontane forest and afromontane forest, Zanzibar -Tanzania	D
16	Elevation, slope, aspect and a terrain ruggedness index	AGC	Multiple types of tropical forest, Colombian Amazon	D
17	Elevation, slope, aspect concavity and convexity	TH	Lowland moist tropical forest, Central Panama	P
18	Elevation	AGB	Mauna Loa, Hawai‘i	P
19	Elevation, aspect and relative position on the slope	AGB	tabonuco forest colorado forest, palm forest and cloud forest, Puerto Rico	P
20	Elevation	AGB	Rain forest, Borneo	P
21	Elevation	AGB	Rain forest, Borneo	P
22	Elevation and aspect	BA	Evergreen broadleaf forest, Vietnam	P
23	Elevation and slope	AGB	Hill dipterocarp forest, Sumatra	P
24	Relative position on the slope	BA and DBH	Tropical rainforests, Costa Rica	P
25	Relative position on the slope	TH and SD	Lowland wet tropical forest, Costa Rica	P
26	Aspect	AGB and SD	Old mixed hardwood forest, USA	P
27	Aspect	AGB and SD	Evergreen sclerophyllous trees and semideciduous shrubs with herb associations) and dwarf shrublands, Israel	D
28	Relative position on the slope	AGB	Mount Zequalla Monastery, Ethiopia	P
29	Relative position on the slope	AGB and BA	Humid tropical montane, Ecuadorian Andes	P
30	Relative position on the slope	AGB	Atlantic Forest, Brazil	P

31	convexity and concavity	AGB	Atlantic rainforest, Brazil	P
32	convexity and concavity	AGB	Montane Ombrophylus Dense Forest, Brazil	P
33	convexity and concavity	AGB	Subtropical mountain moist forest, China	P
34	Elevation	BA and SD	Dry deciduous woodland	D
35	Elevation	BA	Tropical montane forests, Ecuador	P
36	Elevation	BA	Coniferous forest, tropical montane cloud forest and seasonally dry tropical forest, México	P
37	Elevation	TH, DBH and SD	Tropical montane forests, Ecuador	P
38	Elevation	BA	Tropical seasonal dry forest, temperate forest and montane rain forest	D
39	Relative position on the slope	AGB	Tropical seasonal dry forest	P

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Table S2 Variables initially selected to characterize topographic heterogeneity in the study area. m, metres; m a.s.l., metres above sea level; kWh, kilowatts per hour. Letters in parenthesis: a) Wilson and Gallant (2000), b) De Reu et al. (2013), c) Moore et al. (1991), d) Sørensen et al. (2006) and e) Hengl and Reuter (2008).

Variable	**Description**
Elevation above sea level (m)	Indicator for progressive change in climate. Expressed in metres above sea level (m a.s.l.) (a, e)
Aspect (N,S,E,W)	Compass direction of slope exposure. Indicates topographic shading, due to northern location, highlighted by nearby hills. It has been used to indicate more favorably sheltered areas (c, e).
Profile curvature (Degrees/m)	Determines the downhill or uphill rate of change in slope in the gradient direction. Negative values are upwardly convex and indicate accelerated flow of water over the surface. Positive values are upwardly concave and indicate slowed flow over the surface (a, e).
Planar curvature (Degrees/m)	Also called contour curvature. It measures the rate of change transverse to the direction of maximum slope, in the horizontal plane. It measures converging or diverging flow of water. Negative values indicate divergent water flow over the surface, and positive values indicate convergent flow (a, e).
Tangential curvature	Has the same significance as the planar curvature (controls the acceleration and convergence of surface water flow across land surface), but highlights differences in measurement of flow convergence and divergence in flat areas, to avoid extremely large values when slope is small (a, c, e).
Total insolation (kWh/m^2)	Describes the relationship between the topographic surface and incoming solar radiation. It is the sum of direct, diffuse, and reflected radiation components (a, e).
Diffuse insolation (kWh/m^2)	The scattered radiation that reaches the ground (a, e)
Direct insolation (kWh/m^2)	The radiation that reaches the ground under clear skies (a, e)
Slope (%)	Slope in the steepest downslope direction. Ranging from 0 to 100 (a, c)

Topographic position indices using different scales (number of pixels in the immediately surrounding area included in calculation: 1) 5 pixels 2) 11 pixels 3) 15 pixels 4) 19 pixels 5) 25 pixels 6) 35 pixels 7) 45 pixels 8) 61 pixels	A measure of the micro elevation of the sample point, compared to the immediately surrounding area. It is a measurement, in relative terms, of the position of the pixel along the slope. For each pixel in the raster map TPI compares the pixel elevation to the mean elevation of the surrounding cells. TPI values near-zero or zero indicate flat locations. The more positive the TPI, the higher the topographic exposure of the pixel. The more negative the TPI, the lower the topographic exposure of the pixel. The lower the topographic exposure, the more sheltered the area is from sunlight (a, c).
Topographic wetness index	Used to quantify topographic control on hydrological processes. It is a parameter describing the redistribution of water in the landscape and indicates the tendency of a pixel to accumulate water (a, b, c, d, e).
Distance to road (m)	Measure of human impact, distance from sites to the closest roads was estimated.
Distance to human settlement (m)	See above, distance to human settlements.

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Table S3 Relative importance (%) of each of the topographic variables on aboveground biomass as calculated in the regression tree analysis for the entire dataset (first column) and for groups of communities A (second column) and B (third column). cplan, planar curvature; cprof, profile curvature; ctan, tangential curvature; difinsol, diffuse insolation; dirinsol, direct insolation; elevation, elevation above sea level; slope: slope; tpi19, topographic position index 19 x 19 pixels scale; tpi25, topographic position index 25 x 25 pixels scale; tpi61, topographic position index 61 x 61 pixels scale; TWI, topographic wetness index; NA, not applicable.

Variable	**Overall**	**A**	**B**
community	52	NA	NA
cplan	NA	NA	10
cprof	NA	10	NA
ctan	NA	10	NA
difinsol	10	NA	20
dirinsol	11	NA	5
elevation	8	NA	52
slope	10	10	NA
tpi19	NA	35	NA
tpi25	NA	NA	5
tpi61	9	10	7
TWI	NA	25	NA

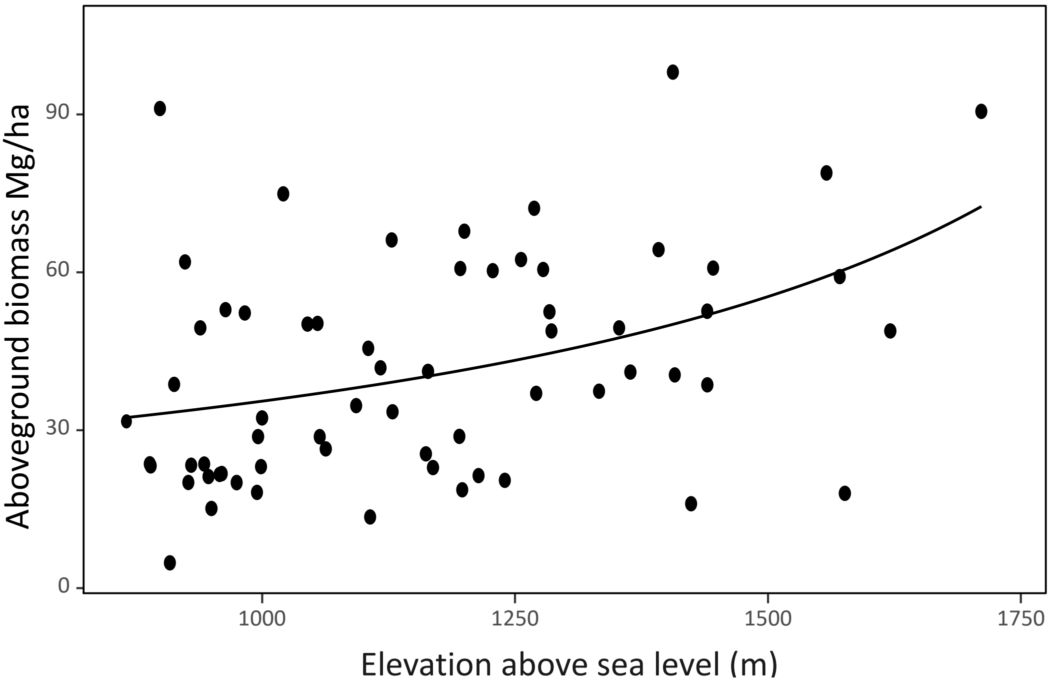

Figure S1 GLM for biomass in Group B as a function of Elevation.

APPENDIX 2

A1. Topographic variables

Here the calculation of independent variables (Table 5.2) (topographic variables and distances to roads and distance to settlements) is described. All the topographic variables were derived from a Digital Elevation Model (DEM), which is a digital representation in raster format of the relief of a surface between points of known elevation, which was obtained from the national statistical institute of Mexico (INEGI 2017). The spatial resolution of this spatial data base is of 15 × 15 metres. This DEM was the main input used to obtain the other topographic variables. Previous to calculation of the topographic variables used as dependent variables, preprocessing procedure was performed in order to remove from DEM local depressions (sinks) that would affect posterior calculations using the depression filling algorithm of Planchon and Darboux (2001).

The topographic variables were derived from the DEM, using RSAGA (Brenning 2008) that provides access to System for Automated Geoscientific Analyses, SAGA v 2.1.4 (Conrad et al. 2015) software within R v 3.4.0 environment (R Core Team 2017). We also used QGIS Desktop 2.18.7 with GRASS 7.2.0 (QGIS Development Team 2016) for data manipulation. R packages used for calculations, data processing and analysis were: raster (Hijmans et al. 2016), spatialEco (Evans 2017), rgdal (Bivand et al 2017).

Table S1 Topographic variables and distance to roads calculation.

Variable (units)	Calculation
Elevation above sea level (m)	Obtained directly form DEM (INEGI 2017)
Aspect (N,S,E,W)	Obtained using R, RSAGA, and SAGA. Method used was poly2zevenbergen. Input: DEM
Profile curvature (Degrees/m)	Obtained using R, RSAGA, and SAGA. Method used was poly2zevenbergen. Input: DEM
Planar curvature (Degrees/m)	Obtained using R, RSAGA, and SAGA. Method used was poly2zevenbergen. Input: DEM
Tangential curvature	Obtained using R, RSAGA, and SAGA. Method used was poly2zevenbergen. Input: DEM
Total insolation (kWh/m^2)	Annual averaged obtained using R, RSAGA, and SAGA: integrated module “Incoming Solar Radiation” (Conrad et al 2015) using the Lumped Atmospheric transmittance atmospheric effect. Input: DEM

Diffuse insolation (kWh/m^2)	Annual averaged obtained using R, RSAGA, and SAGA: integrated module “Incoming Solar Radiation” (Conrad et al. 2015) using the Lumped Atmospheric transmittance atmospheric effect. Input: DEM
Direct insolation (kWh/m^2)	Annual averaged obtained using R, RSAGA, and SAGA: integrated module “Incoming Solar Radiation” (Conrad et al 2015) using the Lumped Atmospheric transmittance atmospheric effect. Input: DEM
Slope (%)	Obtained using R, RSAGA, and SAGA. Method used was poly2zevenbergen. Input: DEM
Topographic position indices using different scales (number of pixels in the immediately surrounding area included in calculation: 1) 5 pixels 2) 11 pixels 3) 15 pixels 4) 19 pixels 5) 25 pixels 6) 35 pixels 7) 45 pixels 8) 61 pixels	Implement the calculation of tpi from De Reu et al. (2013) using spatialEco (Evans 2017) Evans, J.S. (2017) spatialEco. R package version 0.0.1-7, URL:https://CRAN.R-project.org/package=spatialEco>.
Topographic wetness index	This variables was obtained using R, RSAGA, and SAGA. Type of area used was square root of catchment area and catchment slope as type of slope. Input: DEM
Distance to road (m)	This variable was calculated with QGIS Desktop NNJoin plugin ver. 1.2.2 (Tveite 2015). Spatial data bases of roads were obtained from IIEGJ (2011).
Distance to human settlement (m)	This variable was calculated with QGIS Desktop NNJoin plugin ver. 1.2.2 (Tveite 2015). Location of human settlements was obtained from INEGI (2010).

A2. Selection of topographic variables

Prior to the modeling analysis, variance inflation factors (VIF) were used to detect multi-collinearity among the topographic predictors, sequentially dropping the variables with the highest VIF scores, recalculating the VIFs and repeating this process until all VIFs were lower than 7 (Montgomery et al. 2012). In the literature, acceptable VIF thresholds vary from 10 to 3 (Montgomery et al. 2012, Zuur et al. 2010). This means that that the independent variables selected have a coefficient which is inflated by a maximum of seven as a result of linear dependence with other independent variables. Variables were selected out of the 18 for three different sets: firstly for all communities together, and then for the two subgroups (A and B) of communities, as defined by CART analysis, explained in methods section). At the overall level, eleven variables were selected: slope, elevation, cprof, cplan, ctan, dirinsol, difinsol, tpi25, tpi61, TWI and aspect. Ten variables were selected for group A of communities; slope, elevation, cprof, cplan, ctan, dirinsol, tpi19, tpi6, TWI, and aspect. Nine variables were selected for group B of communities; slope, elevation, cprof, cplan, dirinsol, difinsol, tpi25, tpi61 and aspect, which were selected in base of VIF procedure.

A3. CART, MARS and PGLM procedure

The classification and regression tree analysis (CART) performed is extremely resistant to outliers and can be applied to data sets having a large number of independent variables (Steinberg and Colla 1995) to evaluate whether the dependent variables (AGB) can be explained by complex interactions between the independent variables. This procedure makes no distributional assumptions and does not seek cause-and-effect relationships between variables, but rather looks for statistical associations (Steinberg and Colla 1995).

CART performs well in capturing interaction effects among the independent variables and provides the relative importance of each explanatory variable within one fitted tree structure (Clark and Pregibon 1992). CART uses binary recursive partitioning on the dataset along the entire range of variation of the explanatory variables. This is in order to split the data set into homogeneous subsets based on their relationship to sets of several predictor variables. The primary split aims to maximize the reduction in deviance. Every split made finds the predictor variable that results in the greatest change in explained deviance by splitting the dataset (Clark and Pregibon 1992). When changes in explained deviance are not found, the tree is considered fully grown with terminal nodes, which have a conditional mean. This is the predicted value for all sites included in that terminal node. Lower branches were removed from this fully growth tree to avoid over-fitting the data and to ensure that the remaining branches are robust enough through a pruning process using the lowest estimated error rule

(Clark and Pregibon 1992). Model goodness of fit is estimated by R^2, which is a normalized form of the residual sum of squares (RSS) that indicates the percentage of variance explained by each split. CART models were build using a cost-complexity parameter (CP), relative error in the predictions (rel error), mean value of the errors of the cross-validations (xerror) and cross validation standard deviation (xstd) and number of splits (nsplit) obtained from ten cross-validation procedures repeated three times. Each fitted tree provides variables and thresholds for those variables. Also surrogate splits variables and thresholds are provided to identify variables that may be masked for the primary split. CART analysis was conducted using the rpart package v. 4.1-10 (Therneau et al. 2015).

PGLM evaluates breakpoints iteratively along the extent of variation of the independent variables. Piecewise-Generalized Linear Models were fitted using the Segmented Package (Muggeo 2008). The Segmented Package iteratively fitted two or more segments across a range of breakpoints, using GLM models and then returned the model with the lowest residual sum of squares (Muggeo 2003). Changes in the slope of the GLM were assessed using the Davies' test, which chooses a number of fixed breakpoints along the X-axis and looks for statistically significant differences in regression slopes on each side of the breakpoints. Breakpoints estimates were included in the model only when the 95% confidence intervals do not overlap. Because piecewise-regression cannot deal with interaction between segmented variables, no piecewise-model including interactions between these explanatory variables was attempted.

Multivariate Adaptive Regression Splines (MARS, Friedman 1991) is a nonparametric regression procedure with no functional relationship assumption and is used in situations where there are many dimensions to be considered. In this study this analysis was used to evaluate whether forest biomass follows a continuous non-linear function with predictive variables, by fitting multi-variate splines. This analysis allows for the use of multiple variables that may not have common effects across the sample (Osei-Bryson, 2014). It partitions or segments the multi-dimensional space into regions using CP, giving each region its own regression equation. MARS is a two steps recursive procedure that progressively increases the model complexity. A backward procedure removes the least significant function form of the model. Each time the procedure is performed, all possible knots for each variable are evaluated and the ones that minimize prediction error are selected. Eventually, in order to deal with overfitting, the CP of the model is reduced by a "pruning procedure", which removes the functions that contribute least to the overall goodness of fit. Model fit is evaluated at each iteration through a "generalized cross-validation" (GCV) measure of mean square error. A Generalized Linear Model (GLM) argument was specified in the MARS model procedure, with a gamma error and log link, which was repeated independently. This procedure construct the MARS model with several piecewise linear basis functions, which use a threshold value called a knot (Friedman 1991; Faraway 2016). For each iteration the process builds a MARS model with the in-fold data, then measures the relationship (R^2) between predictions from MARS model and the ones made on the out-of-fold data (one tenth of the complete dataset). Then the mean R^2 (CVRsq) of these out-of-iteration R^2s is reported. We obtained the nonlinear model from the MARS procedure describing the basis function (BF), which are those functions that contribute significantly to the fit of the model (Friedman 1991).

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Chapter 5

SPATIAL MODELING OF CARBON IN A LOCAL LANDSCAPE USING TOPOGRAPHIC VARIABLES: POTENTIAL APPLICATIONS UNDER REDD+

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ABSTRACT

The aim of this study was to assess to what extent existing levels of biomass could be spatially predicted using typical landscape characteristics such as slope, wetness index and terrain convexity as modeling variables. Data on these variables can be derived directly from standard contour maps and does not involve the use of remote sensing or satellite imagery. We developed Bayesian geo-statistical models to obtain spatially distributed predictions of above ground biomass in four communities in seasonally dry tropical forests areas in Mexico. The candidate models were chosen using the mean logarithmic score; with the best performing model selected using Root Mean Square Error. The curvature of the terrain, topographic wetness index and slope were significant to explain spatial patterns of biomass. The accuracy of my models was between 65 to 80%. Three variables were used in the modeling procedure: wetness index, tangential curvature and slope. Tangential curvature – the presence of concavity and convexity in the surface – emerged as the most important variable. Significant topographic variables were related with conditions that contribute to move and accumulate humidity in the soil. This method has applications in local level implementation of REDD+ policy, in particular for forest enhancement projects, which promote carbon sinks through increasing carbon stocks in existing forests. The method could be used to identify sites where biomass stocks are currently below their potential levels, and thus attention and investment can be focused on those areas with the greatest potential for natural re-growth.

Keywords: REDD+, carbon stock enhancement, seasonally dry tropical forest, aboveground biomass, Bayesian geostatistical modeling, spatial predictions, terrain convexity

5.1 INTRODUCTION

Estimates of carbon levels in landscapes are a necessary part of the planning and design of interventions aimed at mitigating climate change in the land use sector, for example under the UNFCCC initiative Reducing Emissions from Deforestation and Degradation (REDD+). This is quite challenging (Gibbs et al. 2007). Carbon-density maps with relatively coarse resolution have been constructed at scales ranging from pan-tropical (Saatchi et al. 2011) through regional (Cartus et al. 2014) to state level (Rodríguez-Veiga et al. 2016), although very few have been carried out at landscape or local level. The standard method to estimate carbon levels involves use of remote sensing (RS) images to determine areas under different land cover types, which are then multiplied by data either from secondary sources or from a local biomass (forest) surveys to estimate the mean carbon stock per hectare in each land cover type. Attempts at verification show that the level of agreement between field data on forest above ground biomass (AGB) with pixel level AGB predictions tends to be poor (Mitchard et al. 2014, Ometto et al. 2014), which has been variously explained in terms of measurement error, the size and sparse distribution of the sampling plots, local heterogeneity in plant forms, unreliable allometric models, topography, modeling techniques and RS algorithms selected and spatial mismatches (Chave et al. 2004, Mitchard et al. 2014). The errors in such calculations include errors in the area estimates and in classification of pixels, which depend to some extent on the level of resolution of the images used, as well as on the skill of the interpreter (Mitchard et al. 2014, Rodríguez-Veigaet al. 2017). Moreover, in addition to possible inaccuracy of the stock data due *inter alia* to non-representativeness of the data used, the variance around the mean for carbon stock in any given forest type is often huge (Mitchard et al. 2013). A major reason for this variance is because within any land cover class, biomass responds to physiographic and human variables. While in large scale (national/regional) applications these variations may cancel each other out to give an acceptable average over large areas, at the local or project scale they may significantly distort the picture.

In this paper we present an experiment in which, instead of using remote sensing to determine the areas covered by different forest types, we model above ground biomass across the entire landscape using four key topographic variables to explain variation in AGB as determined by a ground level forest survey. The four topographical variables were derived from standard digitalized contour maps of four communities in an area of seasonally dry tropical forest (SDTF) in Jalisco state in Mexico. Automated programs to analyze landscape features from topographical maps are widely available and can easily be used at the local scale for this kind of analysis. The rational for this approach is to reduce the errors inherent in the use of mean AGB per hectare for each forest type, since there are large variations within forest types due, among other things, to topography. If found to be satisfactory, this method would eliminate the need for, and the errors inherent in, using relatively high cost RS interpretation and could raise the level of precision by accounting for some of the variables that are known to affect within-class biomass variation.

A secondary aim of the paper is to determine whether such modeling could be used to help in the design of forest enhancement projects. The experiment is based on data from a case study in an area of SDTF Mexico, which has been earmarked as an Early Action Area for REDD+. It is an interesting case because – as in many locations where REDD+ is envisaged– it has been suffering from degradation of carbon stocks as a result of human uses such as shifting cultivation, grazing and fuelwood gathering (Morales-Barquero, et al. 2015, Salinas-Melgoza et al. 2017). Reduction of these activities would result in enhancement of forest stocks in the natural vegetation.

The paper is structured as follows; first we briefly discuss the relationship between landscape and forest dynamics and what this means in terms of potential mitigation of carbon emissions. Secondly we present evidence from the literature on the relationship between AGB level and topographic features. There follows an explanation of the Bayesian methods we used for modeling the influence of topographic variables on AGB levels. We present results of the modelling and finally make an assessment of the suitability of this method for REDD+ project development.

5.1.1 LANDSCAPE AND FOREST DYNAMICS IN SEASONALLY DRY TROPICAL FORESTS

Human modified SDTF landscapes are often in the form a shifting mosaic of open areas and forest patches at different successional stages. The clearance made during activities such as shifting cultivation, temporary grazing and firewood collection, is not permanent and should be seen as forest degradation, not as deforestation. The perturbations, either natural (e.g. fire) or human, promote a system of forest dynamics and after clearance, rapid regrowth occurs through lateral crown expansion of neighboring trees, sprouting, and growth of seedlings and saplings. This continuous growth gives rise to the possibility that although standing carbon stock as a whole may be lower than in ´intact´ forest of the same type, the processes of degradation may be balanced by those of regeneration, and over all the system may represent a net ‘carbon sink’ (Gibbs et al. 2007, Mertz 2009, Pelletier et al. 2012, Morales-Barquero et al. 2015, Salinas-Melgoza et al. 2017).

There is plenty of room for carbon sequestration in Mexico. Potential of biomass recovery after 20 years following land abandonment has been estimated to be around 50 Mg/ha/year, with high variability (Poorter et al. 2016). A large proportion of the SDTF in Mexico are in a degraded state due to the human perturbation mentioned above. The main potential under REDD+ in these ecosystems may be not in reducing deforestation, but rather in reducing degradation and supporting enhancement of the carbon stocks. Enhancement of forest carbon stocks implies reversal of degradation and recuperation of carbon stocks, usually by removing or better managing the activities that cause them to degrade. The gains are generally small, ranging from one to five Mg/ha/year, on an annual basis (IPCC 2006, Mora et al. 2017, Rozendaal et al. 2017) and moreover they are not constant over the whole territory of a given community (Hernández-Stefanoni et al. 2010) but follow dynamic spatial patterns. Stock changes of this size are very difficult to quantify from remote sensing, and there are very few alternative methods available (Mitchard et al. 2014).

5.1.2 EVIDENCE FOR THE INFLUENCE OF TOPOGRAPHIC VARIABLES ON ABOVE GROUND CARBON LEVELS

It is important to recognize that topographic features may not only impact biomass density, directly or indirectly, but that they also influence human uses of forest, since activities such as shifting cultivation and grazing are not randomly distributed across the landscape but closely follow the logic of topography. Slope and elevation above sea level have been reported as the main explanatory variables of forest structure, particularly of biomass and canopy height (Salinas-Melgoza et al. 2018). Flat sites tend to have higher water availability, organic matter content and nutrient availability than sloping sites, and as a result forest ecosystems on sites with small slope angles should show higher biodiversity, basal area, and annual net primary productivity than steeply sloping sites (Martínez-Yrízar et al. 1996, Galicia, et al. 1999, Balvanera et al. 2002, Segura et al. 2002, Cielo-Filho et al. 2007, Laurance et al. 2010, Morales-Barquero et al. 2015). In SDTF biomass is usually understood to be determined by water availability (Jaramillo et al. 2003), which is strongly affected by slope (Wilson and Gallant 2000). There is evidence that soil moisture stress increases the effects of human disturbance in SDTF (Chaturvedi et al. 2017).

Local scale topographic factors play a key role in determining AGB levels (Shen et al. 2016). Terrain convexity has shown a positive effect on AGB (McEwan et al. 2011, Xu et al. 2015, Shen et al. 2016), conversely Yauakura et al. (1996) and Xu et al. (2015) found negative effects of convexity on AGB. Furthermore, there are studies that suggest that slope has a negative effect on AGB (Marshall et al. 2012) and that AGB relates to relative position along the hillslope, due to nutrient and water accumulation in flat areas in the low area of the hillslope (Jaramillo et al. 2011).

In an earlier study in the study region slope and elevation above sea level, jointly with a proxy of soil wetness and surface roundness, were found as determinants of AGB in a SDTF (Salinas-Melgoza et al. 2018). The study showed that topographic configuration within the territories of rural communities in human-dominated SDTF landscapes plays a key role in AGB patterns. It also showed that there are groups of communities that share similar topographic configurations and that have similar AGB patterns. This opens the possibility for development of AGB baselines for carbon enhancement REDD+ projects, using manageable field data requirements, thereby lowering costs and time-consumption.

5.2 MATERIALS AND METHODS

5.2.1 STUDY AREA

The study is based on the territory of four rural communities; Agua Hedionda, Ayutita, Chiquihuitlan and Zenzontla, in the state of Jalisco, Mexico. They are located in the center of one of the Early Action Area for REDD+ in Mexico (Fig. 5.1). These communities are characterized by SDTF; the remaining parts are dominated by rainfed seasonal cultivation or irrigated permanent plots. Their land areas and population densities vary markedly (Table 5.1): There is one residential area within the boundaries of Agua Hedionda, none in Ayutita, six in Chiquihuitlan and three in Zenzontla, as established in the Registro Agrario Nacional (RAN). The territory within the boundaries of the Zenzontla is characterized by a narrow valley bounded by undulating hills, while Agua Hedionda, Chiquihuitlan and Ayutita are characterized by undulating steep areas (Appendix 3; Fig. S1). Coefficients of variation in four topographic variables shows that Chiquihuitlan is the community with the greatest topographic variation, followed by Ayutita and Zenzontla, while Agua Hedionda is the least variable (Appendix 3; Table S1). The variation in topography enables the farmers to carry out different productive activities in different places (Morales-Barquero et al. 2015, Borrego and Skutsch 2014). Activities in the four communities are similar, but with some differences; the flat areas are used for permanent rainfed cultivation, the lower slopes and the hill brows are used for shifting cultivation, while the steeper areas provide poles and firewood and cattle may range free (Morales-Barquero et al., 2015). The use of forest resources in the hill slope areas such as firewood and fence posts vary among communities (Morales-Barquero et al., 2015). Shifting cultivation is much more practiced in Agua Hedionda than in the other three communities, due mainly to the fact that it is further an urban centre and has poor transportation facilities, so that off-farm employment opportunities are very limited.

FIGURE 5.1 Location of the four communities in the JIRA (EPSG projection: 32613-wgs84/utm zone 13N).

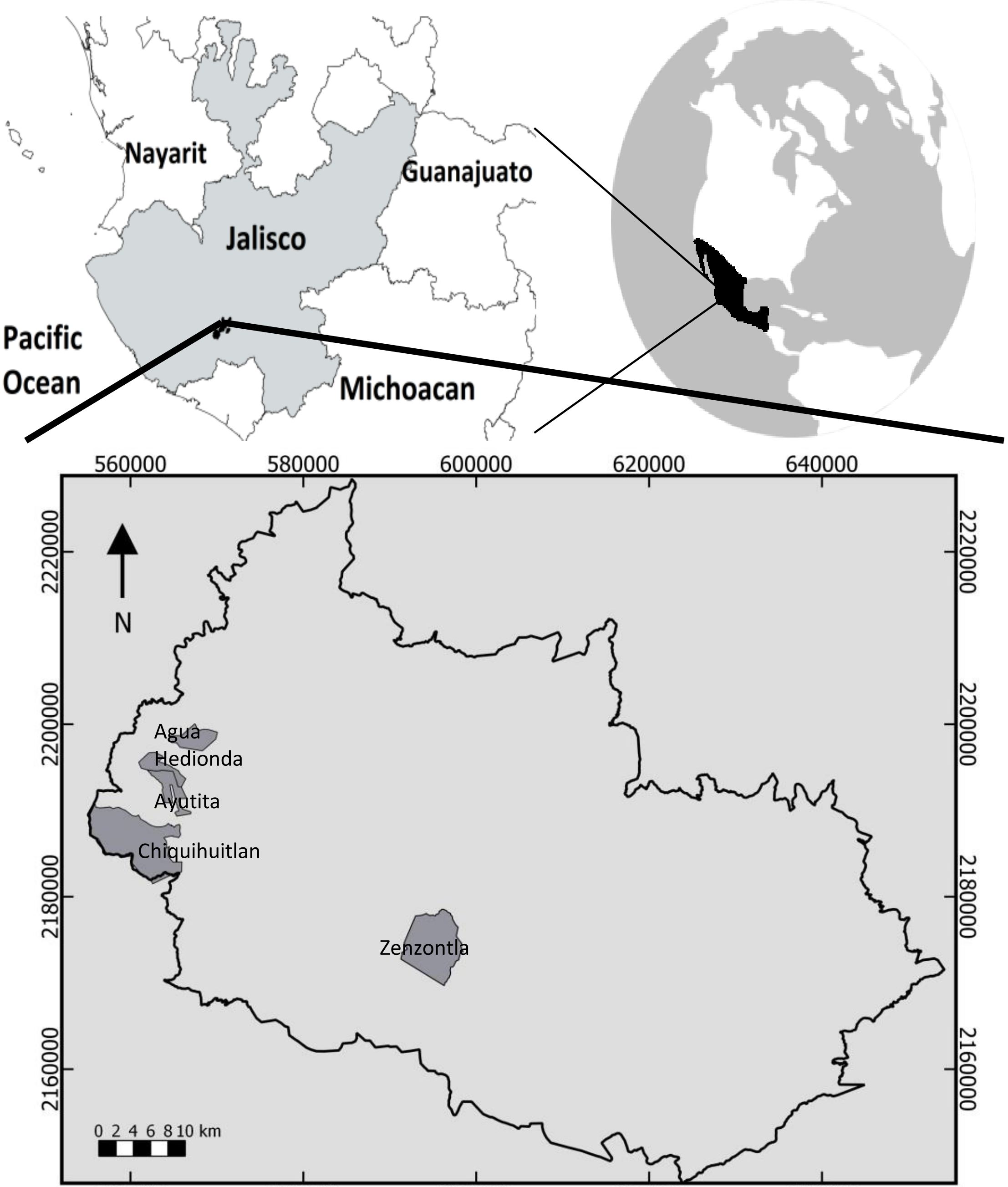

TABLE 5.1 Land areas and population densities for the four communities.

Community	**Area (km^2)**	**Density (inhabitants per km^2)**
Agua Hedionda	14.66	16.2
Ayutita	7.83	42.6
Chiquihuitlan	52.16	4.5
Zenxontla	40.32	9.5

5.2.2 DATA ON ABOVE GROUND BIOMASS (AGB)

To model the AGB of trees we used a subset of data from a detailed forest inventory performed in the JIRA area (Jardel et al. 2012). Data from 89 plots were available from these communities. The location of these sampling points was obtained in three steps: 1) points were uniformly spaced on a rectangular grid of 500 m, 2) points without SDTF coverage were then excluded from the sample and 3) sampling points were drawn randomly from the grid points. Sampling plot distribution was as follows; Agua Hedionda 15 plots, Ayutita with 14, Chiquihuitlan 20 and Zenzontla 40. At the selected grid points, a nested design was used with a circular plot of radius 12.62m, equivalent to 500m^2 and an inner plot of radius 4m, equivalent to 50m^2. In the smaller circle, all the stemmed individuals with diameter at breast height (DBH) >2.5 cm and<10 cm were recorded, while all individuals with DBH > 10 cm were recorded in the bigger circle. In this study only above ground biomass (AGB) data were used. For details see Jardel et al. (2012).

We made model selection using three metrics; mean logarithmic score (LS), Root Mean Square Error (RMSE) and error rate (ER). Furthermore we quantify explanatory variables elevation, slope, topographic wetness index (TWI) and tangential curvature (CTAN) from a Digital Elevation Model (Appendix 4: A1).

5.2.3 STATISTICAL ANALYSIS

First, the dataset was divided in training dataset (80% of the entire dataset) and validation dataset (the remaining 20%). Using the training dataset we modeled community spatially distributed AGB in the following way:

We performed my analysis using a Bayesian framework (BF). We assumed that the spatial distribution of AGB is determined by two components; a spatial autocorrelation and a strong environment influence; these were evaluated jointly using 15 models that incorporate topographic covariates as well as spatial components (Table 5.2). The BF uses prior information from previous comparable studies or from a subsample of the same study or from previous periods. In order to reduce the influence of subjectivity, prior information is incorporated in the Bayesian analysis in the form of distribution parameters of model estimates (Gelman et al. 2014). The purpose of the spatial component was to include the spatial distribution of AGB in the modeling process in order to increase the accuracy of estimates between sample locations, supported by the premise that the closer in the space the sampling points of AGB, the more similar the AGB values are likely to be (Webster and Oliver 2007). We used a Bayesian inference procedure using stationary restricted spatial regression (RSR) modeling approach and three different distribution families, following some of the procedures described in Blangiardo and Cameletti (2015) (Appendix 4: A2). This is a geostatistical procedure, which are not new and are widely used, for example in the mining industry, to identify the location of underground water supplies (Sarma 2009, Webster and Oliver 2007). We evaluated to what extent a forest inventory with a small number of samples can be used to obtain accurate spatially distributed predictions of AGB levels, based on physiographic features. To do this, we obtained model parameters for Agua Hedionda, Ayutita, Chiquihuitlan and Zenzontla communities. As we used a Bayesian approach, prior information and empirical data can be integrated into the analysis. We do not incorporate to the analysis any previous available information by using weakly informative prior distribution parameters, and let the data speak for themselves.

TABLE 5.2 Bayesian geostatistical models with the topographic covariates used. Twi, topographic wetness index; ctan, tangential curvature; slope; elevation above sea level in metres; ω, the spatial correlated random effect.

Model	Covariates
1	slope + ω
2	elevation + ω
3	twi + ω
4	ctan + ω
5	slope + elevation + ω
6	slope + TWI + ω
7	slope + CTAN + ω
8	elevation + TWI + ω
9	elevation + CTAN + ω
10	TWI + CTAN + ω
11	slope + elevation + TWI + ω
12	slope + elevation + CTAN + ω
13	slope + TWI + CTAN + ω
14	elevation + TWI + CTAN + ω
15	slope + elevation + TWI + CTAN + ω

The proportion of variance explained by the spatial correlated random effect u is calculated by comparing s_u^2 and σ_v^2. The former is the posterior marginal variance for the spatial correlated random effect, while the latter is the variance of the marginal unstructured effect. It is calculated in the following way (Blangiardo et al. 2013, Blangiardo and Cameletti 2015):

$$s_u^2/(s_u^2+\sigma_v^2)$$

5.2.4 MODEL SELECTION AND EVALUATION

The modeling procedure for Agua Hedionda, Ayutita and Chiquihuitlan was done with the Bayesian inference procedure (Appendix 4: A2) as described above. We used a selection procedure for the RSR models for the four communities, in two steps using three different metrics. Because the focus of this study was spatial prediction of the AGB, these metrics evaluate predictive performance. The first is the mean logarithmic score (LS), calculated as the negative log of the conditional predictive ordinate (CPO) which is a cross-validation leave-one-out procedure implemented on the training data set. This metric for predictive model selection has been used in other studies using R-INLA (Beguin et al. 2012). LS is asymptotically equivalent to the widely used Akaike Information Criterion (AIC) (Stone 1977). We evaluated whether the assumptions needed by CPO were violated and CPO were calculated manually when needed for those models that failed (Held et al. 2010, Blangiardo and Cameletti 2015). The second performance measurement of predictions used was the Root Mean Square Error (RMSE). This metric relates the error of predictions over the validation data set. This can be done because we obtained predictions of AGB using posterior distributions, which were projected on the space of the study area at a finite set of locations S ={*s1*,... ,*sn*}. The predictions of AGB generated by those posterior distributions could be contrasted against those of the validation data set through a measurement of error (Hooten and Hobbs 2015, Blangiardo and Cameletti 2015).

The last performance measurement metric was the relative root mean square error or error rate (ER), which is calculated by dividing the RMSE by the mean AGB of the validation data set and indicates in percentage the error of predicted AGB data. In all three measure (LS, RMSE and ER), the lower the metric, the better the predictive power of the model (Hooten and Hobbs 2015, Blangiardo and Cameletti 2015). The first step selects a group of candidate models from those performed with the covariates listed in Table 5.2 using the LS metric. The best performing model was selected from the group of candidate models in the second step using the RMSE and ER. Model evaluation was done using predictive performance measurements on the evaluation data set for every model.

5.3 RESULTS

The maps of predicted mean AGB and the standard deviation (SD) associated with those predictions result from the best model for each communities are shown in Fig. S4 (Appendix 3). Mean AGB varies between communities. Mean AGB predictions for Chiquihuitlan show the lowest variation, while Ayutita has the highest. The map of AGB prediction for Agua Hedionda shows that this community has the lowest values, while Ayutita has the highest values. The maps also show that there is a low standard SD for AGB distribution in the four communities. The SD of my predictions of AGB varies for every community. Chiquihuitlan has the lowest SD, ranging between 1.8 to 1.9, while Agua Hedionda has the largest, ranging from 1.5 to 2.8.

5.3.1 MODEL SELECTION

From the total of 48,960 models performed for the four communities, we selected 180 candidate models using the LS metric (Appendix 3; Table S1, S2, S3 and S4). The LS metric for the candidate models ranged from 49.35 to 1409.50, while the validation metric RMSE ranged from 1.55 to 67.27 Mg/ha, giving a performance error rate on the validation dataset of 6.44% and 101.43%. The DIC and WAIC for models of Agua Hedionda and Chiquihuitlan indicate that they are simple and fit the data well, but their values for Ayutita and Zenzontla were higher (Appendix 3; Table S1, S2, S3 and S4).

We found that 89 candidate models out of the 180 were statistically significant; 12 for Agua Hedionda, 36 for Ayutita, 30 for Chiquihuitlan and 11 for Zenzontla. 27 of these significant candidate models were gamma distributed, 28 normally distributed and 34 lognormally. The best performing AGB model for Agua Hedionda, Ayutita and Chiquihuitlan communities were lognormally distributed, while for Zenzontla the best model was gamma distributed (Appendix 3; Table S1, S2, S3 and S4).

A total of 92 different mesh dimensions were obtained in the 180 candidate models. The mesh with both inner and outer triangle dimensions of 2km was the most frequent in the candidate models, followed by the mesh with triangle dimensions of 0.4km in the inner area and 0.5km in the outer area. The mesh of the selected best performing model for each community, i.e. the one that best captures the spatial autocorrelation structure (lowest RMSE and ER) were those with inner triangle dimensions of 1 and 1.9km and outer triangle dimensions of 0.6 and 0.9km, for Agua Hedionda and Ayutita respectively; while for Chiquihuitlan and Zenzontla the mesh has inner triangle dimensions of 0.4 and 1.1km and outer triangle dimensions of 0.6 and 1.2km (Appendix 3; Table S1, S2, S3 and S4).

5.3.2 THE BEST PERFORMING AGB MODEL FOR THE FOUR COMMUNITIES

The best performing AGB model for Agua Hedionda includes the covariate ctan, for Ayutita community ctan and twi, while the model for Chiquihuitlan includes slope and the model for Zenzontla, ctan. We found that the spatial random effect ($_{\omega}$) was statistically significant for the four communities (Table 5.3). The proportion of spatial variance explained by the spatial auto-correlated random effect for each one of the four models was 99%, which is higher than the variance of the non-spatially structured component (the residual variance) (Table 5.3). This suggests that the highest source of the variation for AGB was related to the spatial component of the topographic covariates. These spatial effects were higher for Agua Hedionda, Ayutita, Zenzontla than for Chiquihuitlan. This indicates that the spatial structure of topographic features within the territory of the four communities controls the spatial patterns of AGB. Overall we found two patterns of response of AGB along the spatial gradients of topographical configurations of slope, tangential curvature and topographic wetness index. The first patterns of response of AGB was found at Agua Hedionda, with a positive relationship between tangential curvatures and AGB; this indicates that AGB was maximized at higher tangential curvatures, which indicates convex sites, conversely the lower values of AGB were found at lower tangential curvature values (concave sites) (Table 5.3). The second one was found in Ayutita, Chiquihuitlan and Zenzontla communities. The pattern for these communities was negative, with lower levels of AGB at higher values of tangential curvature, topographic wetness index and slope (Table 5.3). The posterior mean of the range of the spatial effect for the four communities ranged from 0.82 to 1.05 km (Table 5.3), which would suggests that AGB is influenced by underlying environmental process that operates on a scale of around 1 km.

5.3.3 MODEL PERFORMANCE

The lower RMSE were for Chiquihuitlan and Agua Hedionda; 3.98 and 7.97 Mgha, respectively, followed by Zenzontla with 14.58 Mg/ha and Ayutita with 21.62 Mg/ha (Table 5.4). These RMSEs mean that the performance error rate on the validation dataset of the models were of 33% for Agua Hedionda and Ayutita, 35% for Zenzontla and 21% for Chiquihuitlan community (Table 5.4).

TABLE 5.3 Summary of posterior estimates and their associated statistics from the selected Bayesian geostatistical model for AGB estimates for the four communities. SD; standard deviation; CI 95%= 95% credible interval.

	Agua Hedionda		**Ayutita**		**Chiquihuitlan**		**Zenzontla**	
Term	Mean(SD)	CI 95%	Mean(SD)	CI 95%	Mean(SD)	CI 95%	Mean(SD)	CI 95%
Intercept	**2.95(0.003)**	2.94–2.95	**5.34(0.02)**	5.29–5.38	**3.5988(0.0124)**	3.5728–3.6248	**3.61(0.02)**	3.57–3.66
Slope	NA	NA	NA	NA	-0.0128(0.0003)	-0.0134–-0.0123	NA	NA
ctan	**104.64(0.506)**	103.59–105.68	**-24.25(0.65)**	-25.59–22.91	NA	NA	**-0.08(0.02)**	-0.13 – -0.03
twi	NA	NA	-0.54(0.01)	-0.55 – -0.53	NA	NA	NA	NA
$\sigma^2{}_{\epsilon}$	**0.0001(0.0003)**	0.00001–0.00078	**0.0002(0.0003)**	0.00001–0.00079	**0.0001(0.0003)**	0.00001–0.0007	**0.014(0.012)**	0.003–0.046
$\sigma^2{}_{\omega}$	**0.67(0.31)** [99%]	0.27–1.48	**0.75(0.39)** [99%]	0.28–1.80	**0.18(0.09)** [99%]	0.049–0.42	**0.63(0.16)** [97%]	0.40–1.02
ρ(km)	**0.94(0.33)**	0.43–1.72	**0.91(0.35)**	0.36–1.74	**1.05(1.06)**	0.18–3.93	**0.82(0.21)**	0.45–1.27

Notes: $\sigma^2{}_{\omega}$, variance of the spatial correlated random effect; $\sigma^2{}_{\varepsilon}$, the noise variance in the observations (the residual variance); *ρ,* practical range (the distance at which autocorrelation equals 0.1). In brackets in the line of $\sigma^2{}_{\omega}$, the proportion of variance explained by the spatially structured component. Bold values are statistically significant at the 95% level. NA, not applicable

TABLE 5.4 Bayesian geostatistical model performance parameters for of Agua Hedionda, Ayutita and Chiquihuitlan Zenzontla communities

	RMSE (Mg/ha)	Error rate (%)	Range (Mg/ha)	DIC	LS	WAIC
Agua Hedionda	7.97	33.20	13.81—18.31	2.60	52.19	0.58
Ayutita	21.62	32.59	39.06—65.24	19.50	54.08	18.23
Chiquihuitlan	3.98	20.79	19.81—20.94	4.27	60.69	1.52
Zenzontla	14.58	35.42	30.47—68.71	185.12	122.14	181.69

Notes: RMSE, root-mean-square error; error rate, relative root-mean-square error (error rates); range, range of predicted AGB values; DIC, deviance information criterion; LS, mean logarithmic score of CPO; WAIC, Watanabe-Akaike information criterion.

5.4 DISCUSSION

The goal of this study was to assess to what extent four topographic variables, data on which can be derived from simple contour maps, could be used to ´predict´ levels of AGB within four communities. We highlight two findings. First, the Bayesian geostatistical approaches used in this study predicted AGB values with an error rate of 20% (a mean difference of 3.98 Mg/ha) for Chiquihuitlan and in the other cases; 33% for Agua Hedionda, 35% for Zenzontla and 32% for Ayutita; in other words, the accuracy of my model predictions with respect to observed AGB was between 80% and 65%. Second, we found that the configuration of local topography has a strong effect on AGB levels. The topographical configuration of slope was related to a positive effect on AGB, while tangential curvature and topographic wetness index were related to a negative effect, which is to say that AGB follows a gradient along the hillslope. We discuss these two points in more detail below.

We used an out-of-sample model performance evaluation strategy to evaluate model performance. This means that my full dataset was split into a training dataset which we used to perform the models and a completely independent dataset to evaluate the models´ performance in predicting AGB. My prediction error rates are from 20% to 35%, which fall well within the range of accuracy of those in many studies that have estimated AGB using RS methods (Saatchi et al. 2011, Mitchard 2014). For example, Mitchard (2015) analyzed the information of 23 studies and estimated that their relative error rates range from 19% to 53%. These authors also found that when analyzing the data from those 23 studies the error (over- or under-estimates) may be five times higher than those reported by the studies themselves (Mitchard 2015). These findings indicate that my modelling method results in accuracy levels which are comparable with the performance of AGB estimates based on RS. We suggest therefore that RS techniques, which involve considerable methodological complexity, may not be the best option for project level AGB predictions. Cost of technology and expertise, signal saturation issues, modelling procedures, pixel sizes, temporal coverage of imaginary, errors in geo-location and different sources of RS and plot-level AGB data, are often mentioned as drawbacks in the use of RS for AGB estimation (Mitchard 2015, Wells et al. 2017, Rodríguez-Veiga et al. 2017).

5.4.1 Explaining the error levels and improving on them

The reasons why the RMSE between predicted and observed ABG is not perfect may be related to: a) other physiographic variables not considered and b) human uses of forest. The former is related to model inadequacy, due to the over-simplifications in modelling of such complex spatial variability of AGB. The latter, which we believe is playing a key role, results from the fact that human uses change the natural ABG levels and these human uses are not distributed evenly over the territory, and in addition, the intensity of human uses are different in these settlements. It is not surprising that Chiquihuitlan, with the lowest community area to population ratio (4.5 people/km^2), has the best matching of AGB to topographic features, since human activities would be expected to have an overall lower average effect. However, population density is not the only factor in the balance, since although human uses may have some relation to topography (e.g. clearing for agriculture tends to occur on the flatter areas), the correlation is not perfect and the areas utilized cannot easily be identified from maps in the way the physiographic variables are. My study showed, however, that *despite* the unmeasured impact of human use, the accuracy of my model predictions with respect to observed AGB in my case studies was between 20 and 65%.

We believe that my error rates could be reduced markedly by stratification of each of the study areas by human uses, thereby lowering sample variation. Intensive shifting cultivation, light shifting cultivation, free grazing and extraction of forest resources (firewood and poles) could be identified, for example using a participatory community mapping exercise, as input data for the modeling.

5.4.2 The significance of tangential curvature in determining AGB levels

We found, as expected, that configuration of local topography has a strong effect on AGB levels. This configuration involves variables that affect the flow and accumulation of water and the removal and deposition of soil nutrients at different points along the catena (Moore et al. 1991, Warrick 2001, Rodríguez-Iturbe and Porporato 2004, Bachmair and Weiler 2011), which in turn result in variation in AGB (Shen et al. 2014). This is particularly relevant for SDTF, where water availability is the factor which most limits growth (Maass 1995, Maass and Burgos 2011, Brienen et al. 2010). In these systems, species spend most of the year in stressful conditions with high temperatures, nutrient shortage and very little water, but in the rainy season a number of processes are sequentially triggered to create ideal conditions for growth (Maass and Burgos 2011, Brienen et al. 2010). Pulses of water availability promote release of nutrients that have accumulated during the dry season; and water drives nutrient redistribution in the soil (Jaramillo et al. 2011, Maass and Burgos 2011). In other words, it is the coupled pattern of water and nutrient availability that is the key to determining variations in growth patterns along the catena (Maass and Burgos 2011, Brienen et al. 2010).

In this study, the effect of water flow and its convergence and divergence over the surface was measured using tangential curvature and slope, while the effect of topography in modeling the water accumulation process was measured using topographic wetness index (Wilson and Gallant 2000). These variables configure the gradients in topography in such a way that negative tangential curvature indicates concave topography, which is frequently present at the bottom of the slope, but also in localized hollows that provide sheltered sites, while tangential curvature implies convex topography which would be found mainly in exposed sites near the top of the catena (the brow of the hill) (Wilson and Gallant 2000). My results point to the importance of tangential curvature in determining AGB levels and can be compared with those of Yauakura et al. (1996) and Xu et al. (2015). We found that AGB levels are higher in concave locations and lower in convex locations in Ayutita, Chiquihuitlan and Zenzontla. This can be explained by the coupled pattern of water flow and nutrient deposition as described above, which enable growth to continue for longer during the dry season than at other positions along the catena since there is more moisture and fewer nutrition restrictions in these locations even if soil is shallow (Bachmair and Weiler 2011).

The fact that the opposite was the case for Agua Hedionda is therefore interesting, and needs an alternative explanation. In physiographic and ecological terms, there is little to distinguish Agua Hedionda from the other communities we studied, but AGB within Agua Hedionda community shows a strong and positive reverse relationship with tangential curvature, with greater AGB densities in convex sites. This result seems similar to those of McEwan et al. (2011), Xu et al. (2015) and Shen et al. (2016), but in these studies water is not the main limiting factor, as it is in SDTF; their ecological conditions are quite different. We believe that the inversion of the expected pattern as found in Agua Hedionda relates to the human uses of the SDTF in this community. Although the population density of Agua Hedionda is not the highest among the cases studied, shifting cultivation is practiced to a much greater extent here compared to the other communities. This is because the community is more isolated than the other communities, where families depend to a large extent on employment in the nearby city of Autlan. Agua Hedionda is not only further from the city, but has only dirt roads and no transportation service. As a result, families depend much more on their own local resources for subsistence. Shifting cultivation is overwhelmingly concentrated on the lower hill slopes, which include the concave depressions at the base of the catena, and this activity depresses the natural biomass levels in these zones enormously. This finding again demonstrates the importance of human activity in determining AGB levels, but it also suggests that the methodology we have employed may have practical, applied uses beyond mere scientific interest, as we discuss in the following section.

5.4.3 Implication for the use of the model in the design of REDD+ forest enhancement projects

Reducing Emissions from Deforestation and forest Degradation (REDD+) is an international policy which has been adopted in the Paris Agreement of the United Nations Framework Convention on Climate Change (UNFCCC). It includes five elements: (1) reducing emissions from deforestation, (2) reducing emissions from forest degradation, (3) conservation of forest carbon stocks; (4) sustainable management of forests and (5) enhancement of forest carbon stocks. Although there is some confusion in definitions associated with REDD+ projects (Joseph et al. 2013), the majority focus on reducing deforestation or on reforestation/afforestation (Kirby and Potvin 2007, Lawlor et al. 2013, Holmes et al. 2016, Holmes et al. 2017), with some also incorporating conservation and sustainable forest management. Very few projects are set up to credit reductions in degradation and in its mirror image, forest enhancement (Herold and Skutsch 2011, Joseph et al. 2013, Fischer et al. 2016), which refers to increases in carbon stocks in forest that remains forest. Forest carbon stock enhancement activities also imply reversal of degradation, usually by removing or better managing the activities which cause the forest to degrade; they promote a net carbon sink through increases in carbon stocks, in forest areas that remain forest, through natural regeneration. There is considerable interest in this issue among organizations that are promoting forestry in the voluntary carbon sector, such as Climate Action Reserve (John Nickerson, personal communication 21.3.2016), as well as those supporting national approaches to REDD+ such as FAO and CLUA (personal communication, Donna Lee, 1.8.2017), because it is increasingly recognized that at the community level, there may be more opportunities in degradation and enhancement than in reducing deforestation.

Clearly, a number of conditions are needed to set up such projects, including the creation of incentive schemes which focus on carbon gained through natural forest regeneration, and capacity building (CONAFOR 2017). A technical difficulty is that annual gains in AGB per hectare tend to be low; for SDTF, they are between one to five Mg/ha/year (IPCC 2006, Mora et al. 2017, Rozendaal et al. 2017), which means that estimates of AGB increases will have to be extremely accurate. What my modeling procedure could contribute in this context is spatial focus, in terms of where within the community territory REDD+ enhancement efforts could best be targeted. Taking data from a few forest sampling plots to train the model and evaluate its performance, the most suitable sites within the community may be identified, that is, those where AGB is well below its potential as determined by the modeling procedure. This should greatly increase the efficiency of the interventions subsequently undertaken.

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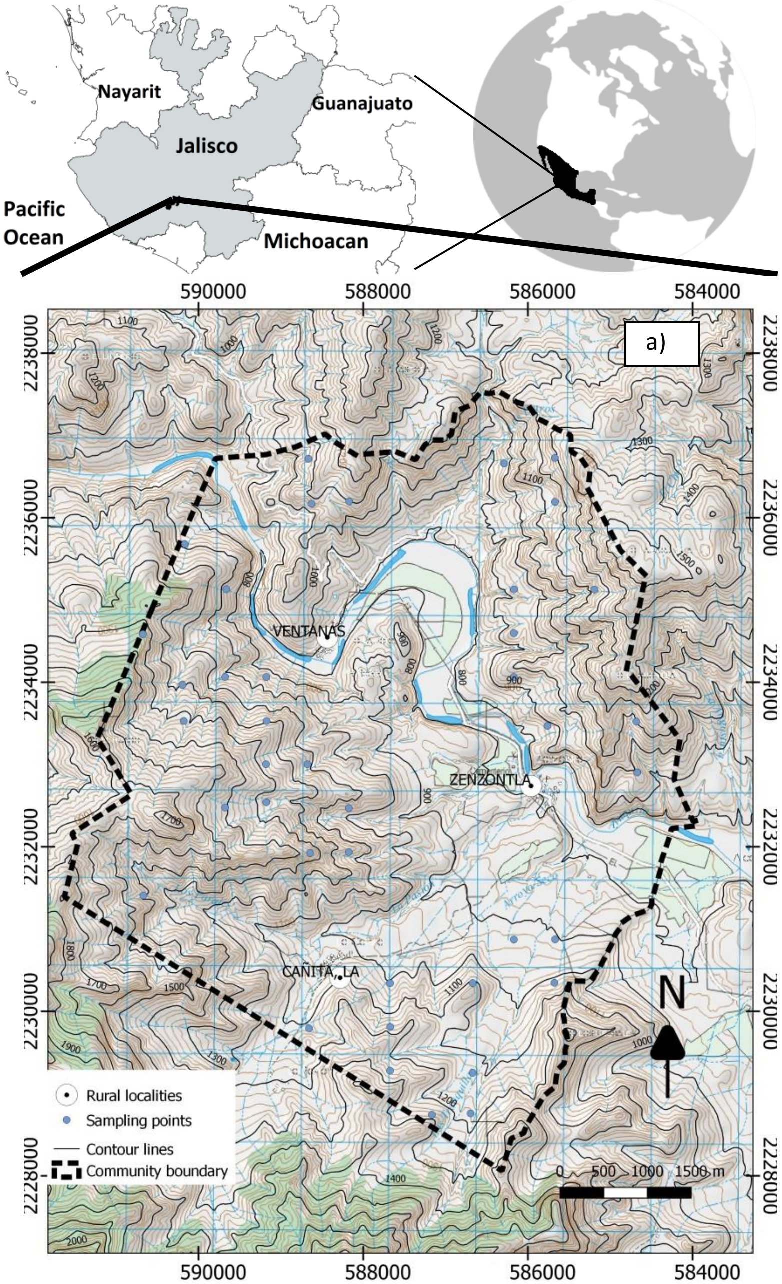
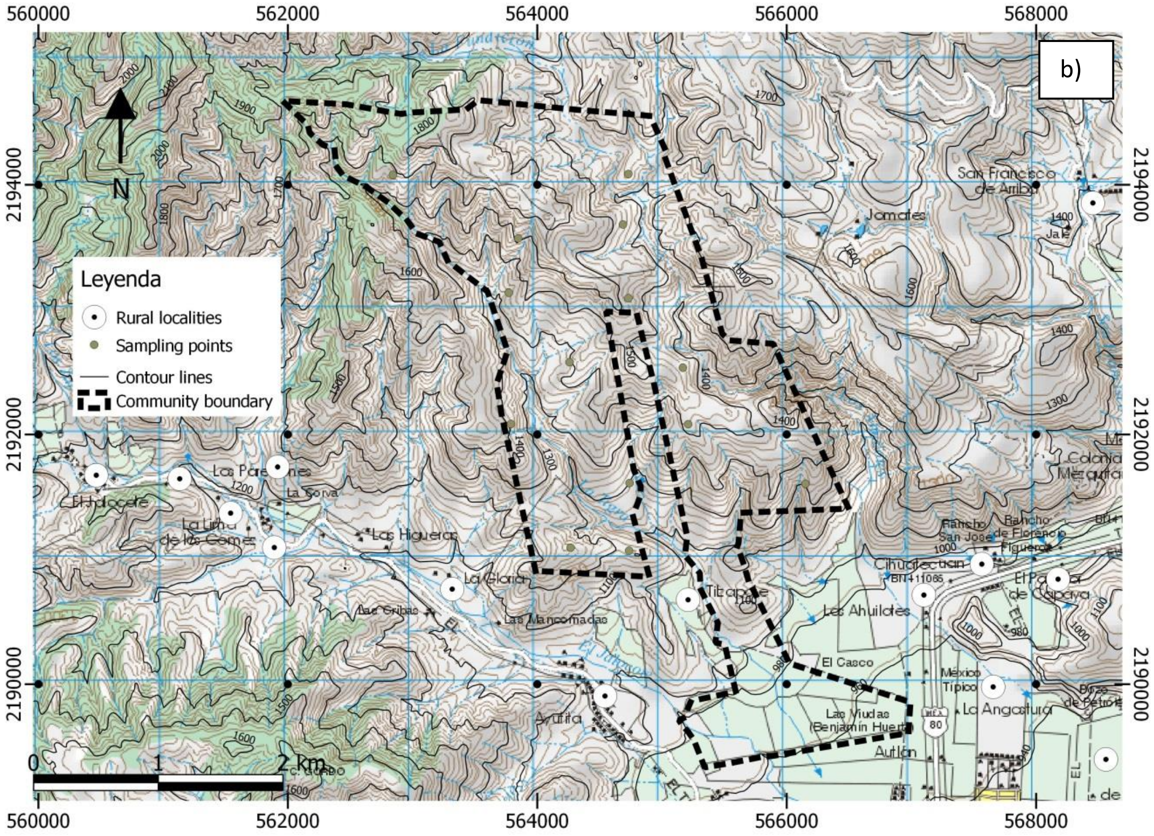
APPENDIX 3

Figure S1 Topographic map of the four communities a) Zenzontla, b) Ayutita, c) Agua Hedionda and d) Chiquihuitlan. Source: INEGI (2001) (EPSG projection: 32613-wgs84/utm zone 13N).

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Rural localities
Sampling points
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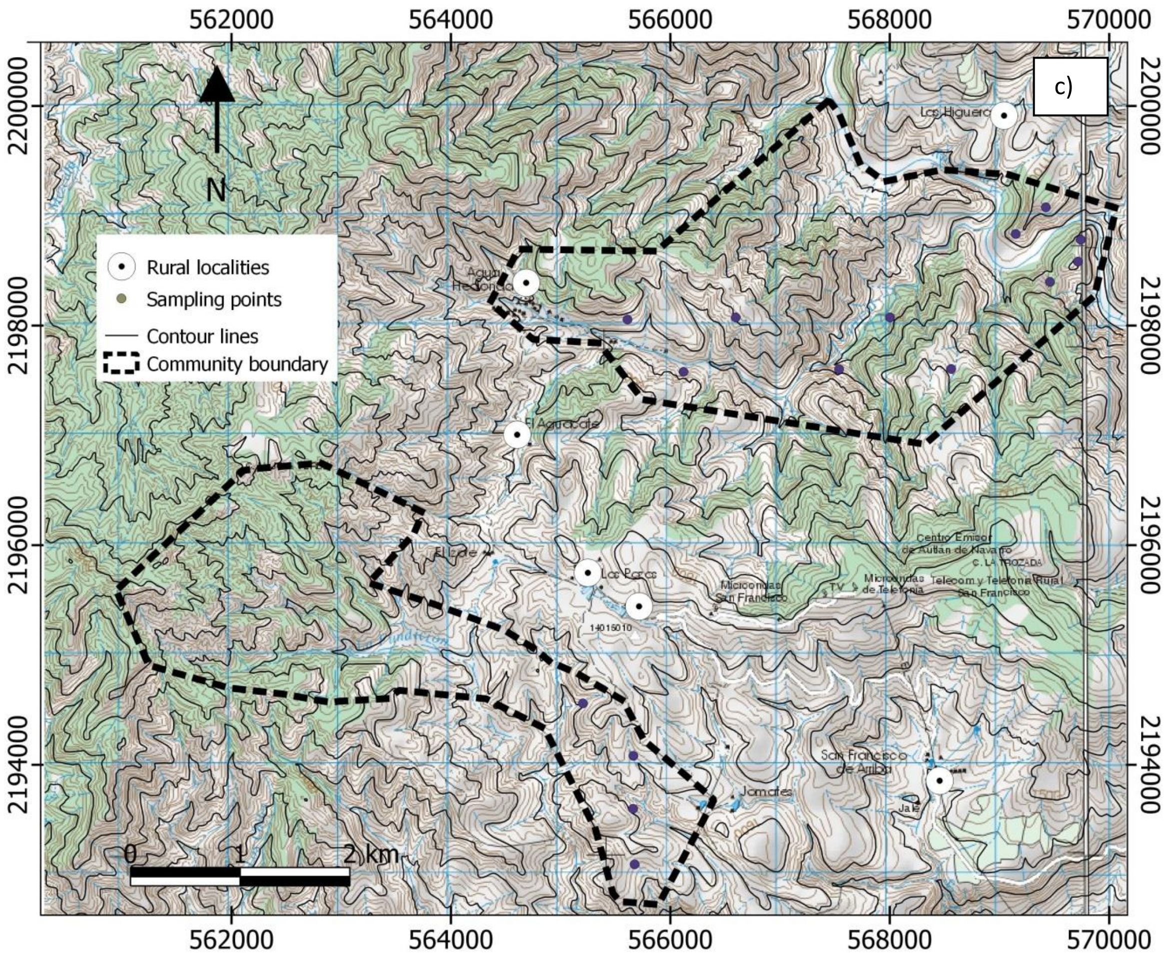
Jomates
Jala
Colonia Mezquitan
Rancho San José
Rancho de Florencio Figueroa
Cihuatectlan
El Palmar de Capaya
Tibapane
Los Ahuilotes
El Casco
México Típico
La Angostura
Las Viudas (Benjamín Huerta)
Autlán
El Chacate
Los Paredones
La Sorva
La Lima de los Gómez
Las Higueras
La Gloria
Las Gribas
Las Mancomadas
Aurita
80



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El Aguacate
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Microondas de Telefonia
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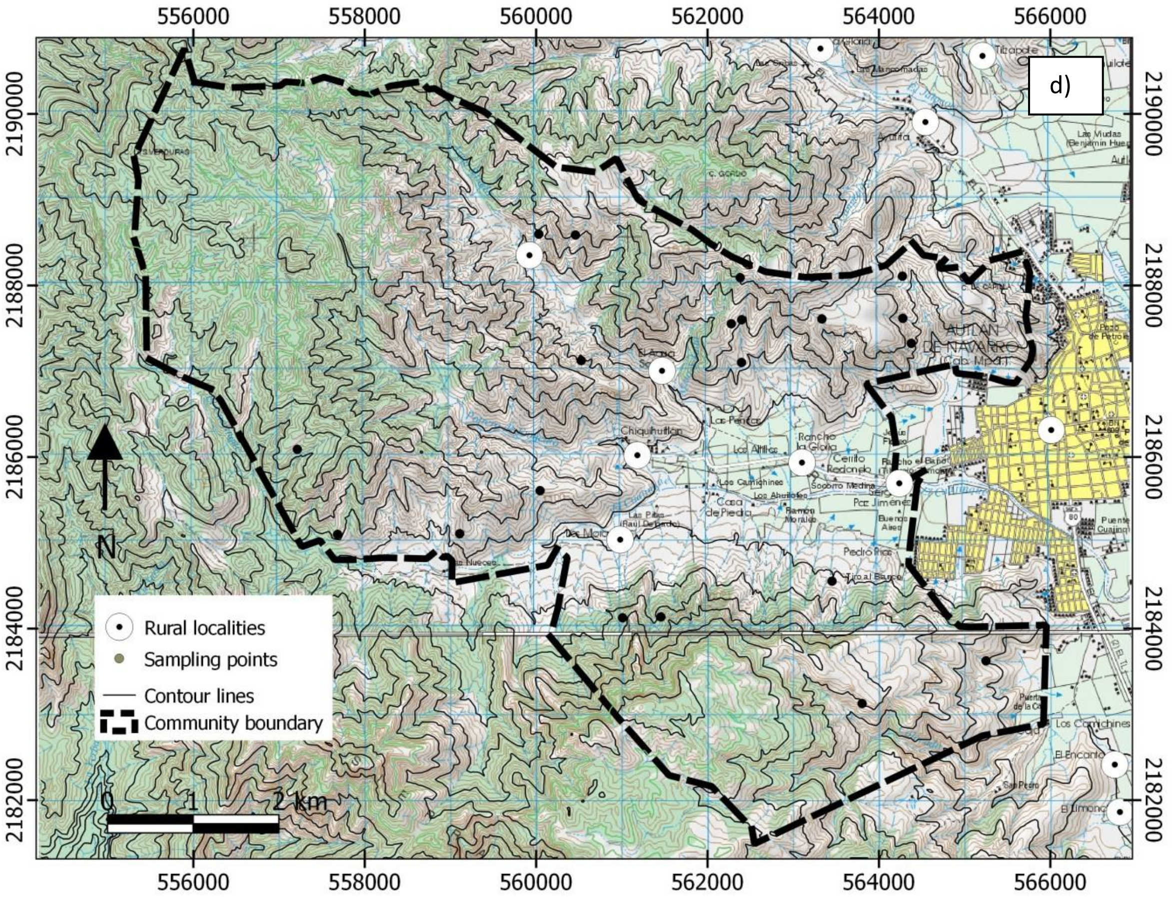

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INEGI (Instituto Nacional de Estadística, Geografía e Informática). (2001). El Chante E13B23. Topographic Map 1:50,000 scale.

Table S1 Coefficients of variation for topographic variables within the four communities and . Twi, wetness index; ctan, tangential curvature; altitude, elevation above sea level and slope.

	Agua Hedionda	Ayutita	Chiquihuitlan	Zenzontla
		TOPOGRAPHY		
twi	39.53	23.86	37.72	33.55
ctan	2,516.68	3,389.21	3,246.06	4,169.22
slope	24.08	29.94	20.81	43.78
elevation	18.25	12.02	7.89	14.40

Figure S2 Overlay of meshes used for the SPDE model for Zenzontla community. Each mesh uses different triangle edge length in the inner and outer area: a) 0.4, 0.5 km, b) 1.1, 1.7 km, c) 0.4, 2.0 km and d) 2.0, 2.0 km. Black circles, location of the sampling points; thicker black line, boundary of rural community.

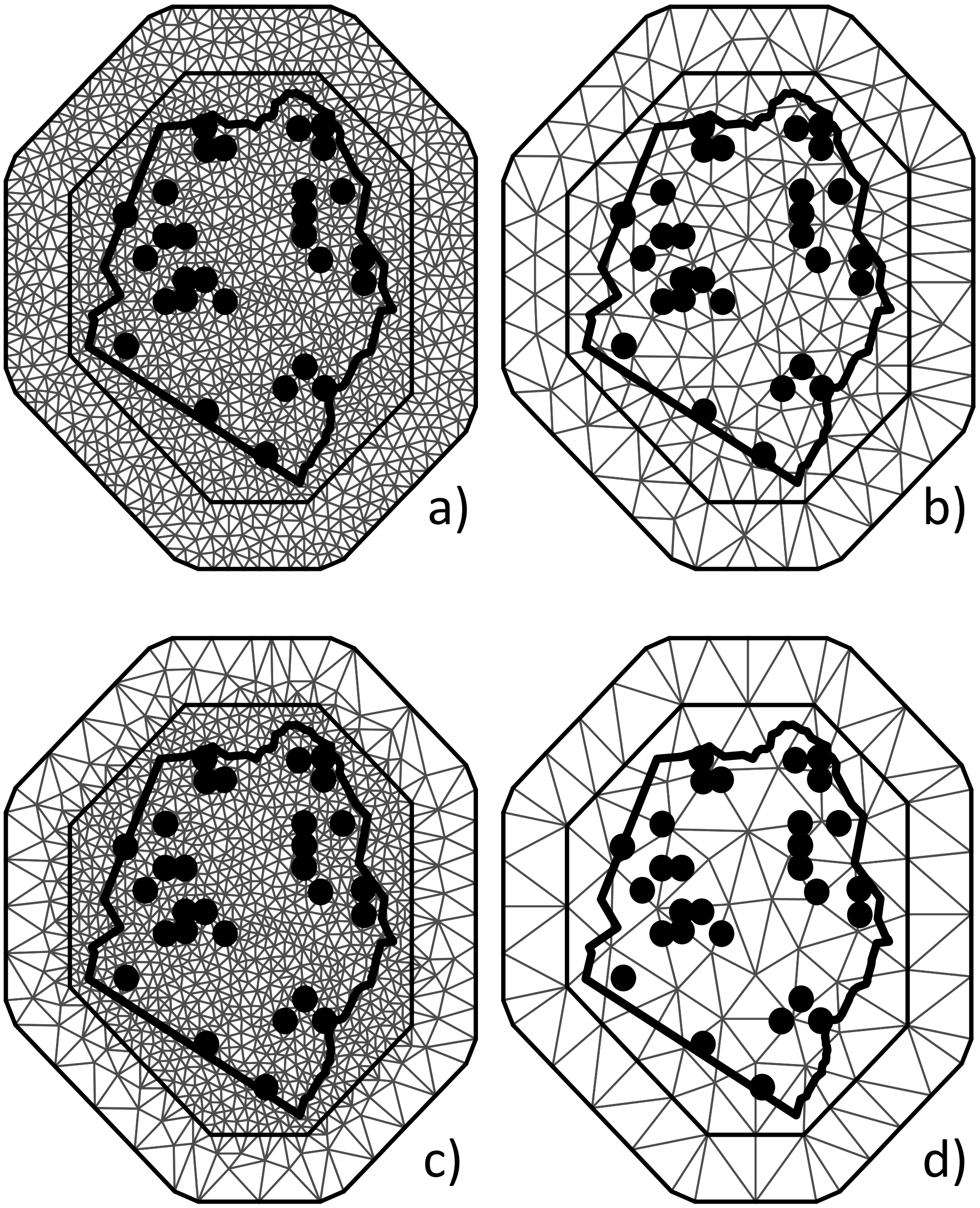


Figure S3. Overlay of meshes used for the SPDE model for a) Agua Hediondab) Ayutita and Chiquihuitlan. The same triangle edge length in the inner and outer area was used in each mesh:1.1, 1.7 km. Black circles, location of the sampling points; blue line, boundary of rural community.

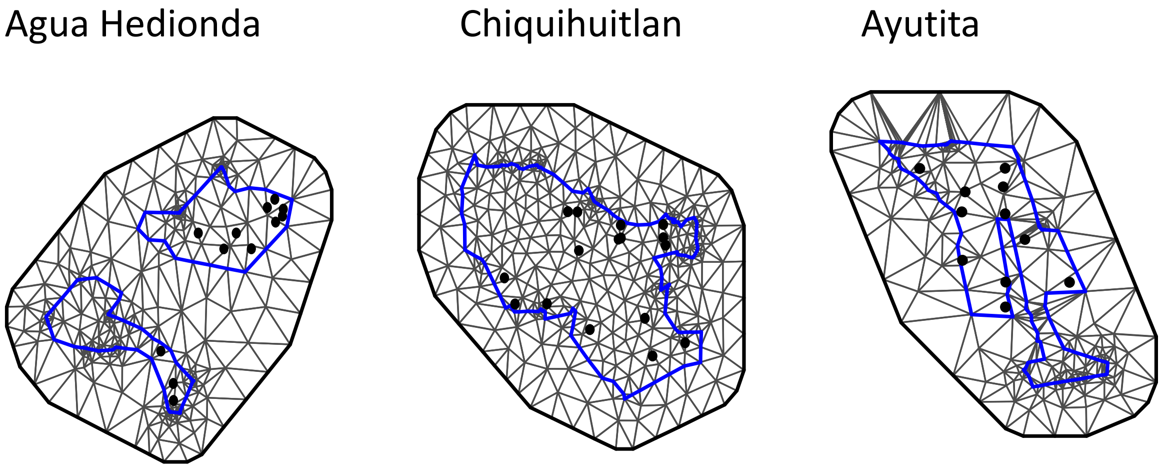


Table S1 Candidate models of AGB for the two probability distributions under RSR approach for Agua Hedionda community. Inner, largest allowed triangle edge length (in km) for tringles in the inner area of the SPDE model; Outer, largest allowed triangle edge length (in km) for tringles in the outer area of the SPDE model; RMSE, Root Mean Square Error (Mg/ha); DIC, deviance information criterion; LS, mean logarithmic score of CPO; WAIC, Watanabe-Akaike information criterion; *, evaluated parameter lies in the 95% posterior Bayesian credible intervals; NS, evaluated parameter does not lies in the 95% posterior Bayesian credible intervals. Best performimg AGB for this community model is shown in bold.

Model	Inner	Outer	RMSE	ER	DIC	LS	WAIC	Significance
				Gaussian				
1	0.9	1.5	3.95	16.45	114.97	57.86	115.14	NS
2	1	1.8	4.54	18.90	116.60	58.73	117.06	NS
3	1.3	0.9	1.55	6.44	114.70	61.31	115.68	NS
4	0.9	1	3.17	13.22	116.84	58.23	116.34	NS
5	1.2	1.3	4.89	20.36	116.16	58.86	116.83	NS
6	1.9	1.9	3.36	13.99	114.38	59.50	114.72	NS
7	0.5	0.8	3.58	14.92	114.71	57.78	114.99	NS
8	1.3	1.9	6.97	29.05	113.90	59.38	114.58	NS
9	1.5	1.1	3.79	15.79	117.21	58.30	116.34	NS
10	1.3	1.3	1.55	23.23	115.51	60.38	115.99	NS
11	0.7	1.1	5.92	24.66	115.38	60.10	116.00	NS
12	0.7	1.7	4.34	18.08	116.08	58.85	116.85	NS
13	0.7	1.8	2.39	9.96	114.73	59.60	115.04	NS
14	1.2	2	6.84	28.49	113.85	59.41	114.62	NS
15	1	1.1	5.64	23.50	115.20	60.09	116.01	NS
				Gamma				
1	1.9	2	21.08	87.84	110.60	57.13	110.88	*
2	0.4	0.5	21.33	88.89	71.38	67.48	70.10	*
3	0.4	0.5	21.12	88.01	72.61	70.12	71.56	*
4	0.4	0.5	21.30	88.75	72.29	53.65	71.67	*
5	1.9	2	21.18	88.25	111.63	59.12	112.65	NS
6	0.4	0.5	21.25	88.53	71.32	66.44	69.58	*
7	0.4	0.5	21.32	88.82	72.35	54.72	71.44	NS
8	0.4	0.5	21.42	89.24	71.13	70.40	69.87	*
9	0.4	0.5	21.32	88.85	72.37	56.17	71.51	NS

10	0.4	0.5	21.30	88.76	72.42	56.47	71.51	NS
11	0.4	0.5	21.38	89.08	71.16	72.76	69.72	*
12	0.4	0.5	21.31	88.81	72.93	56.99	71.91	NS
13	0.4	0.5	21.32	88.82	72.48	58.00	71.21	NS
14	0.4	0.5	21.34	88.91	72.83	59.52	71.80	NS
15	0.4	0.5	21.33	88.86	72.86	59.97	71.63	NS
LogNormal								
1	0.9	1.8	8.09	33.69	112.24	56.72	112.03	NS
	0.4	0.6	7.97	33.22	2.92	92.29	0.91	
2	1.4	1.4	9.03	37.61	114.01	57.86	114.63	NS
3	1.7	0.8	7.15	29.80	111.71	61.48	112.93	NS
4	**1**	**0.6**	**7.97**	**33.20**	**2.60**	**52.19**	**0.58**	*****
5	1	0.9	8.72	36.33	113.76	58.19	114.23	NS
6	1.2	1	8.41	35.05	111.80	61.98	112.02	NS
7	1.4	2	8.74	36.43	96.53	54.90	97.37	NS
8	1.4	1.4	10.49	43.70	112.41	61.06	113.39	NS
9	1	0.5	8.50	35.42	2.39	54.75	0.21	*
10	0.4	0.7	8.30	34.59	2.15	55.65	0.05	*
11	1.9	1.6	10.40	43.35	112.85	63.59	113.88	NS
12	1.9	1	8.92	37.15	91.45	55.46	92.54	NS
13	0.9	0.5	8.57	35.71	2.46	56.76	0.33	*
14	1	0.5	8.70	36.25	2.42	53.56	0.25	*
15	1.9	1	9.07	37.78	92.53	60.07	93.71	NS

Table S2 Candidate models of AGB for the two probability distributions under RSR approach for Ayutita community. Inner, largest allowed triangle edge length (in km) for tringles in the inner area of the SPDE model; Outer, largest allowed triangle edge length (in km) for tringles in the outer area of the SPDE model; RMSE, Root Mean Square Error (Mg/ha); ER, Error Rate; DIC, deviance information criterion; LS, mean logarithmic score of CPO; WAIC, Watanabe-Akaike information criterion; *, evaluated parameter lies in the 95% posterior Bayesian credible intervals; NS, evaluated parameter does not lies in the 95% posterior Bayesian credible intervals. Best performimg AGB for this community model is shown in bold.

Model	**Inner**	**Outer**	**RMSE**	**ER**	**DIC**	**LS**	**WAIC**	**Significance**
				Gaussian				
1	1.7	0.5	33.45	50.43	-64.33	220.52	-66.40	*
2	1	1.2	31.20	47.04	-63.97	898.20	-65.47	*
3	1	1.6	22.21	33.48	-64.35	1409.50	-66.54	*
4	1.4	1.6	28.31	42.68	-64.11	241.69	-65.33	*
5	1.2	1.8	31.48	47.46	-64.68	678.87	-66.76	*
6	0.6	1.7	36.02	54.32	92.11	49.35	91.38	*
7	0.6	0.5	37.92	57.17	101.045	51.021	101.84	NS
8	0.5	0.6	32.70	49.30	-64.12	783.39	-65.97	*
9	1.4	1.6	25.91	39.07	-63.27	249.04	-65.85	*
10	0.6	1.8	27.96	44.07	98.91	51.03	99.54	NS
11	1.2	0.8	28.52	43.00	-64.43	974.05	-66.62	*
12	1.2	1	30.62	46.17	-63.80	318.36	-65.40	*
13	1.2	1.7	33.79	50.94	-63.45	144.14	-64.89	*
14	0.6	1.8	28.60	43.11	101.3	50.759	100.16	NS
15	1.2	1.2	30.42	45.87	-63.44	278.06	-65.00	*
				Gamma				
1	1.5	0.6	67.10	101.18	61.50	57.63	58.45	*
2	0.5	0.8	67.25	101.39	78.70	56.39	79.58	*
3	1.7	1	66.99	101.01	78.65	56.34	79.15	*
4	0.5	0.6	67.13	101.21	77.38	58.31	76.67	*
5	0.7	1.3	67.23	101.36	80.13	55.02	81.82	*
6	1.8	0.9	67.00	101.01	77.08	50.71	76.44	*
7	2	0.9	67.20	101.33	78.11	55.33	78.29	*
8	1.8	1	67.13	101.21	79.04	58.83	79.46	NS
9	1.8	0.6	67.25	101.40	77.88	56.77	77.70	NS

10	1.7	1	66.91	100.89	77.82	55.82	77.54	*
11	1	2	67.08	101.14	79.95	51.97	80.26	*
12	1.7	0.5	67.27	101.43	78.31	56.31	77.85	*
13	0.5	2	66.99	101.00	76.47	50.98	73.50	NS
14	1.9	0.6	67.11	101.19	77.51	56.10	76.64	NS
15	1.9	0.9	67.05	101.10	77.42	53.91	76.51	NS
				LogNormal				
1	0.4	0.5	37.27	56.19	18.44	97.21	16.33	*
2	1.4	1.6	34.61	52.18	18.99	57.88	17.24	*
3	1.8	0.6	27.80	41.91	18.43	55.46	16.55	*
4	1.5	0.5	33.17	50.01	18.43	55.75	16.39	*
5	1.2	1.3	34.77	52.42	18.89	58.40	16.54	*
6	2	1.9	36.29	54.71	19.94	52.84	17.73	*
7	1.9	1.7	33.52	50.53	19.34	54.94	17.68	*
8	1.8	0.5	34.47	51.97	18.672	63.709	16.839	*
9	1.3	1	34.95	52.69	18.37	55.62	16.60	*
10	**1.9**	**0.9**	**21.62**	**32.59**	**19.50**	**54.08**	**18.23**	*****
11	0.5	1.5	34.45	51.95	18.79	54.73	16.87	*
12	1	1.4	33.77	50.91	18.81	56.89	16.75	*
13	1.8	1.6	35.99	54.27	18.76	53.35	16.98	NS
14	2	0.9	29.46	44.42	18.70	53.11	17.10	*
15	1.7	1.6	31.47	47.44	20.30	54.73	18.01	*

Table S3 Candidate models of AGB for the two probability distributions under RSR approach for Chiquihuitlan community. Inner, largest allowed triangle edge length (in km) for tringles in the inner area of the SPDE model; Outer, largest allowed triangle edge length (in km) for tringles in the outer area of the SPDE model; RMSE, Root Mean Square Error (Mg/ha); DIC, deviance information criterion; LS, mean logarithmic score of CPO; WAIC, Watanabe-Akaike information criterion; *, evaluated parameter lies in the 95% posterior Bayesian credible intervals; NS, evaluated parameter does not lies in the 95% posterior Bayesian credible intervals. Best performimg AGB for this community model is shown in bold.

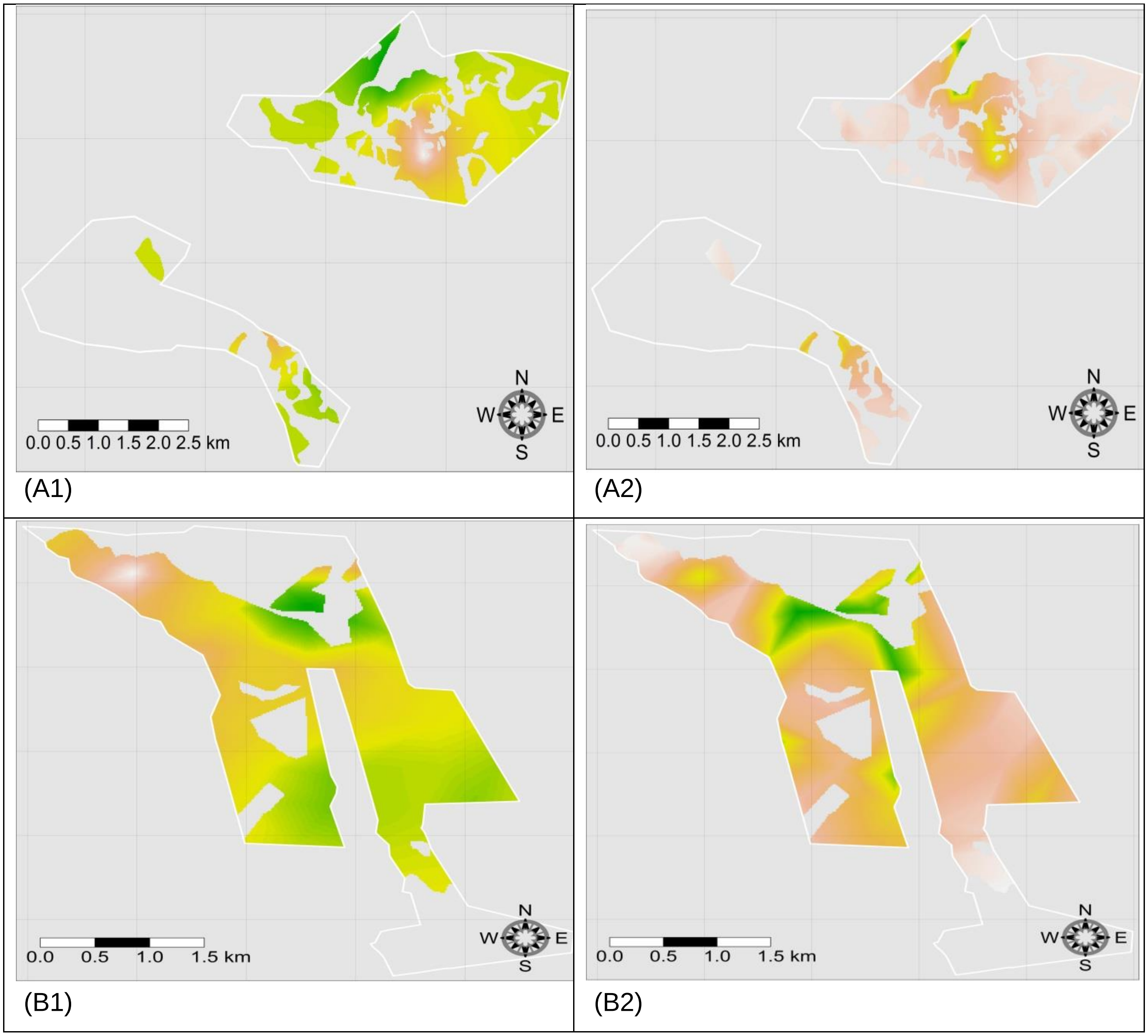
Model	Inner	Outer	RMSE	ER	DIC	LS	WAIC	Significance
Gaussian								
1	0.7	0.8	5.58	29.16	-98.32	655.84	-101.25	*
2	0.6	1	4.82	25.17	-98.61	456.34	-100.91	NS
3	1.1	1.7	11.54	60.29	-98.93	687.09	-100.95	*
4	1.4	1.5	15.85	82.83	-98.43	422.92	-101.15	*
5	1.5	0.5	5.37	28.05	-99.04	460.45	-101.69	*
6	1.3	0.8	5.91	30.89	-98.28	602.42	-101.26	*
7	0.4	1.4	5.83	30.47	-98.45	333.82	-100.80	*
8	1.4	1.6	13.64	71.24	-99.15	303.90	-101.07	*
9	0.7	0.5	5.23	27.30	-98.54	484.86	-100.99	*
10	0.8	1.1	6.10	22.21	-98.63	556.81	-101.12	*
11	1.7	1.9	8.84	46.19	-98.44	232.48	-100.32	*
12	1.4	1.7	11.01	57.52	-98.24	447.79	-100.57	*
13	0.4	0.7	5.54	28.92	-98.81	333.92	-100.87	*
14	0.5	1.7	5.88	30.70	-99.41	648.44	-102.51	*
15	1.3	1.3	5.49	28.69	-98.15	445.38	-100.74	*
Gamma								
1	0.4	1.6	16.52	86.32	90.17	61.34	88.67	*
2	0.4	0.9	16.52	86.29	91.44	61.94	90.00	NS
3	0.4	0.9	16.54	86.41	92.54	63.46	92.30	NS
4	0.4	1.7	16.50	86.23	92.77	63.62	92.23	*
5	0.4	1	16.51	86.24	89.35	60.97	87.99	NS
6	0.4	0.7	16.53	86.34	90.21	62.38	88.51	NS
7	0.4	0.5	16.51	86.25	90.34	62.93	88.96	NS
8	0.4	1.3	16.52	86.31	90.02	61.58	87.78	NS
9	0.4	1.8	16.50	86.18	91.98	63.29	90.70	NS

10	0.4	1.2	16.51	86.26	91.81	64.21	90.62	*
11	0.4	1.8	16.51	86.25	88.85	61.25	87.32	*
12	0.4	0.8	16.50	86.19	89.26	62.69	87.18	NS
13	0.4	1	16.51	86.26	90.04	64.15	88.58	NS
14	0.5	0.5	16.49	86.17	88.90	62.22	87.07	*
15	0.6	0.5	16.49	86.18	89.02	62.89	86.39	*
LogNormal								
1	**0.4**	**0.6**	**3.97**	**20.79**	**4.27**	**60.69**	**1.52**	*****
2	0.8	2	4.13	21.59	127.56	64.06	127.55	NS
3	0.7	2	3.62	18.93	127.79	64.53	128.38	NS
4	1.7	0.8	4.13	21.59	127.14	64.66	128.42	NS
5	0.6	0.5	4.10	21.40	3.63	63.16	1.66	*
6	1.9	0.5	3.86	20.17	3.75	66.46	1.64	*
7	1.2	2	4.14	21.65	127.31	65.21	128.63	*
8	0.4	1.8	16.53	86.35	3.52	63.41	1.86	*
9	1.2	2	4.25	22.18	128.57	65.40	129.47	NS
10	0.4	1.5	3.82	19.97	4.13	63.87	1.56	*
11	1.1	2	4.93	25.76	3.33	56.87	1.61	NS
12	0.4	0.6	4.42	23.09	3.60	62.00	1.58	*
13	1.5	0.5	3.91	20.43	3.92	63.55	1.23	*
14	0.5	0.8	4.54	23.72	4.06	56.79	1.33	*
15	0.5	0.5	4.50	23.51	3.34	58.31	1.42	*

Table S4 Candidate models of AGB for the two probability distributions under RSR approach for Zenzontla community. Inner, largest allowed triangle edge length (in km) for tringles in the inner area of the SPDE model; Outer, largest allowed triangle edge length (in km) for tringles in the outer area of the SPDE model; RMSE, Root Mean Square Error (Mg/ha); ER, Error Rate; DIC, deviance information criterion; LS, mean logarithmic score of CPO; WAIC, Watanabe-Akaike information criterion; *, evaluated parameter lies in the 95% posterior Bayesian credible intervals; NS, evaluated parameter does not lies in the 95% posterior Bayesian credible intervals. Best performimg AGB for this community model is shown in bold.

Model	Inner	Outer	RMSE	ER	DIC	LS	WAIC	Significance
					Gaussian			
1	2	2	16.92		238.34	127.25	239.48	NS
2	2	2	16.81		239.29	127.46	241.23	NS
3	2	2	16.30		229.32	124.57	230.50	*
4	2	2	16.43		232.72	125.78	234.03	*
5	2	2	16.76		239.21	127.81	240.35	NS
6	2	2	17.07		234.17	126.01	235.32	NS
7	2	2	16.36		232.80	125.82	233.95	NS
8	2	2	16.36		229.64	125.08	230.15	NS
9	2	2	16.29		232.45	125.93	233.47	NS
10	2	1.9	18.11		229.80	124.23	230.48	NS
11	2	2	16.96		234.44	126.74	235.15	NS
12	2	2	16.21		232.81	126.15	233.32	NS
13	1.9	2	21.03		259.60	130.43	260.37	NS
14	1.9	2	19.70		260.74	131.18	261.91	NS
15	2	2	18.48		242.58	128.27	243.55	NS
					Gamma			
1	1.7	1.2	15.35		182.98	120.62	179.14	NS
2	1.7	1.2	15.93		182.19	120.23	179.06	NS
3	1.5	1.4	18.51		187.98	120.86	185.70	*
4	**1.7**	**1.2**	**14.58**	**35.42**	**185.12**	**122.14**	**181.69**	*****
5	1.7	1.2	15.37		184.63	121.48	180.27	NS
6	1.7	1.2	17.26		185.15	121.54	181.98	*
7	1.7	1.2	14.22		185.77	122.62	183.12	NS
8	1.7	1.2	16.71		186.64	122.33	183.16	NS
9	1.5	1.2	14.57		185.21	123.46	181.50	NS

10	2	2	19.36	223.04	120.68	223.47	NS
11	1.7	1.2	17.02	184.91	122.60	181.51	NS
12	2	2	16.05	225.67	124.20	226.17	NS
13	1.6	1.1	21.31	189.18	122.45	187.58	*
14	2	2	19.49	223.44	121.80	223.79	NS
15	1.1	1.8	21.19	189.71	123.51	187.47	NS
LogNormal							
1	1.7	1.2	16.88	40.84	121.40	35.60	*
	0.4	0.6					
2	1.7	1.2	17.15	39.96	120.91	35.81	*
3	2	2	17.18	218.02	121.71	219.03	*
4	2	2	16.53	225.33	123.62	227.08	NS
5	1.5	1.2	16.59	40.64	120.60	35.31	NS
6	2	2	17.28	220.50	122.44	221.62	NS
7	1.7	1.2	15.14	40.27	122.91	35.63	*
8	2	2	16.86	217.60	121.97	218.18	NS
9	2	2	16.23	225.45	123.83	226.46	NS
10	2	2	19.11	222.20	121.06	222.72	NS
11	1.1	1.7	17.19	41.09	119.68	36.79	*
12	2	2	15.78	225.16	123.59	225.74	NS
13	2	2	20.92	233.61	124.33	234.79	NS
14	2	2	19.26	222.53	121.96	222.94	NS
15	2	2	20.77	233.54	125.41	234.56	NS



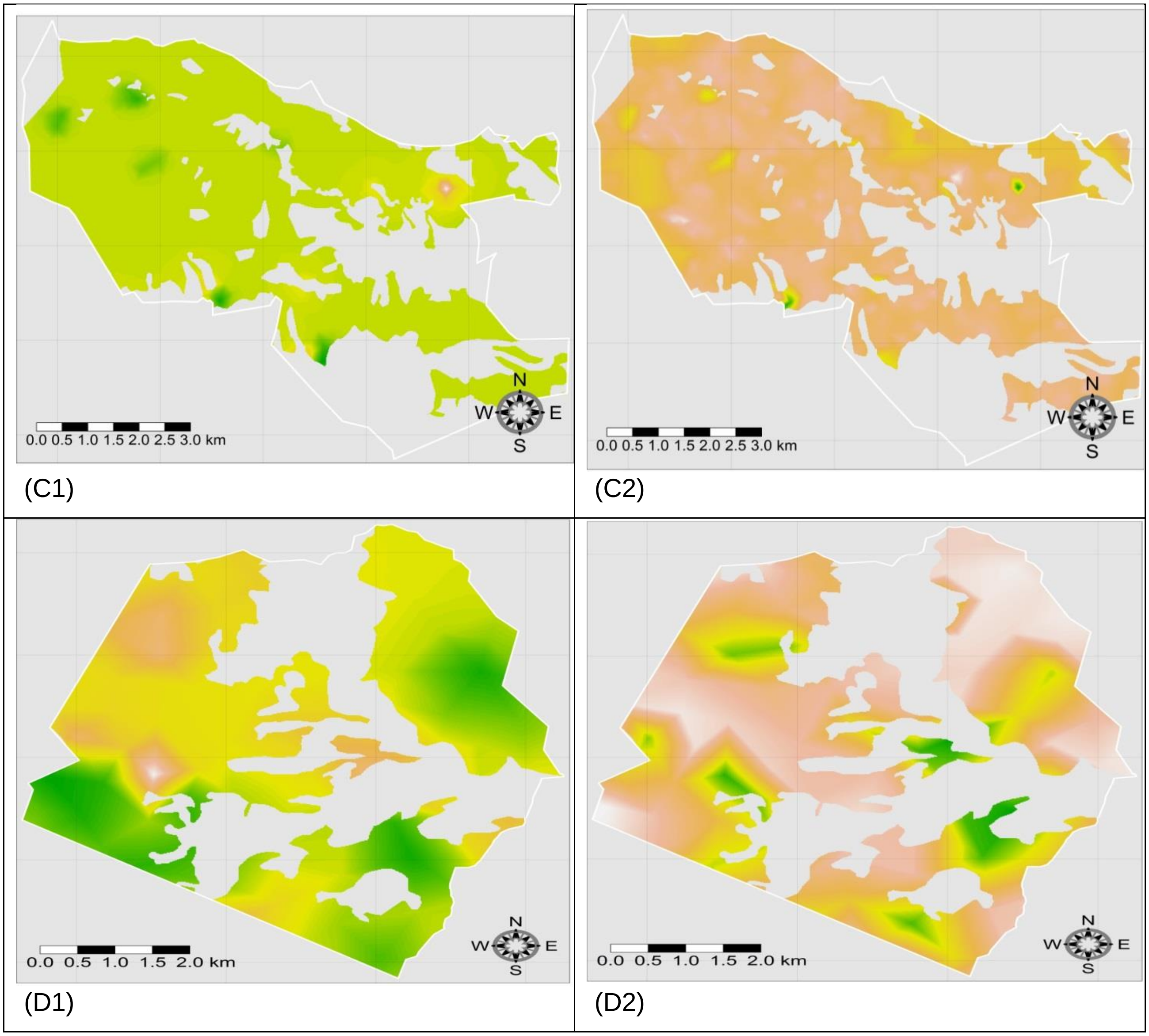
(A1)

(A2)

(B1)

(B2)

Figure S4 Predicted mean AGB within SDTF cover of Agua Hedionda (A1) and Ayutita (B1), and posterior standard deviation map for Agua Hedionda (A2) and Ayutita (B2).



(C1) (C2)

(D1) (D2)

Figure S4 (cont). Predicted mean AGB for AGB within SDTF cover of Chiquihuitlan (C1) and Zenzontla (D1), and posterior standard deviation map for Chiquihuitlan (C2) and Zenzontla (D2).

APPENDIX 4

A1. Selection and quantification of the explanatory variables

Four covariates; elevation, slope, topographic wetness index (TWI) and tangential curvature (CTAN) were selected based on our earlier studies in the region which indicated that these have the greatest predictive power (Salinas-Melgoza et al. 2017a). Values for these variables were derived from a Digital Elevation Model (DEM) of the study area, with a spatial resolution of 15 × 15 metres (INEGI 2017). Local depressions in the DEM were corrected using the Planchon and Darboux (2001) algorithm. These four topographic variables were obtained using SAGA v 2.1.4 (Conrad et al. 2015) through RSAGA (Brenning 2008), within an R V. 3.4.0 environment (R Core Team 2017). Elevation was obtained from the DEM and expressed in kilometres. Slope (in percent) and CTAN were obtained using the 2nd degree polynomial algorithm (Zevenbergen and Thorne 1987). We used the SAGA TWI algorithm (Boehner and Seige 2006), which assigns similar TWI values to two grid cells that will likely become saturated at the surface under similar basin moisture conditions given their combined contributing areas and local slope gradients. All the four covariates were matched and extracted to each sampling point.

A2. Bayesian inference procedure with geostatistical additive spatial models

The Bayesian modeling procedure was carried out in two steps.

First we identified and selected the probability distributions for the observed data. Gamma, Lognormal and Gaussian probability distribution were fitted to the observed data and evaluated using the Chi-square goodness-of-fit criteria from the gofstat function in the fitdistrplus R-package (Delignette-Muller and Dutang 2015). We decided that observed data on AGB in the SDTF in Zenzontla, Jalisco may be seen as a random field with non-Gaussian structure, because tendencies to both the Gamma and the Lognormal distribution were found; both Gamma and the Log normal distributions were used in this study.

Next, since the aim of this study was to obtain spatial predictions of AGB (included as Biom*i* in the equations below) at locations without observations after selection of the most appropriate probability distribution, we proceed to select model with best predictions of AGB, in two steps; 1) we made spatial predictions of AGB with Bayesian computing following two modeling approaches and 2) we selected the best in terms of predictive performance.

In order to carry out these two steps, the forest inventory (i.e. the complete dataset) was split into a) a training dataset (80% of sample points) and b) a validation dataset (the remaining 20%). The training dataset was used to construct the models, while the evaluation dataset was used to assess the performance of the models. From all the candidate models we finally selected the model with the best performance.

We used the Integrated Nested Laplace Approximation (INLA) to construct Bayesian hierarchical models. INLA performs Bayesian hierarchical modeling for latent Gaussian Markov Random Field (GMRF) (Rue et al. 2009, Rue et al. 2017). Although implementation of INLA for specific purposes is an open research area, this inferential framework has been used in several research fields (Rue et al. 2017). It involves a deterministic approach to approximate Bayesian inference more accurately and faster than Markov Chain Monte Carlo approximations. This inference enabled us to obtain posterior quantities of interest, for which summary statistics of interest, such as posterior means, variances or quantiles may be computed (Rue et al. 2017). Furthermore, INLA is well suited for model geostatistical applications (Bivand et al. 2015).

The modeling approaches used in this study was the stationary restricted spatial regression (RSR) (Hodges and Reich 2010), which incorporates a representation of the continuous spatial process under study and addresses the issue of spatial confounding.

1.1 Restricted spatial regression (RSR)

In a previous study, Salinas-Melgoza et al. (2018) found that the four spatially distributed fixed effects used in their study suffer some extent of collinearity. This multicollinearity among spatial covariates and the spatially random effects has been shown to lead to spatially structured confounding, which may change the estimates of the fixed-effect coefficients (Hodges and Reich, 2010). Spatial predictions from data observed at point locations has therefore been addressed with geostatistical models (Diggle and Ribeiro, 2007), such as RSR (Hodges and Reich 2010). In this approach, topographic covariates were considered as fixed effects, while the spatial component was included as a random effect. The RSR attenuates the spatial confounding effect, constraining the spatial random effect to be orthogonal to the fixed effects (Hodges and Reich 2010). The SPDE it is a model that represents a continuous spatial process (i.e. spatial distribution of AGB) or Gaussian Field within the area of interest (i.e., a specific “spatial domain”), using a discretely indexed spatial random process to deal with geostatistical data using the Matèrn covariance function (Lindgren et al. 2011). The SPDE is thus used to model the spatially correlated effect that is not explained by the topographic variables and hence addresses the spatial confounding.

The SPDE model is used to map the spatial effect using an approximation of the spatial domain that represents the GMRF on a mesh, which is built up in triangles of specific dimensions (Lindgren et al. 2011). The SPDE considers the study area as a bounded domain characterized by the community´s territorial boundaries (Blangiardo and Cameletti 2015). The mesh is divided into an inner and an outer area, the former within the bounded domain and the latter area an enlargement of the original spatial domain to avoid the influence of boundary effect on observations (Blangiardo and Cameletti 2015). The triangle dimension of the mesh is mainly adjusted by the largest allowed triangle edge length for both the inner and outer areas (Blangiardo and Cameletti 2015). The smaller the triangle edge length, the finer the representation of the GMRF. There is a tradeoff between the accuracy of the GMRF representation and the computational cost of running the model; the finer the GMRF approximation (smaller the number of mesh triangles), the higher the computational resources needed (Blangiardo and Cameletti 2015). In order to evaluate the mesh best suit the ABG spatial predictions, a number of meshes with different triangle dimensions were build, with the same smoothness parameter υ =2. Triangle edge length dimension for these meshes varied from 0.4 km to 2.0 km for triangles in the inner area, to 0.5 km to 2.0 km in the outer area, increasing 0.1 km each time (for visualization of the SPDE models used in this study see Appendix 2; Fig. 2S and 3S). This gives rise to inner and outer areas characterized by larger triangles, but with lower accuracy. The combinations of different inner and outer area triangle dimensions yield a total of 272 possible meshes, which were used to represent the spatial correlation structures in the RSR predictive modeling approaches.

1.2 Specification of the models

The models under consideration evaluated different distributions (Gaussian, Lognormal or Gamma) for the observed levels of AGB in the modeling procedure;

$y_i \sim D(\eta_i , \sigma^2{}_e)$

where D is the evaluated distribution, yi is the AGB measured at site si(i=1 , … , n), and $\sigma 2e$ is the variance of the measurement error, denoted by:

$$Biom_i = b_0 + \sum_{topo=1}^{topo} \beta_{topo} x_{topo_i} + \omega_i$$

Where b0 is the intercept and β1,…,t are the fixed effects related to topographic covariates *x*1,…,*xtopo*. The term ωi is the latent spatial process (i.e., the true unobserved AGB measurements).

In order to make fair comparison between different models, they were scaled to have global variance equal to 1 (Sørbye and Rue 2014). These models are based on the default prior distributions for INLA, but weakly informative prior normally distributed with a mean equal to zero, and a standard deviation of 100 was selected for every fixed effect (for the regression coefficients). By doing this, no prior assumptions about topographic variables distribution parameters were included in the analysis.

We evaluated 15 separate Bayesian hierarchical additive geostatistical models (Table 5.2) for both of the modeling approaches and for the three distribution families selected. These models consider the four topographic variables elevation, tangential curvature (ctan), slope and topographic wetness index (twi) as covariates, with AGB as response variable (Appendix 1; Table S3). Furthermore for RSR approach, the spatial dependence structure was included as a random effect to represent the spatial component in the form of the SPDE model. RSR models are based on a stationary spatial dependence structure in which the spatial correlation is invariant in space and is the same throughout the spatial domain (Sarma 2009). This combination of modeling approaches, distributions and topographic covariates resulted in the development of 12,240 for each community, yield in total 48,960 different performed models. Using this approach we obtained the distance at which the spatial autocorrelation is almost null or close to 0.1 (the range *r*). In order to compare the spatial variation against the noise variance in the observations, we also obtain the variance of the spatial correlated random effect (spatial variance, $\sigma 2_{\omega}$) and the observation measurement error variance (nugget effect, $\sigma 2_{\varepsilon}$). In order to denote statistically significant effect in the selected models, we used the 95% posterior Bayesian credible intervals, which indicate the probability that the evaluated parameter lies in the interval of 0.95. These models were solved using the R-package R-INLA (Rue et al. 2009, Martins et al. 2013, Lindgren et al. 2011, Lindgren and Rue 2015, Rue et al. 2017) see http://www.r-inla.org

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Chapter 6

CARBON EMISSIONS FROM DRYLAND SHIFTING CULTIVATION: A CASE STUDY OF MEXICAN TROPICAL DRY FOREST

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Highlights

- Under REDD+, shifting cultivation should be considered degradation rather than deforestation;
- Carbon stocks in old fallows (>20 years) are higher than those in old growth forests which have never been used for shifting cultivation.
- Extending length of fallows increases rates of carbon emissions
- Shortened fallow cycles result in higher carbon stocks and lower emissions at the landscape level;
- Cycle lengths could be optimized for carbon sequestration in a land sharing approach

ABSTRACT

The chapter considers the relation of shifting cultivation to deforestation and degradation, and hence its impacts in terms of carbon emissions and sequestration potential. There is a need to understand these relationships better in the context of international policy on Reduced Emissions from Deforestation and Forest Degradation (REDD+). This chapter reviews the way in which shifting cultivation has been incorporated in global and national estimations of carbon emissions, and assembles the available information on shifting cultivation in Seasonally Dry Tropical Forests (SDTF) in Mexico, where it is widely practiced. It then takes the case of two villages, Tonaya and El Temazcal, which lie within the basin of the River Ayuquila in Jalisco, Mexico. Field data for the typical carbon stocks and fluxes associated with shifting cultivation are compared with stocks and fluxes associated with more intensive agricultural production in the same dry tropical forest area to highlight the carbon sequestration dynamics associated with the shortening and potential lengthening of the fallow cycles. The biomass density in the shifting cultivation system observed can reach levels similar to that of old growth forests, with old fallows (>20 years) having higher carbon stocks than old growth forests. Per Mg of maize produced, the biomass-related emissions from shifting cultivation in the traditional 12 year cycle are about three times those from permanent cultivation. We did not, however, take into account the additional emissions from inputs that result from the use of fertilizers and pesticides in the case of permanent agriculture. Shortening of the fallow cycle, which is occurring in the study area as a result of government subsidies, results in higher remaining stocks of carbon and lower emissions at the landscape level.

Keywords: slash-and-burn, swidden cultivation, carbon stocks, REDD+, land sparing, Borlaug hypothesis.

6.1 INTRODUCTION

Shifting cultivation (SC), also known as swidden cultivation or slash and burn, is a traditional continuous cyclic agricultural system that is still widely used, and studied, in tropical countries (Grigg 1974, Aweto 2013a, Nigh and Diemont 2013). It entails rotation between cultivated plots and regenerating fallow/secondary forest (Kass et al. 1993, Kleinman et al. 1995, Aweto 2013b). Forest or secondary vegetation is cut, the debris is burned, and a cultivation phase of two or three years starts, with very limited use of pesticides or fertilizers. After a few years of cultivation the yield falls and the farmer moves on, clearing new land. The old cultivated plot is fallowed, leaving the vegetation to recover and allowing secondary forest re-growth. Shifting cultivators often return to re-cultivate the fallowed plot some time later; the rest period may range from 5 to 50 years (Aweto 2013a).

During the colonial period, shifting cultivation was generally considered ´wasteful´ and ´primitive´ (Geertz 1963, Spencer 1966, Kuchelmeister 1993). Despite the fact that during the last 25 years many scientific articles have vigorously contested the negative effect of shifting cultivation (Rambo 1990, Fox et al. 2000, Ickowitz 2006), this point of view is still very common. Shifting cultivation has been blamed as a leading cause of tropical forest cover loss (Geist and Lambin 2001, 2002) and thus, in the context of climate change, for the associated carbon emissions (Houghton 2012, Nigh and Diemont 2013). That opinion is reflected in many national policy documents relating to mitigation, as submitted to the Forest Carbon Partnership Facility of the World Bank (e.g. Democratic Republic of Congo 2016, Ghana 2015, Dominican Republic 2015).

The aim of this paper is to consider the impact of shifting cultivation on carbon stocks and fluxes, and its potential for carbon sequestration in the context of the policy on Reduced Emissions from Deforestation and Forest Degradation (REDD+), and to compare this with alternative forms of production of maize. We focus on one ecosystem, tropical deciduous forest, typified for the case of Mexico by selva baja caducifolia (Miranda and Hernández–Xolocotzi 1963) and commonly known as Tropical Dry Forest (TDF). This is a dryland vegetation type, similar to the cerrado of Brazil and the miombo of East Africa. We examine the impact of maize production on carbon stocks, and consider the related carbon sequestration potential in TDF in Mexico, based on a detailed study in two villages, El Temazcal and Tonaya, in Jalisco state, Mexico.

We set out to answer three questions based on this case study: (1) per Mg of maize produced, how much carbon is emitted in shifting cultivation systems as compared to a permanent cultivation system and what are the remaining carbon stock levels in each case; (2) what would be the effects on carbon emission rates and stocks of shortening or lengthening the fallow period; and (3) what is the potential for carbon sequestration in these dry land farming systems. While the answers to these questions may be of immediate relevance to policy makers designing interventions for national REDD+ programmes, they are also of scientific interest in relation to the Borlaug hypothesis (Angelsen and Kaimowitz 2001, Lobell et al. 2013). This posits that switching to sedentary agriculture (*e.g.* more intensive cultivation with higher yield per unit area) will ´spare´ more forest for conservation purposes.

6.1.1 LITERATURE REVIEW

6.1.1.1 Carbon stocks in shifting cultivation systems

Although many studies have discussed possible schemes, challenges and opportunities for SC in the context of reducing carbon emissions and increasing carbon sequestration (Mertz 2009, Hett et al. 2012, Antunes et al. 2013, Aryal et al. 2014), few studies have quantified the emissions from SC in the context of REDD+ (Mertz 2009). It is obvious that during clearance there will be emissions, not only as a result of loss of the woody vegetation but also because carbon concentrations in soil are lowered as a result of soil oxidation and because the litter supply to the soil is temporarily disrupted. Carbon stocks would be expected to increasing during the fallow phases due to accumulation of organic matter in soil (Antunes et al. 2013), although the time needed to reach the original stock levels may vary greatly (Lebrija–Trejos et al. 2008). For example, Detwiler and Hall (1988) found a loss of 18% in soil carbon (including both mineral and soil organic carbon, SOC) during the clearance phase, and Don et al. (2011) found increases of between 38% and 50% in SOC when the land is in the fallow or secondary succession stage, between 7 and 37 years after cultivation. There is little doubt about the general nature of these dynamics, although the cycle lengths of shifting cultivation systems vary from location to location. What is more in doubt are the effects of different fallow lengths on carbon stocks. It is commonly suggested that longer fallow lengths are associated with higher levels of above-ground biomass and higher concentrations of soil carbon (Read and Lawrence 2003, Lebrija–Trejos et al. 2008). We argue that both a space and a time frame are needed to analyze this properly, since it is emissions over time, not stocks that are of primary interest in the context of REDD+.

Under a shifting cultivation regime, the landscape is a mosaic of forests of different ages in a continuum of forest succession (Aweto 2013a). Shortening the SC cycles is usually thought to result in lower average above-ground biomass (Lawrence et al. 2010 Schmook 2010). We argue that this depends on the context and rationale for the shortened cycle. Cycles may be shortened as a result of population pressure and the need to bring a higher proportion of the total area into cultivation at any one time, but they may also be shortened as a result of policy measures, such as subsidies. If as a result of shortened cycles other areas that were earlier part of the cultivation cycle are abandoned completely, it is quite possible that over the entire area, average carbon stocks will rise. The case of Programa de Apoyos Directos al Campo (PROCAMPO), a grant paid to small farmers all over Mexico, is an example; farmers may register land for this scheme, but the money is paid only provided the land is under cultivation or pasture (Sadoulet et al. 2001). In the first three years of fallow following the cultivation period the land may be counted as pasture because re-growing trees have not yet reached a height of more than a couple of metres, and the area is used for grazing. Once the trees become taller and denser the area will no longer be eligible for the subsidy. Since registration of land was on a one-off basis, it is in farmers´ financial interest to bring the plot back into cultivation after three years of fallow. In addition to PROCAMPO, farmers have in recent years been able to obtain subsidies for inputs such as fertilizers and herbicides, which may reduce their dependence on the natural recovery processes of long fallows. In my study area, farmers mentioned that an additional reason for shortened cycles is to reduce the labour requirements, since clearing fallow of 3 or 4 years growth is much less burdensome than clearing old fallows.

Another factor to be considered is the carbon that may potentially be sequestered in forest in which stocks have been temporarily lowered by farming. Hence, continuous ´harvesting´ of the trees, such that the average tree population remains youthful, may result in higher average annual uptake of carbon. Recent research in humid tropical forests (rainforest in the Maya region of Central America, Amazon and Panama) has suggested that shifting cultivation is much less damaging to carbon stocks than had been earlier thought (Pelletier et al. 2012, Nigh and Diemont 2013). Whether the new plot is cut in previously un-touched (primary) forest or in a secondary forest may, however, have important consequences for CO_2 emissions and carbon sequestration (Detwiler and Hall 1988, Fukushima et al. 2008, Lawrence et al. 2010).

Clearly, there are different pathways of vegetation change in tropical dry forest succession (Romero-Duque et al. 2007, Lebrija–Trejos et al. 2010). Cyclical use of forest resources may result in a steady state, with carbon stocks that are sustained, even if they are lower than they would be in ‘intact’ forest (Lawrence et al. 2010, Antunes et al. 2013). However, it could also result in continuous loss of stocks as a result of over–exploitation from additional activities, such as timber harvesting, fire wood collection and grazing (Morales-Barquero et al. 2014). This could also be a result of increasing pressure of shifting cultivation due to need to bring more of the total area into production (Eaton and Lawrence 2009, Lawrence et al. 2010). The spatial–cyclical character of SC thus necessitates analysis at the level of the management unit (i.e. the whole area used in the cycle), not the pixel or the individual patch currently under cultivation, and the time horizon should be long (e.g. 20 years)

6.1.1.2 Definitions of deforestation and degradation under REDD+

Under UNFCCC policy (the Marrakech Accords) a forest is considered to become non–forest when it falls below a certain threshold for canopy cover (crown density), and remains so on a permanent basis (>20 years) (UNFCCC 2001).The threshold lies between 10% and 30% and is selected by each country to meet its own requirements. Mexico has selected 30%, whereas Ghana for example has selected 15%. Following definitions used by FAO, an area that is temporarily destocked, but which is expected to revert to forest at the threshold level, is considered forest. Degradation has not been formally defined in UNFCCC documents up to now, although for the purposes of REDD+, it is understood to mean a lowering of biomass (and hence carbon) stocks while the forest retains a canopy cover above the selected threshold (FAO 2011). One can therefore argue that temporary de–stocking (e.g. in areas that are managed using a sustainable logging cycle with replanting) is a form of degradation. In SC systems, one part of the management unit is under cultivation while the rest is under successional forest re-growth. The canopy cover may be temporarily below the threshold in one patch, but will return within a few years; on average, the tree cover remains above the level required to be considered forest. Depending on the length of the cultivation and fallow cycles, and the growth rates of the trees during the fallow periods, SC may not lead to a continued decline in stocks, only to an average stocking level that is lower than that of the ´intact´ forest. What is clear is that in most cases SC does not lead to permanent (> 20 years) removal of tree cover, which is what is implied by ‘deforestation’ in the context of REDD+. For the purposes of REDD+ it is therefore more appropriate to consider SC as a cause of forest degradation rather than of deforestation (Houghton 2012, Pelletier et al. 2012).

Shifting cultivation has been a stable and popular cultivation system throughout agricultural history, mainly because, although yields per hectare are low, it gives relatively high returns to labour (Raintree and Warner 1986, Seidenberg et al. 2003), and requires little capital. As such it is an efficient and sustainable food production system as long as population densities are low and the potential area for cultivation is abundant, so that the fallow period matches or exceeds the time necessary for recovery of the sites. However, much higher yields per hectare could be achieved with use of inputs such as fertilizers and pesticides.

Reduced Emissions from Deforestation and Forest Degradation policies commonly assume that intensification of agriculture would raise yields in areas already under production, reducing the need for further expansion into the forests (land sparing), thus reducing forest carbon emissions (Carter et al. 2015, Salvini et al. 2014). Higher yields might at the same time reduce the cultivation area needed and enable some cultivation areas to recover their forest status, thus increasing carbon sequestration (Carter et al. 2015). A switch from traditional shifting cultivation systems to permanent agriculture is often suggested as part of such a strategy (West et al. 2010). This has been modeled following optimization approaches that would allocate resources in the most efficient way, using a binary view of landscapes (agriculture/forest) to spare land and reduce deforestation (Pirard and Belna 2012, Byerlee et al. 2014), following the so-called Borlaug hypothesis (Angelsen and Kaimowitz 2001, Lobell et al. 2013). This kind of proposal is widely propagated in policy documents associated with REDD+, for example, in the Regional Strategy for REDD+ in the Yucatan Peninsula (ECOSUR 2012) and Mexico has been identified as one of the six priority countries with the potential to mitigate agriculture-driven deforestation emissions through such land sparing (Perfecto and Vandermeer 2010, Carter et al. 2015). On the other hand, fallow periods are shortening in some Mexican tropical dry forest (Chávez 1983, Lambert 1996, Abizaid and Coomes 2004, Cuanalo and Uicab-Covoh 2005, Dalle and de Blois 2006), and a reversal of this trend has also been proposed as a route to increasing carbon stocks and lowering emissions.

Thus, both intensification of agriculture (sedentarization) and de-intensification (extending fallow periods) are being proposed for improved environmental management in general and for the mitigation of carbon emissions in particular. Policy makers must understand the conditions that have given rise to shortened cycles before conclusions can be drawn about the carbon outcomes of different intervention options

6.1.1.3 Carbon characteristics of Tropical Dry Forest

Tropical dry forest (TDF) is widely distributed in Mexico (Miranda and Hernández–Xolocotzi 1963, Rzedowski 1978) in the drylands along the Pacific Ocean coast, the Gulf of Mexico and in some regions of the eastern coast (Fig. 6.1). It currently covers 60% of the total area of tropical vegetation (Trejo and Dirzo 2000), although earlier it was much more widespread. Multiple–stemmed trees account for 58.0% of total basal area (Durán et al. 2006, Álvarez-Yépiz et al. 2008). A characteristic of the carbon pools in many tropical dryland ecosystems is that above-ground biomass in living trees represents only a small part of the total carbon, with soil carbon often being the larger part (Scharlemann et al. 2014). Shrubs, litter and woody debris hold a very small proportion (Gibbs et al. 2007), and this has been confirmed in Mexico (Hughes et al. 1999, Jaramillo et al. 2003).

The most recent estimations of total forest carbon stocks in primary tropical dry forest in Mexico show wide variations: 46.7 to 571 Mg/ha (Delaney et al. 1997, Jaramillo et al. 2003, 2011, Vargas et al. 2008, Kauffman et al. 2009). Tropical Dry Forest has lower total carbon content than does tropical moist forest, even taking into account the high levels of carbon in the soil (Lai 2004). Above-ground carbon stocks in much Mexican TDF are well below those in the intact forest, because so much of this forest is degraded (Trejo and Dirzo 2000, Morales-Barquero et al. 2015). However, the few studies of the distribution of carbon have shown that in secondary TDF soil carbon levels are almost as high as in primary forest (INECC 2010).

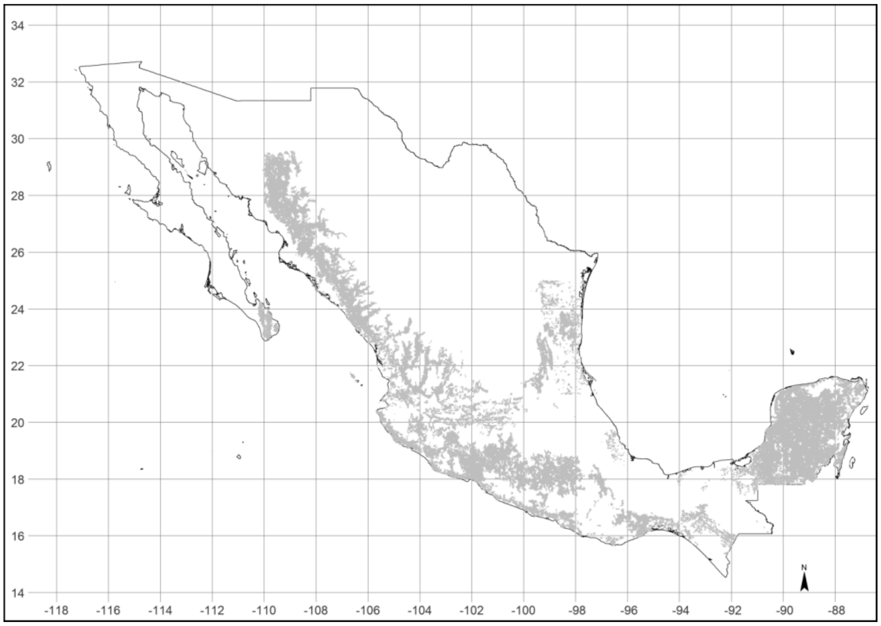

FIGURE 6.1 Geographical distribution of Tropical Dry Forest in Mexico (gray area). Data: INEGI 2010.

6.1.1.4 Shifting cultivation in Mexico

Shifting cultivation is common in Mexico, often practiced by farmers as a secondary, extensive, production activity to complement the more intensive cultivation of rainfed or irrigated permanent plots (Hernández–Xolocotzi 1988, Hernández–Xolocotzi et al. 1995, Moreno-Calles et al. 2014). The better-quality, low-lying agricultural lands suited to permanent, and particularly to irrigated, agriculture are limited in availability, and the more marginal areas on the hillsides are usually used in a cyclic system with a long fallow period. Shifting cultivation is known by different names in different regions (e.g. milpa, coamil, ecuaro, tlacolol and tamagua); in the study area (Jalisco state) the term ´coamil´ is used. However, the geographic extent and distribution of shifting cultivation in Mexico is not clear. Government statistics, in Mexico as elsewhere, record areas under agriculture but do not differentiate between permanent (irrigated or rainfed) and shifting cultivation (Mertz 2009).

The shifting cultivation system in the state of Jalisco takes place on slopes or stony areas that are naturally covered by TDF. A piece of land is cleared, the majority of standing trees are removed from the plot, the debris is dried for one to five months and then burned. Then the farmer makes planting holes using a wooden stick with an iron blade (coa), into which the maize seeds are placed, often in combination with beans and squash. Shifting cultivation plots are usually used to produce maize for two years and then left fallow for periods ranging from 5 to 10 years, (Chávez 1983, Gerritsen 2002, Borrego and Skutsch 2014). Cattle are frequently allowed to graze on the area during the fallow, and occasionally the cleared areas are turned into permanent pastures and never return to cultivation. Shifting cultivation plots are usually found on hillsides with slopes > 12% and not on the plains (Chávez 1983). The nature of the terrain forces farmers to use hand tools rather than ploughs pulled by horses or tractors. The use of chemical inputs (fertilizers, herbicides) is much less than on permanent plots, not least because of the initial fertilizing effect of the burning, but in general yields per hectare are lower than on permanent plots, although the returns to labour are relatively high.

6.2 CASE STUDY

6.2.1 STUDY AREA

The villages of Tonaya and El Temazcal lie in the center of the basin of the River Ayuquila in Jalisco state (19°42.224’ N, 103°54.962’ W), western Mexico (Fig. 6.2), at approximately 990 m a.s.l., in an area where the natural vegetation is seasonally dry tropical forest, with some oak and coniferous forests on the higher slopes. The area is semi–arid with rainfall of approximately 650 mm per annum, falling almost entirely between June and September (Jardel et al. 2012). Regosols and lithosols account for ~80% of the surface area in Tonaya and 93% for El Temazcal: these soil types have little organic matter. Regosols predominate***; they a***re young soils with depths >20 cm, but with a layer that becomes hard and crusty when vegetation is removed, preventing the penetration of water. Lithosols are shallow (depth <20 cm), and not well suited for agriculture.

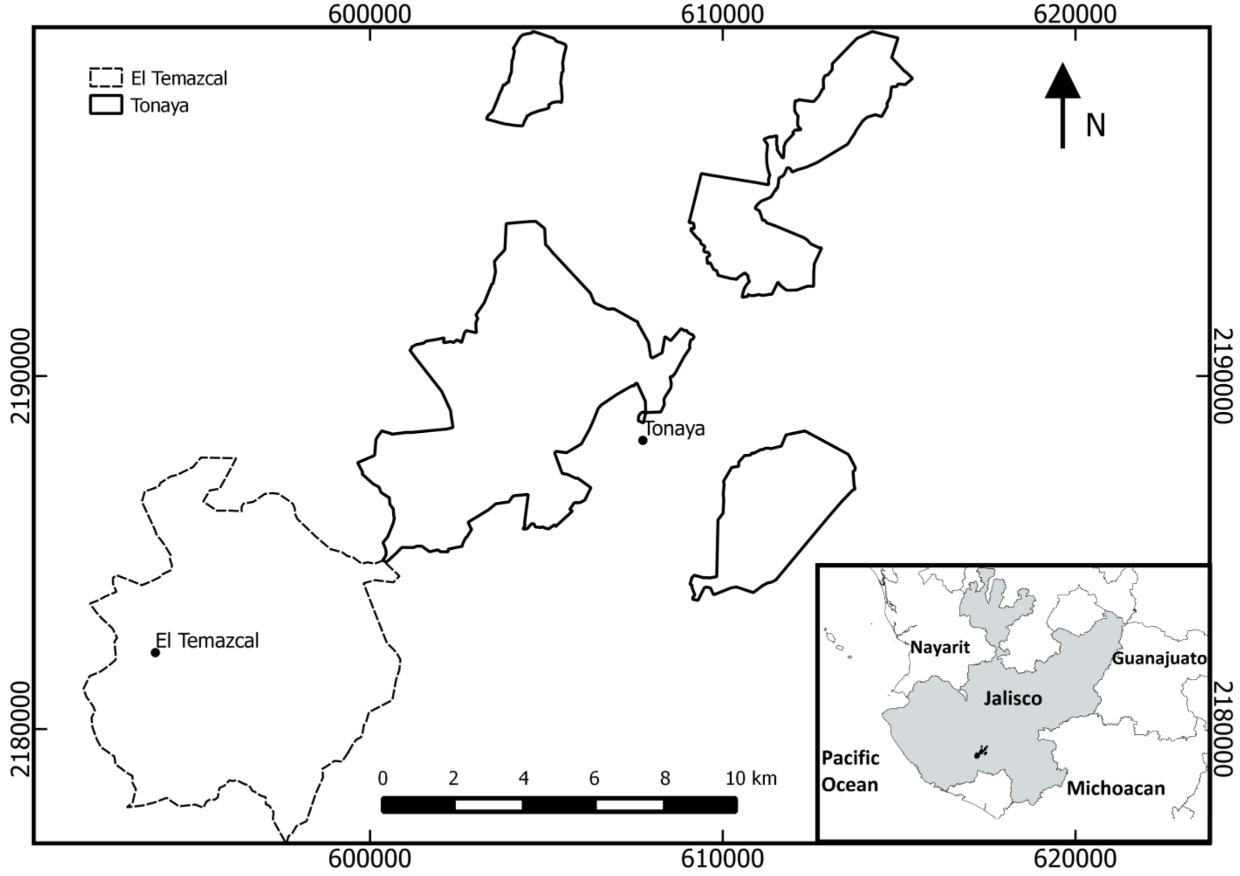

FIGURE 6.2 Location of communities in Jalisco state, western Mexico in which shifting cultivation was investigated (EPSG projection: 32613-wgs84/utm zone 13N).

Many of the farmers have a plot for permanent agriculture (PA) in the valley. These fields are cultivated either once or twice a year, year in year out, with considerable use of chemical fertilizers and other inputs (Gerritsen 2002, Borrego and Skutsch 2014). They may also have a forest plot on the slopes for shifting cultivation (SC). In the terrain that is used for SC there is a mosaic of forest states; areas that have recently been slashed and burned and are now being cropped, combined with plots at various stages of the fallow cycle (FP). Shifting cultivation plots in the study area are usually between 0.24 and 0.72 ha (Chávez 1983). The older fallows that had been under fallow for 10-20 years may be considered secondary forests (Jardel et al. 2012). Some hill slopes have been cleared for permanent pastureland (PL). There are also a few patches of old growth (primary) forest (OG). These are areas which have never been used for SC and where big trees have never been felled, although there may be small scale extractive activities: e.g. for poles and firewood. The way in which the hill slope landscape is managed varies between communities.

In Tonaya the farmers select tree species to retain in the shifting cultivation plots, leaving in particular a few individuals of hardwood species with straight trunks and large branches, which are well suited for fence posts and house supports and construction materials. The root stocks of these species are left intact which allows rapid regeneration by coppicing. In El Temazcal in addition to cutting trees for firewood and fence posts, there is an active selection of tree species and in the fallow patches they remove species with small crowns and allow a few larger-crowned species to gain space in the canopy, thereby increasing shade for cattle in the fallow period.

6.2.2 MATERIALS AND METHODS

6.2.2.1 Data collection

Data on biomass and soil carbon (including both mineral carbon and SOC) were obtained in a survey carried out in August 2013 and March 2014. Plots were set up in FP and OG, where above-ground biomass was measured and soil samples taken for laboratory analysis of carbon content. Soil carbon data were also obtained from SC, and for comparison, also from permanent agriculture plots (PA) and permanent pasture land (PL).

A total of 23 FP sites were identified where maize had been grown in the previous 10 years, 10 in Tonaya and 13 in El Temazcal, and in addition 5 sites of PA, 4 of shifting cultivation plots (the cultivation phase), 6 of OG and 6 of PL were sampled. In addition, we have data on above-ground biomass on 15 plots in old fallow (OF). For these we do not have soil carbon data, but we conservatively assume that this is not higher than that of fallows of 10 years (FP3). The 23 FP sites were of different ages up to 20 years, which we divided into three age categories (FP1: years 3-6, FP2: years 7-9 and FP3: years 10-20, in each case following two years of cultivation), with 8, 5 and 10 sampling plots respectively for the FP1, FP2 and FP3 classes. Information on plot age was obtained from the owners. Old-fallow forest plots (fallows older than 20 years) supply information on the level of carbon stocks that could be achieved within the next 20 years if SC were to be halted; these were used as a reference (baseline) level.

Sites were selected with the assistance of local farmers to represent the different stages of the SC cycle. Within each of these areas, a sampling plot was laid out in a central location. Circular sample plot of 11.28 m radius (area 400m^2) were used following IPCC guidance (Penman et al. 2003); circular plots are easy to lay out accurately and have the smallest circumference/area ratio (de Vries 1986). Diameter at breast height (DBH: 1.3 m height) was measured for all the trees with DBH $\geq$ 2.5 cm, using diameter tapes or calipers, and the species and genus was identified; in case taxonomic identity for individuals cannot determined, individuals were labeled and grouped based on morphological sameness. Trees of less than 2.5 cm DBH were counted as woody stems. The dry above-ground biomass of trees was estimated using the general allometric equation of Martínez–Yrízar et al. (1992) (Equation 1). Above-ground biomass of multi–stemmed trees was calculated separately for each stem if the split was below 1.3 m. To obtain estimates of the above-ground carbon (AGC), we used a conversion factor of 0.5. For details of the species in each category see Appendix 5: Table S1.

Equation (1)

$$log_{10}B = -0.5352 \ + 0.9996 \ \log \mathrm{BA}$$

where B is above-ground dry biomass in kg, BA is stem basal area (cm^2).

Sites with essentially no shrubs or trees (permanent pasture sites, cultivation phase of shifting cultivation plots and permanent agriculture sites) were considered to have zero AGC. This gives a conservative estimate of AGC stocks for the cultivation stage of the shifting cultivation system since, as mentioned above, it is common for farmers to leave one or two trees standing. Grass, litter and belowground biomass were not measured.

Data on soil carbon were obtained by collecting four soil cores from the top 10 cm (ca. 16–44 g each, with a bulk density of 0.59–1.58 g cm^{-3}) at the northern, southern, eastern and western limits of each sampling plot. The four samples from each site were pooled to form a single sample and were sent for laboratory analysis, which followed the OHHW protocol with the CHNS/O Perkin Elmer 2400 Series II Elemental Analyzer in CHN mode (Ryu and Tenney 2005). Total carbon was obtained for each plot as the summation of AGC and soil carbon.

6.2.2.2 Statistical analysis of field data

We used analysis of variance to examine differences in carbon storage in the cultivation phase of shifting cultivation (CF) and fallow stages of shifting cultivation (FP), in old fallow (OF), in permanent agricultural plots (PA), permanent pasture land (PL), and old-growth forest (OG). Above-ground C and soil carbon were considered dependent variables, with land-use class as the independent variable. The fallow phases were analyzed in two ways, first as three phases of different ages (FP1, FP2 and FP3) and then as a single category (FP). Aboveground and soil C values were log and square root transformed when necessary to meet ANOVA assumptions regarding the homogeneity of error variances and distribution of residuals. The normality of the data distribution for AGC and soil carbon was tested separately for each class using the Shapiro–Wilk test while homogeneity of variances was evaluated using Bartlett’s test. The data set for AGC with the fallow phase considered as a single factor, and the other dependent variables, all fulfilled ANOVA assumptions (one–way ANOVA). Soil carbon and AGC analyzed as three separate fallow phases, and AGC with fallow phases as a group did not meet the ANOVA assumptions and so the Kruskal–Wallis One-Way ANOVA on Ranks was run instead, reporting the Kruskal-Wallis chi-squared approximation values (MacFarland and Yates 2016). In order to identify the treatments which are responsible for significant variation, two type of post hoc test were performed, a Tukey's HSD when distribution was normal and pairwise comparisons using Tukey and Kramer (Nemenyi) test with Tukey-Dist approximation for independent samples when the distribution was non-normal. All the statistical tests were performed using the libraries stats and PMCMR of the R software (R Core Team 2013, Pohlert 2014) and were performed at a 0.05 significance level.

The differences in carbon stocks for AGC were tested at two levels of plot aggregation: (1) all plots in the fallow stage versus old growth sites, (2) the plots in fallow stage were grouped by age class categories. Soil carbon was analyzed in a similar way. To show the relation between soil carbon density and AGC density across the different wooded land uses, the mean ratios for both were calculated for FP1, FP2, FP3 and OF.

6.2.2.3 Estimation of carbon balance for production of 1 Mg of maize

Before the introduction of the PROCAMPO subsidy, the SC cycle in the study areas typically consisted of 2 years of cultivation phase followed by 10 years in fallow phases. Farmers who do not receive PROCAMPO may still follow this model. We compared: (a) the carbon stocks and emissions that would in the long run pertain in this shifting cultivation system (12-year cycle) compared with those in a permanent cultivation system over the same time period; (b) the average carbon emissions and stocks in different SC production regimes (6-year, 12-year and 24-year cycles, with 2 years cropping in each), under the assumption that the shortened cycles are not due to pressure on the land (which is the situation today in the study area; the six year cycle appears to be a response to the PROCAMPO intervention) and (c) a six-year SC system under land pressure, i.e. in which the shortened cycles are the result of an increase in demand for land (a hypothetical situation). To create a fair basis for comparison all calculations were made for production of one Mg of grains maize, holding land area constant within each comparison, and using old fallow (OF) as the baseline, since this represents the state of forests in the area when shifting cultivation is no longer practiced. The calculations are made on the basis of the long run proportion of land which would be under cultivation and under each fallow phase in the different systems (i.e. weighted by the length of each of these phases). All losses of carbon were annualized over a nominal period of 20 years. This is not in any way related to cycle lengths, but is used to as a common base to model the long run annual emissions that would result for each farming system.

Responses of 39 farmers to a questionnaire indicated average maize yields of 1.684 Mg/ha for SC and 3.768 Mg/ha for PA. Estimation of the carbon stock in parcels of SC and PA were based on the area needed to produce one Mg of maize in each system. In the 12 year SC system this is 0.60 ha for cultivation and 3.00 ha fallow, since the cultivation plot is used for 2 years, rotated 6 times; the total area required is therefore 3.60 ha. On average, at any one time 0.6 ha will be in cultivation, 1.20 will be under FP1 (years 3-6), 0.9 under FP2 (years 7-9) and 0.9 under FP3 (years 10-12). The larger area under FP1 is because FP1 is a four year phase while FP2 and FP3 last for 3 years. For PA the cultivation area is continuously 0.27 ha and to allow a fair comparison we assume that the farmer keeps the remaining part of the 3.60 (3.33 ha) in its baseline state (OF).

6.2.2.4 Estimating carbon impacts of shifting cultivation versus permanent agriculture

Using the carbon levels measured in the field we obtained the average annual carbon sequestered in each system for the production of 1Mg maize per year, taking into account an equal area of land and using OF as the baseline. Using calculations shown in Appendix 6 (Table S1), and as explained in section 3.2.3, we then calculated the annualized emissions from PA and SC. The AGC for the CP of SC and for PA was considered to be zero, although in practice in SC a little woody vegetation is left in the cultivation area. The only carbon pool considered for permanent agriculture was the soil carbon, while for SC the carbon stocks were estimated as the weighted values of those of the CP and the different FP stages (see Table 6.1).

6.2.2.5 Estimating carbon impacts of changing lengths of fallow

Tests of the effect of different lengths of SC fallows on carbon stocks assumed that the farmer is essentially free to select his cycle length (i.e. his choice is not constrained or forced by pressure on the land). To grow 1Mg of maize requires 0.60 ha in cultivation per year. In a 24-year cycle, this would require a total area of 7.20 ha, of which on average 6.60 ha would always be in various stages of fallow. We assume that yields (Mg/ha) would remain constant at the different cycle lengths modeled; in reality farmers use some application of fertilizers in the shortened cycles to maintain yields. We have not included the carbon values of this either in permanent agriculture or in shortened cycles since we was unable to find reliable information available about quantities used in these different systems. We made calculations (see Appendix 6, Table S2) over this area also for the 12 and 6-year cycles, assuming that the unused areas would retain their OF vegetation.

6.2.2.6 Estimating effect of land under pressure

Finally we created a scenario (Appendix 6, Table S3) in which the shortened cycle length (6 years) is due to (hypothetical) increased demand for land to be brought into production (i.e. population growth is forcing more farmers onto the same area of land). In this case, there are 4 sets of a 6-year SC system distributed over the same 7.20 ha, and no land is left under OF.

6.3 RESULTS

6.3.1 SOIL CARBON STOCKS

Overall, soil carbon makes a much larger contribution to total carbon (50.44 ± 3.10 Mg/ha) than does AGC (11.31 ± 1.53 Mg/ha) in all the land cover types examined (Table 6.1). The highest average soil carbon levels were found in the CP and in FP3 (fallow in years 10-20 of the cycle); the lowest were in the sites under permanent agriculture. Within the shifting cultivation system, soil carbon accounts for around 85-87% of total carbon in fallow stages. The high soil carbon levels in the CP appear to fall by about one-third in the first fallow period and then increase gradually, but there is a very high variation between sites (Fig. 6.3a). In old–growth (OG) sites, soil carbon forms 64% of the total carbon stock.

The differences in log values of soil carbon in the different land uses were statistically significant (F = 2.82, df = 6, $p < 0.05$). FP2, FP3, CP and PL all had significantly greater soil carbon density than PA (Tukey HSD test, $p < 0.05$). On average, there was about 10% more carbon in soils under the shifting cultivation regime than in OG forests.

6.3.2 ABOVE-GROUND CARBON STOCKS

Above-ground C is the highest in OG forest, and as would be expected is much lower in land under fallow, again with a high degree of variation between sites (Fig. 6.3b).

Fallow phase 3 was distinctive in having small trees with DBH ≥ 2.5 cm, but at the same time it harbors the highest number of stems and has the highest average DBH of the three fallow phases. Old fallow shows the highest number of stems per hectare, but has fewer individual trees than FP3, owing to the coppicing characteristics of the species involved (Table 6.1).

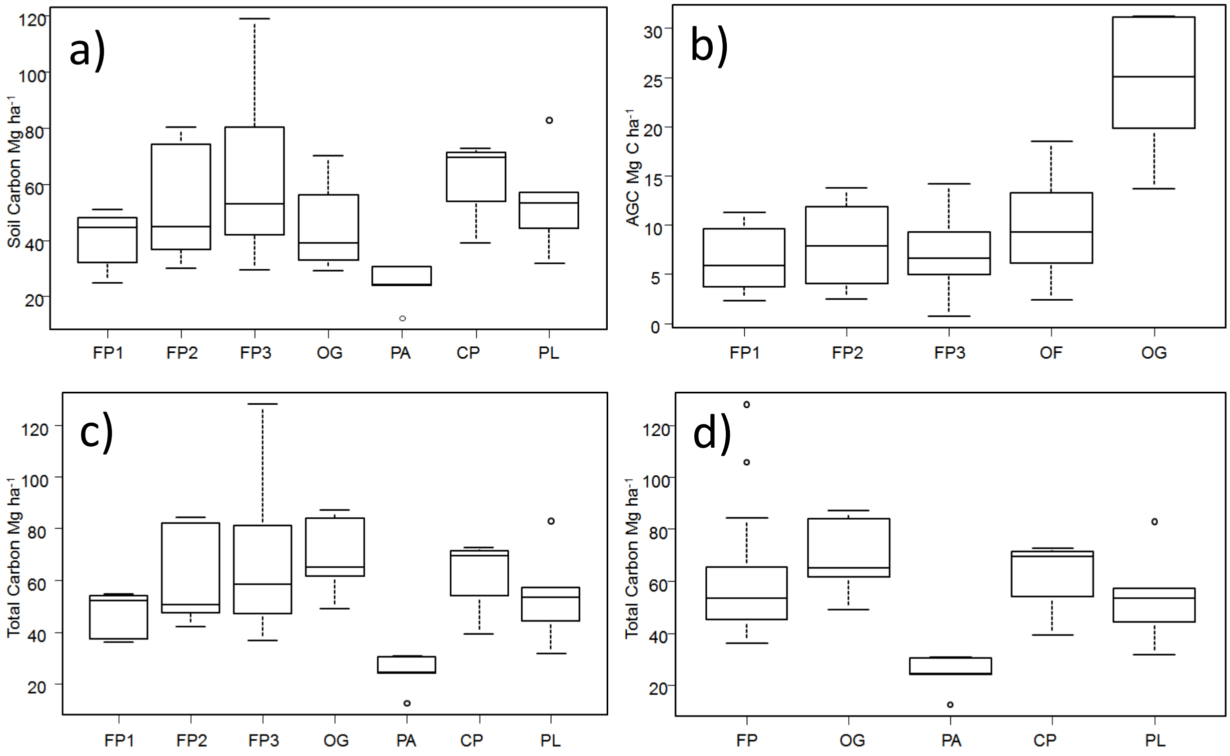

FIGURE 6.3 Carbon stocks in the study area for shifting cultivation plots and different forest categories: a) Above-ground C split by the fallow age classes, b) Soil carbon split by the fallow age class, c) Total carbon split the fallow age class and d) Total carbon in the three separate fallow phases; FP1, fallow phase of shifting cultivation years 3–6; FP2, fallow phase of shifting cultivation years 7-9; FP3, fallow phase of shifting cultivation years 10-20; FP, all fallow phases of shifting cultivation; OF, old–fallow forest (>20 years); CP, cultivation phase of shifting cultivation; OG, old growth forest; PA, permanent agriculture; PL, permanent pasture; AGC, Above-ground C. For each plot, the horizontal lines forming the top and bottom of each box respectively indicate the 25th and 75th percentiles (interquartile range) of the dataset and the horizontal middle one indicates the median. The whiskers of each plot extend to ± 1.5 interquartile range, to show variability outside the 25th and 75th quantiles and statistical outliers are represented by a dot.

There were statistically significant differences in overall AGC (Kruskal–Wallis chi-squared = 17, df= 4, $p< 0.05$). Old-growth forest has a significantly higher AGC carbon density than FP1 and FP3 (Nemenyi test, $p < 0.05$). In general, the stocks of above-ground carbon in areas within the shifting cultivation system (12-year cycle) are about 30% of those in OG and about 40% of those in the extended SC system (OF), which is in line with the findings of Houghton (2005).

TABLE 6.1 Mean and standard deviation (in parenthesis) of carbon stocks and other characteristics of sampled sites for shifting cultivation plots and different forest categories in study areas.

Class	No. of sites	Soil C (Mg/ha)	AGC (Mg/ha)	Total C (Mg/ha)	DBH (cm)	No. of trees/ha with DBH≥2.5cm	No. of stems/ha (includes multi–stemmed trees)
FP	23	52.22 (18.51)	7.03 (3.73)	59.25 (23.16)	9.1 (8.8)	1,096 (533)	2,202 (1,110)
FP1	8	40.65 (9.81)	6.46 (3.41)^{a}	47.12 (8.57)	7.4 (6.3)	1,318 (407)	2,278 (907)
FP2	5	53.23 (22.66)	7.97 (4.85)$^{a, b}$	61.21 (20.30)	8.6 (8.5)	1,025 (86)	1,725 (1,124)
FP3	10	60.97 (27.85)	7.01 (3.71)^{a}	67.99 (29.21)	11.2 (10.7)	955 (407)	2,380 (1,283)
OG	6	44.37 (16.03)	24.31 (6.95)^{b}	68.68 (14.46)	40.4(34.0)	1,154 (140)	1,750 (466)
OF	15	60.97 (27.85)[1]	9.66 (4.51)$^{a, b}$	70.63	10.7 (1.0)	1,221 (497)	2,658 (1,144)
CP	4	62.72 (15.85)	NA	62.72 (15.85)	NA	NA	NA
PL	6	53.69 (17.08)	NA	53.69 (17.08)	NA	NA	NA
PA	5	24.33 (7.40)	NA	24.33 (7.40)	NA	NA	NA

Notes: FP, mean over entire fallow phase of shifting cultivation; FP1, fallow phase years 3–6; FP2, fallow phase years 7-9 ; FP3, fallow phase years 10-20; OG, old–growth forest; OF, Old fallow forest; CP, cultivation phase of shifting cultivation; PL, permanent pasture; PA, permanent agriculture; AGC, above-ground carbon; DBH, mean diameter at breast height; NA, not available. 1 Without field data on soil carbon in the OF plots, we can assume, conservatively, that the soil carbon in OF will be the same as in FP3. Means sharing the same superscript (a and b) in AGC column show results of Nemenyi test ($P<0.05$), which indicate classes statistically not different from each other.

6.3.3 TOTAL CARBON STOCKS

In aggregate, PA shows the lowest total carbon density (Table 6.1), and includes the site with the lowest carbon in the whole sample (12.38 Mg/ha). The site with the highest carbon level (128.04 Mg/ha) was in the FP3 set.

The log of total carbon stock differed significantly with land use ($F = 7.3$, $df = 6$, $p< 0.05$); in particular, the stocks in the second and third age classes of fallow phases (FP2 and FP3), CP and PL were higher than those in PA (Tukey HSD test, $p < 0.05$) (Fig. 6.3c). There were differences ($F= 9.26$, $df = 4$, $p< 0.05$) in the log of total carbon density as well when the three fallow age classes were grouped into one class (Fig. 6.3d). Permanent agriculture had significantly lower C stocks than the other land use classes (FP1, FP2 and FP3, taken individually, FP as a whole, CP, OG, OF and PL) (Tukey HSD test, $p < 0.05$) (Fig. 6.3d).

Average carbon stocks in areas under shifting cultivation regimes (including the fallow areas) are only about 14% lower than those of OG, and 16% lower than those in the OF.

6.3.4 CARBON STOCKS AND FLUXES UNDER DIFFERENT MAIZE PRODUCTION SCENARIOS

The total area (cultivation plot plus fallow plots) required to produce 1 Mg maize in a 12-year SC system is 3.60 ha. The total carbon stocks over this area would be 210 Mg, taking into account the varying amounts of carbon in the different fallow stages (Table 6.2). The carbon stocks associated with production of 1 Mg maize through PA in this same area would be 242 Mg, taking into account that most of the area would remain under OF forest (the ´land sparing´ scenario). My results thus indicate that in the process of producing 1 Mg maize annually, the total carbon stocks in the permanent agriculture system are higher than those in shifting cultivation (Table 6.2).

The stock in an equivalent area of OF would be 254 Mg, thus the loss in stock if this land were converted from OF to SC and PA would be 43 Mg C and 12 Mg C respectively. To calculate an emission rate (annualized losses), an arbitrary (and conservative) time horizon of 20 years was used. This results in yearly emissions of 2.19 Mg C for 1 Mg maize per year for SC and 0.63 Mg C for 1 Mg maize per year for PA (Table 6.2).

TABLE 6.2 Carbon impacts of shifting cultivation versus permanent agriculture for production of 1 Mg/yr of maize. See Appendix 6, Table S1 for calculation details.

	PA	**SC**
Maize yield (Mg/ha)	3.76	1.68
Cropping area needed to produce 1 Mg maize (ha)	0.27	0.60
Area required for fallow (ha)	-	3.00
Total area required for agricultural system (ha)	0.27	3.6
Land spared for OF (ha)	3.33	-
Carbon stock in cultivated area (Mg)	6.47	37.63
Carbon stock in fallow areas (Mg)	-	172.82
Carbon stock in OF area (Mg)	235.20	-
Total carbon stock (Mg)	241.67	210.46
Total carbon stock in baseline (absence of any farming) (Mg)	254.27	254.27
Loss of carbon stock (Mg)	12.60	43.81
Annual carbon loss, over nominal production period of 20 years for	0.63	2.19

production on 1Mg maize per year (Mg)

Notes: OF, old fallow plot; PA, permanent agriculture; SC, shifting cultivation.

For the case of different fallow lengths under absence of land pressure, we consider a unit of land of 7.20 ha, which is what is needed for the operation of a 24-year SC to produce 1 Mg maize. The scenario with the longest cycle (24 years) has the lowest total carbon stocks (458 Mg C), because apart from the small patch that is under cultivation in any one year, the rest of the area is all under fallow. The shortest cycles show the highest carbon stocks (476 Mg C); since only a small part of the remaining area is under fallow, while most of the land remains as OF forest (Table 6.3). Against the baseline of OF forest, losses would be 50.15, 43.82 and 32.96 Mg C respectively for the 24-year, the 12-year and the 6-year cycle and the associated emissions would be 2.51, 2.19 and 1.65 Mg C per Mg maize per year respectively, annualized over an arbitrary period of 20 years.

TABLE 6.3 Carbon impacts of changing lengths of fallow. Average carbon stocks for shifting cultivation plots over three different fallow lengths (6- year, 12-year and 24-year cycles). See Appendix 6, Table S2 for calculation details.

	SC 6-year cycle	**SC 12-year cycle**	**SC 24-year cycle**
Maize yield (Mg/ha)	1	1	1
Rotation[1]	3	6	12
Cultivation area needed per year for production of 1 Mg maize (ha)	0.60	0.60	0.60
Area under fallow (ha)	1.20	3.00	6.60
Area remaining under OF (ha)	5.40	6.60	0.00
Total area including fallow plots (ha)	1.80	3.60	7.20
Carbon stock in cultivation area (Mg)	37.63	37.63	37.63
Carbon stock in fallowed area (Mg)	56.54	172.82	420.76
Carbon stock in OF area (Mg)	381.40	254.27	0.00
Total carbon stock (Mg)	475.58	464.72	458.39
Carbon stock in baseline (absence of any farming) (Mg)	508.54	508.54	508.54
Loss in carbon stock (Mg)	32.96	43.82	50.15
Annual carbon loss, over nominal production period of 20 years for production on 1Mg maize per year (Mg)	1.65	2.19	2.51

Notes: OF, old fallow; SC, shifting cultivation system. [1] Plot is cultivated for 2 years, so in a 24-year cycle there are 12 cohorts

The final scenario considers what would happen if cultivation cycle were to be shortened in response to a need to produce more food from the same area, i.e. as a result of increased population pressure, but still using the same basic technology (i.e. without use of fertilizers, etc). We assume that instead of 1 Mg maize, 4 are required from the same area, such that four shifting cultivators, each operating a 6-year SC cycle, are working at the same time in the 7.20 ha area described in the example above. This would result in long-run carbon stocks of 377 Mg, for the production of 4 Mg maize (Table 6.4). Annual emissions would be 1.65 Mg C per 1 Mg maize per year. The emission factor is the equivalent to that of the 6 year cycle without land pressure, despite the fact that later stages of fallow are excluded. This results from the fact that there is much more land in the relatively carbon-rich cultivation phase in the land pressure scenario, which compensates for the carbon in OF.

TABLE 6.4 Effect of land under pressure on carbon stocks and emissions when maize production rate increased by a factor of 4 over the shifting cultivation area. See Appendix 6, Table S3 for calculation details.

	SC 6 years with four farmers
Cropping area per year needed to produce 1 Mg of maize (ha)	0.60
Total production area needed (ha)	7.20
Area under cultivation (ha)	2.40
Area fallowed (ha)	4.80
Carbon stocks in cultivation area (Mg)	150.53
Carbon stocks in fallowed area (Mg)	226.18
Total carbon stocks (Mg)	376.70
Carbon stock in baseline (absence of any farming) (Mg)	508.54
Carbon loss due to cultivation	131.83
Carbon loss per Mg maize produced (Mg)	32.96
Emissions per Mg maize, annualised over nominal 20 years (Mg/year)	1.65

Notes: OF, Old fallow; SC, shifting cultivation system

6.4 DISCUSSION

This study contributes to understanding on carbon emissions from shifting cultivation and the carbon sequestered in dryland systems under both intensification and de-intensification of this agricultural system. Based on my results and consistent with previous studies (Hett et al. 2012, Mertz 2009, Rambo 1990, Ickowitz 2006), we argue that shifting cultivation does not result in deforestation (forest cover loss), but in temporary removal of trees, modifying the vegetative cover to a mosaic landscape of secondary growth forests (Fox et al. 2000). The quantitative estimations of carbon emissions obtained in this study provide tangible evidence that shifting cultivation should be considered as forest degradation, not deforestation. Although the role of this agricultural system on emissions has been widely discussed in the literature in the context of deforestation (Houghton et al. 2003, Houghton and Goodale 2004, Nigh and Diemont 2013), the forest succession characteristics which shifting cultivation involve have not been fully taken into account in estimating emissions and my study provides some information to fill this gap. This also considering that fallows lies in the fact that new wody vegetation resulting from the secondary succession process can act as ‘carbon banks’, with higher potential in storing carbon than mature forest.

Dry tropical forest in Mexico shows wide variations in forest biomass (Delaney et al. 1997, Jaramillo et al. 2003, Vargas et al. 2008, Kauffman et al. 2009, Jaramillo et al. 2011). Above-ground biomass for the study area is at the lower end of the scale, as a result of the fact that the area has been impacted by human uses like agriculture and cattle ranching at least since Mexico's colonial era and heavily used for shifting cultivation over the last fifty years. My results agree with other reports that above-ground carbon stocks increase rapidly in the years following cultivation, the early forest successional stages (Read and Lawrence 2003, Chazdon et al. 2007, Lebrija–Trejos et al. 2010, Williams-Linera et al. 2011, Pelletier et al. 2012). Where the fallow phase is long, the carbon stocks would reach levels similar to those of old growth forests after 20 years, although more of this carbon is in the soil and less in the above-ground pools. This trend shows the high potential of this dryland farming system for sequestering carbon. In addition, the time needed for carbon level to recover to the levels found in these forests is in reality highly variable (Lawrence and Foster 2002, Lebrija–Trejos et al. 2008).

The finding that soil carbon forms such a large proportion of the total carbon in the TDF ecosystem is not new (Delaney et al. 1997, Jaramillo et al. 2003, 2011, Vargas et al. 2008, Kauffman et al. 2009, Scharlemann et al. 2014). Soil carbon is the largest carbon pool in the terrestrial biosphere (Jobbágy and Jackson 2000), and for tropical dry forest the amount of carbon contained in soils varies greatly (Post et al. 1982, Jaramillo et al. 2003, Marín-Spiotta and Sharma 2013, Campo et al. 2016). Values approaching those we found in my case studies are reported for TDF in Mexico by the Instituto Nacional de Investigaciones en Cambio Climático (INECC 2010). However, most of this carbon is in the upper layers of the soil; TDF soils are in general shallow (Trejo and Dirzo 2000), and their exposure, for example through the creation of fields for permanent cultivation, can result in rapid loss of much of this carbon, as my data show.

Our study reveals, however, that the presence of so much soil carbon mitigates or helps to balance the losses of carbon in above-ground vegetation when the clearance is only temporary as in shifting cultivation. The burning produces charcoal and ash that increase soil carbon, as in the very high levels we observed in the cultivation phase of shifting cultivation. These values then drop in the first fallow period but increase rapidly in the second fallow phase; faster, indeed, than the recovery of the above-ground carbon stocks. In the case of permanent agriculture on the other hand, soil carbon levels are rapidly depleted and do not recover. In all, the case study provides evidence to support findings in other studies that the rate of recapture of carbon stocks in the fallow periods following cultivation is high (Pelletier et al. 2012, Nigh and Diemont 2013). Moreover, we show that the secondary forest which develops on the fallows if they are left for over 20 years bears more total carbon stock than old growth forest which has never been in the SC cycle.

This has important implications as regards climate policy in areas of the kind we were studying, which are dominated by small scale and subsistence production. Shortened cycles are frequently blamed for increased levels of deforestation and degradation and for increased carbon emissions (Houghton 2012, Nigh and Diemont 2013, Geist and Lambin 2001, 2002, see also the analysis of drivers in many of the REDD+ Readiness documents, Salvini et al. 2014). However, my study indicates that shortened cycles do not result in increased emissions, but rather in decreased emissions, even when the reason for the shortened cycle is increased pressure on the land, i.e. when a larger proportion of the land is brought into production. In reality, cycles in the study area have been shortening in the past decade for various reasons other than land pressure, including government subsidy programmes and may also in part be a labour saving strategy. However, as with my analysis of permanent agriculture, we did not take account of the emissions that would result from the (limited) use of fertilizers in the most shortened cycles. We was not able to make a quantitative longitudinal analysis of the impacts of repeated cycles of SC, which have been observed to result in lowered soil carbon levels in some parts of Mexico, such as the Yucatán (Eaton and Lawrence 2009) but note that many of the plots we studied had been in a SC cycle for generations, without noticeably reduced soil carbon levels. We have not made a detailed analysis of the impact on biodiversity, which might also be affected.

Our results therefore have relevance to the debate on land sparing. Agricultural intensification is the most common intervention proposed in the readiness documents of 43 REDD+ countries to tackle agriculture-driven deforestation and forest degradation (Salvini et al. 2014), and is regularly advocated as a means of reducing deforestation in general (Carter et al. 2015). It is also being advocated in Mexico in the context of climate change mitigation and REDD+ (ECOSUR 2012, Quintana Roo 2016, Chiapas 2016, JIRA 2015). The idea of ´land sparing´ through agricultural intensification (the Borlaug hypothesis) is, however, controversial. At the local level, intensification could have the perverse effect of increasing deforestation if it results in improved profitability, as this could raise the demand for land, illustrating the Jevons paradox (Angelsen and Kaimowitz 2001, Rudel et al. 2009, Perfecto and Vandermeer 2010, Gockowski and Sonwa 2011, Pirard and Belna 2012, Byerlee et al. 2014). However the Borlaug hypothesis is widely supported (e.g. Grau and Aide 2008) and there is evidence that at the global level technology–driven (rather than market driven) intensification may be correlated with lower deforestation rates (Andersen et al. 2002, Byerlee et al. 2014). We believe that the intensification we observed in the case study area, which has led to lower emissions rates, is neither the result of population pressure nor market driven but mainly the unintended result of a government subsidy programme, PROCAMPO, as well as the availability of subsidies for fertilizers and changes in farmers´ time budgets.

Our study also adds to the discussion around the Borlaug hypothesis in that the modeling of outcomes demonstrates lower emissions from agricultural systems based on intensive crop production (permanent agriculture) than from shifting cultivation, for a given level of production of food. We must underline however that this does not take into account the much higher energy inputs that intensive crop production requires in the form of fertilizers and pesticides and the long time scales they require for recovery of soil physical status. An analysis of this would be needed to make a fair comparison, but was beyond the scope of this study.

The alternative strategy sometimes proposed in the context of improved environmental management (Dalle and de Blois 2006, Eaton and Lawrence 2009) is to lengthen shifting cultivation cycles (de-intensification of agriculture). We have shown that at least in my case study area this will increase, rather than reduce emissions.

Despite the fact that my results show lower emissions under permanent agriculture, and lower emissions under shortened SC systems than under traditional cycle lengths, we urge caution in the promotion of policies to curtail shifting cultivation and to move towards more intensified ´spatially segregated’ landscapes in which there is permanent agriculture and untouched forest (van Noordwijk et al. 2012). In part this is because as noted above we did not include in my calculations the emissions from fuel and fertilizers that would undoubtedly be associated with permanent cropping systems. There are however other reasons. Under land sparing schemes the goals are strictly separated; agricultural production is maximized in some areas, and other areas are set aside for carbon sequestration (Perfecto and Vandermeer 2010). The alternative, land sharing (Perfecto and Vandermeer 2010), which aims at both objectives on the same area of land, may in the long run be a better solution. We have shown that shifting cultivation with shortened cycles may be a good step towards intensification and towards reduced emissions. The values of carbon stocks we found in the cultivation and fallow phases indicate that there may be room to optimize total carbon stocks in shifting cultivation systems, and reduce emission rates, by managing the lengths of the cycle better. Decreases of the amount of land under cultivation in SC could also be achieved by improving local management strategies (for a case in the Yucatan, Mexico, see Pascual (2005)).

6.5 CONCLUSION

Our study shows that shifting cultivation results in a lowering of above-ground carbon stocks in the forests affected, which in terms of REDD+ should be considered to constitute degradation. In very few cases does it result in deforestation, since the forest remains forest over the long term. My indications are that it results in more carbon emissions per tonne of maize than would be produced in permanent agricultural systems, although my calculations do not include the additional emissions that would be associated with the much higher energy inputs used in permanent agriculture, which would reduce the observed difference. However, we show that per tonne of maize produced, shorter SC cycles result in higher overall stocks of carbon and lower emissions. In the study area, recent reductions in the cycle appear to be a response to a variety of policy initiatives and financial incentives rather than to population pressure or market forces.

These findings are very significant for REDD+ policy, since shifting cultivation is often held to be the cause of deforestation and either its replacement by permanent agriculture (´agricultural intensification´ or ´sedentarization of agriculture´), or lengthening of fallows are often advocated as the means to reduce carbon emissions. If my findings are correct, they suggest that policies on shifting cultivation may need to be nuanced in the context of climate change. Cycles could be optimized to increase carbon stocks while maintaining the traditional benefits of SC systems in a land sharing scenario. At the very least, the reasons for shortened fallows would need to be thoroughly investigated at the local level before a policy either to eliminate shifting cultivation all together, or to extend the cycle length, is promoted.

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APPENDIX 5

Table S1. List of tree species found in the different land categories, grouped by family. Taxonomic information from Tropicos.org (2016).

Specie	**FP1**	**FP2**	**FP3**	**OG**
Anacardiaceae				
Comocladia engleriana Loes.				X
Cyrtocarpa procera Kunth				X
Spondias purpurea L.		X	X	
Apocynaceae				
Thevetia ovata (Cav.) A. DC.	X			
Bignoniaceae				
Crescentia alata Kunth	X			
Tabebuia chrysantha (Jacq.) G. Nicholson		X		X
Tabebuia rosea (Bertol.) DC.	X			
Bombacaceae				
Pseudobombax ellipticum (Kunth) Dugand				X
Boraginaceae				
Cordia alliodora (Ruiz & Pav.) Oken				X
Burseraceae				
Bursera sp1. Jacq. ex L.	X	X	X	X
Bursera sp2 Jacq. ex L.				X
Caricaceae				
Jacaratia mexicana A. DC.				X
Celastraceae				
Wimmeria lanceolata Rose			X	X
Cistaceae				
Helianthemum glomeratum (Lag.) Lag.	X	X	X	
Convolvulaceae				
Ipomoea arborescens (Humb. & Bonpl. ex Willd.) G. Don+				X
Euphorbiaceae				
Croton pseudoniveus Lundell		X		
Jatropha cordata (Ortega) Müll. Arg.				X
Fabaceae				

Acacia farnesiana (L.) Willd.	X	X	X	X
Acacia macilenta Rose	X	X	X	X
Acacia macracantha Humb. & Bonpl. ex Willd.	X	X	X	X
Acacia pennatula (Schltdl. & Cham.) Benth.	X			
Acacia riparia Kunth			X	X
Albizia tomentosa (Micheli) Standl.	X	X	X	X
Bauhinia divaricata L.			X	
Eysenhardtia polystachya (Ortega) Sarg.				X
Leucaena esculenta (Moc. & Sessé ex DC.) Benth.	X	X	X	X
Lysiloma acapulcense (Kunth) Benth.	X		X	
Lysiloma divaricatum (Jacq.) J.F. Macbr.	X	X	X	X
Pithecellobium dulce (Roxb.) Benth.	X	X	X	
Pithecellobium lanceolatum (Humb. & Bonpl. ex Willd.) Benth.	X	X	X	X
Prosopis laevigata (Humb. & Bonpl. ex Willd.) M.C. Johnst.			X	
Senna atomaria (L.) H.S. Irwin & Barneby		X	X	X
Senna hirsuta (L.) H.S. Irwin & Barneby	X		X	
Leguminosae				
Leguminosae sp1	X			X
Malpighiaceae				
Lasiocarpus ferrugineus Gentry	X	X		X
Malvaceae				
Ceiba pentandra (L.) Gaertn.			X	X
Guazuma ulmifolia Lam.	X	X	X	X
Heliocarpus terebinthinaceus (DC.) Hochr	X	X		
Meliaceae				
Cedrela salvadorensis Standl.				X
Mimosaceae				
Enterolobium cyclocarpum (Jacq.) Griseb.	X	X	X	
Moraceae				
Ficus sp L.				X
Ficus sp2 L.			X	
Myrtaceae				
Eugenia sp1 L.	X		X	

Psidium sartorianum (O. Berg) Nied.	X			
Myrcianthes fragrans (Sw.) McVaugh			X	
Piperaceae				
Piper sp1 L.				X
Rhamnaceae				
Ziziphus mexicana Rose	X	X	X	X
Rubiaceae				
Hintonia latiflora (Sessé & Moc. ex DC.) Bullock			X	X
Rutaceae				
Zanthoxylum fagara (L.) Sarg.	X			X
Zanthoxylum sp1 L.	X	X		X
Salicaceae				
Casearia corymbosa Kunth	X	X	X	X
Sapindaceae				
Paullinia fuscescens Kunth				X
Sapotaceae				
Sideroxylon capiri (A. DC.) Pittier				X
Theophrastaceae				
Jacquinia pungens A. Gray				X
NA				
Sp1				X
Sp2	X		X	X
Sp3		X	X	
Sp4				X
Sp5				X
Sp6		X		
Sp7				X
Sp8	X		X	X
Sp9		X		X
Sp10				X
Sp11			X	
Sp12		X	X	
Sp13	X			

Sp14				X
Sp15				X
Sp16			X	X
Sp17	X			
Sp18	X			
Sp19			X	
Sp20	X	X	X	X
Sp21	X	X	X	
Sp22				X
Sp23	X	X	X	

FP1, fallow phase 1 of shifting cultivation cycle (3rd–4th year); FP2, fallow phase 2 (5th–7th year); FP3, fallow phase 3 (8th–20th year); OG, old growth forest which has not been used for shifting cultivation; NA, unidentified species. Sp, name of group of individuals based on morphological sameness.

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APPENDIX 6

Table S1 Carbon impacts of shifting cultivation versus permanent agriculture for production of 1 Mg of maize/year.yr 1 of maize. (12 year shifting cultivation cycle with 2 years cultivation phase). Variables are lettered and calculations are shown in bold using those letters.

Letter variable	Variable	Value	
a	Carbon stocks in Coamil cropping area (Mg/ha)	62.72	
b	Carbon stocks in FP1 (Mg/ha)	47.12	
c	Carbon stocks in FP2 (Mg/ha)	61.21	
d	Carbon stocks in FP3 (Mg/ha)	67.99	
e	Carbon stocks in PA plots (Mg/ha)	24.33	
f	Carbon stocks in OF (Mg/ha)	70.63	
		PA	**SC**
g	Maize yield (Mg/ha)	3.76	1.68
h	Cropping area needed to produce 1 Mg maize (ha)	0.27	0.60
j	Total production area including fallows	0.27	3.60
k	Years under cultivation	12	2
m	Years under FP1	0	4
n	Years under FP2	0	3
p	Years under FP3	0	3
q	Area (ha) under FP1 (**m/12*j**)	0	1.20
r	Area (ha) under FP2 (**n/12*j**)	0	0.90
s	Area (ha) under FP3 (**p/12*j**)	0	0.90
t	Area (ha) under OF (**3.6-j**)	3.33	0
u	Carbon stock cropping area (Mg), (**e*h**), (**a*h**)	6.47	37.33
v	Carbon stock FP1 (Mg), (**b*q**)	0	56.54
w	Carbon stock FP2 (Mg), (**c*r**)	0	55.09
x	Carbon stock FP3 (Mg), (**d*s**)	0	61.19
y	Carbon stock OF (Mg), (**f*t**)	235.20	0
z	Total carbon stock (Mg), (**u+v+w+x+y**)	241.67	210.16
AA	Carbon stock in baseline (**3.60*f**)	254.27	254.27
BB	Carbon lost as result of agriculture (**AA-z**)	12.60	44.11
CC	Carbon loss per Mg maize/year, annualised over nominal 20 years (**BB/20**) (Mg/year)	0.63	2.21

Table S2. Carbon impacts of changing lengths of fallow. Average carbon stocks for shifting cultivation plots over three different fallow lengths (6- year, 12-year and 24-year cycles). Variables are lettered and calculations are shown in bold using those letters.

Letter variable	Variable	Value
a	Carbon stocks in cultivation stage (C; years 1 and 2) of cycle Mg/ha	62.72
b	Carbon stocks in FP1 (years 3-6) Mg/ha	47.12
c	Carbon stocks in FP2 (years 7-9) Mg/ha	61.21
d	Carbon stocks in FP3 (years 10-20) Mg/ha	67.99
e	Carbon stock OF Mg/ha	70.63

		SC 6-year cycle	**SC 12-year cycle**	**SC 24-year cycle**
f	Maize yield Mg/ha	1.6	1.6	1.6
g	Cultivation plot needed per year for production of 1 Mg maize	0.6	0.6	0.6
h	Rotation multiplier [1]	3	6	12
j	Total production area including fallow (**g*h**)	1.80	3.60	7.20
k	Years under cultivation phase	2	2	2
l	Years under FP1	4	4	4
m	Years under FP2	0	3	3
n	Years under FP3	0	3	11
p	Years under OF (following first 20 years of cycle)	0	0	4
q	Total years in cycle	6	12	24
Production area				
r	Area (ha) under C per year (**k/q***j)	0.60	0.60	0.60
s	Area (ha) under FP1 ha per year (**l/q*j**)	1.20	1.20	1.20
t	Area (ha) under FP2 ha per year (**m/q*j**)	0	0.90	0.90
u	Area (ha) under FP3 ha per year (**n/q*j**)	0	0.90	3.30
v	Area (ha) under end of fallow OF ha per year	0	0	1.20

	(**p/q * j**)			
w	Area (ha) of OF untouched by production (**7.20-j**)	5.40	3.60	0.00
Carbon stocks				
A	Carbon stock in cultivation area Mg (**r*a**)	37.63	37.63	37.63
B	Carbon stock in FP1 area (Mg), (**s*b**)	56.54	56.54	56.54
C	Carbon stock in FP2 area (Mg), (**t*c**)	0	55.09	55.09
D	Carbon stock in FP3 area (Mg), (**u*d**)	0	61.19	224.37
E	Carbon stock in end of fallow OF area (Mg), (**v*e**)	0	0	84.76
F	Carbon stock in untouched OF (Mg), (**w*e**)	381.40	254.27	0
G	Total carbon stocks (Mg), (**A+B+C+D+E+F**)	475.58	464.72	458.39
H	Total carbon stocks in baseline (Mg), (**7.2 ha*e**)	508.54	508.54	508.54
BB	Difference (Mg) (**H-G**)	32.96	43.82	50.15
CC	Emissions per Mg Maize/year, annualised over 20 years (**BB/20**) (Mg/year)	1.65	2.19	2.51

[1] Plot is cultivated for 2 years; total area needed in 6/12/24 year cycles is therefore 3/6/12 times this area, including fallows

Table S3 Effect of land under pressure on carbon stocks and emissions when maize production rate increased by a factor of 4 over the shifting cultivation area. (4 sets of 6 year shifting cultivation cycle on 7.20ha). Variables are lettered and calculations are shown in red using those letters.

Letter variable	Variable	Value
a	Carbon stocks in Coamil (cultivation phase)(Mg/ha)	62.72
b	Carbon stocks in FP1 (Mg/ha)	47.12
c	Carbon stocks in OF (Mg/ha)	70.63
d	Cropping area (ha) per year needed to produce 1 Mg of maize	0.6
e	Years under cultivation	2
f	Years under fallow FP1	4
g	Total production area (ha) needed	7.20
h	Area (ha) under cultivation (**4*d**)	2.40
j	Area (ha) under fallow FP1 (**g-h**)	4.80
k	Carbon stock in cultivation areas (Mg), (**a*h**)	150.53
m	Carbon stock in fallow areas (Mg), (**b*j**)	226.18
n	Total carbon stock (Mg), (**k+m**)	376.70
p	Carbon stock in baseline (Mg), (7.2 ha*c)	508.54
q	Carbon loss due to cultivation (Mg), (**p-n**)	131.83
r	Total maize production per year (Mg)	4
s	Carbon loss per Mg maize produced (**q/r**)	32.96
t	Emissions per Mg maize/year, annualised over nominal 20 years (**t/20**) (Mg/year)	1.65

Chapter 7

DISCUSSION OF RESULTS

7.1 INTRODUCTION

This final chapter first presents a general discussion with a view to answering the research questions of the thesis. It then highlights in general terms the original contributions that this study has made to the knowledge and the policy implications of these. Finally, it considers limitations of the study and suggests future research that could be done to overcome the limitations.

As will be recalled from Chapter 1, the overarching research question in this thesis concerns assessing the ability of SDTF to provide ecosystem services, in particular carbon services, which could be developed and rewarded through international policy of reduction for deforestation and degradation (REDD+). This research question was broken down into a logical tree of component elements under this overarching question (Fig. 1.1 in Chapter 1), and several researchable sub-questions were identified, the answers to which are summarized here.

7.2 SUB-RESEARCH QUESTION 1:

How are above ground biomass patterns related to multiple biophysical factors, such as elevation, slope and insolation, and also human factors in the region of Ayuquila, Mexico? (Fig. 7.1)

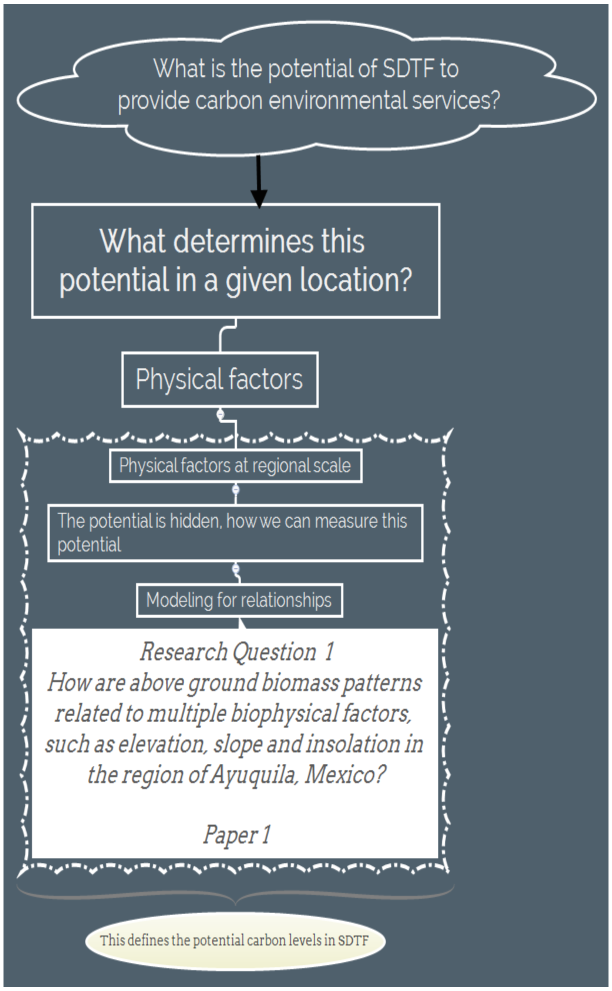


FIGURE 7.1 Elements of the overall diagram which relate to question 1

The first finding of my study, as described in Paper 1 (Chapter 4) is that there are different biomass responses within a general pattern, depending on two sets of variables. On the one hand, a number of topographic variables both regional and local were found to be determinants of biomass patterns. On the other hand, human activities were also found to have an important role in biomass patterns. These two types of variables have a complex relationship and finding their footprint in the structure of the forests may depend in part on the method that is used. Within the topographic variables are some that are considered regional, such as elevation above sea level and diffuse insolation. Elevation influences a number of other variables that are reflected in a progressive change in micro-climate along the hillslope. Some of those are also intimately and directly connected with elevation (Körner 2007), for example radiation from the sun, which is dispersed by small suspended solid particles and atmospheric gases in the atmosphere, vapors and particles of dust. The higher the elevation, the lower the amount of diffuse insolation that can reach the vegetation. Some other variables are not related to elevation above sea level, such as geology (Körner 2007).

An analysis of variance of field biomass data helped me to show that these data vary widely between rural communities; this means that in the Ayuquila basin I find some communities with high levels of biomass and some communities with little biomass. For example, Chiquihuitlán, El Temazcal and Tonaya communities have very similar, low, levels of biomass. But some sites within Agua Hedionda have levels as low as the average in these three communities, although its overall average is much higher, and a similar distribution is found in Zenzontla (i.e. a very large range). The Ayutita sites had very high biomass levels in relation to the other communities.

I also looked for linear relationships between biomass and topographic variables. I started with simple linear relationships between independent and dependent variables; ideally, these models aim to indicate that a change in a unit of the independent variable is reflected in a proportional change in the magnitude of the dependent variable (AGB). Through this relationship, it is possible to make predictions relying only on the values of independent topographic variables. I found two linear models that significantly explained the relationships between topography and biomass. The first model includes two variables, one local and one regional: slope and elevation. This model shows an additive effect between these two variables, explaining 19% of the variation in my data. In this model, the relative importance of slope and altitude in explaining the variation of the AGB is very different in different parts of the area studied, with elevation being the more important explanator (73% of the 19%). This suggests that a large proportion of the variation in AGB values is determined by large differences in elevation and my predictions are very marked by this effect.

The second model also includes both types of variables; elevation as a regional variable and slope, topographic humidity index and a terrain curvature index indicating concavity and convexity sites (ctan), all as local variables. In this model, a more sophisticated approach was taken in that sampling sites within any one community territory were considered to be not independent of each other, though independent of those in other communities. This is because from field observations, I was able to distinguish that even contiguous communities may have different ways of managing the forest (see Chapter 6). This model was the best for explaining the variation of biomass within the entire study area, explaining 21% of the variance. The relative importance of the significant variables included in this model is distributed; a larger number of significant variables are included in the model with elevation and ctan having the highest explanatory value, and slope and topographic humidity index having the lowest.

Additionally, I found four non-linear models that helped me to explain the AGB variation; however, the complexity of these models is greater than that of a linear model and some do not allow predictions. Three of these models apply overall to the entire area, one of them to very specific conditions. The first, a CART model, split the six communities into two groups (Group A and Group B), as their biomass levels are explained by different sets and weights of the topographic variables. This model explains 30% of the variation in my data. This model separates the communities of Agua Hedionda, Chiquihuitlán, Temazcal and Tonaya into one group and the remaining two, Zenzontla and Ayutita, into another group. This is despite the fact that as noted above, in many ways Agua Hedionda and Zenzontla appears to have more in common than Zenzontla and Ayutita. In this model, the importance of non-independence of sites within any one community can clearly be seen; altitude was the key variable for the second group. The second non-linear model, a piecewise linear model, relates AGB to a combination of altitude and slope thresholds. In this combination of thresholds, biomass behaves very differently above 1400 m above sea level and when the slope of the terrain is higher than 47%. This piecewise model explains 24% of AGB variation. The third non-linear model, also a piecewise linear model, relates AGB to a threshold of the distance between the sampling point and the nearest road. I found that at distances of less than 2,200 m, AGB levels are higher as you move away from the road, but this ratio is reversed after that threshold. This model helped me to explain 20% of the variation in my AGB data. I also performed a MARS model that shows a non-linear relationship between biomass for communities at higher sites and certain diffuse insolation thresholds.

Within the group of communities that the CART analysis distinguished as group A (Agua Hedionda, Chiquihuitlán, Temazcal and Tonaya) it was found that there is a slight negative relationship between the biomass of the sites and values that are less than 11.8 on the topographic position index at the scale of 19 pixels; however, above this value, the relationship is reversed and becomes very positive, indicating higher values at more sheltered sites. On the other hand, the communities of group B (Zenzontla and Ayutita) showed a positive relationship only between biomass and elevation. The variation explained by these models was 27% for group A, and 14% for group B.

Most studies related to this tropical forest type have been made in highly conserved forest (Jaramillo et al. 2003), where there is no human influence; in my case studies, there is a great deal of human activity going on which lowers biomass levels in some places. I found that in my study area, sites in the low areas of the region have lower biomass levels than those found in the highland, which is in some ways an unexpected outcome. It can be explained by the fact that most human activities are carried out in this area, largely because these low areas have the best conditions for crop production. The flatest areas located in these lowlands are already mostly devoid of vegetation, because deforestation had been carried out here to make way for agricultural crops on a permanent basis. While human extractive activities of low impact such as firewood collection, fence posts and shifting cultivation are regularly performed in areas with slightly steeper slopes, stony terrain and less nutrients, livestock grazing in the forest also impacts forest recuperation. The effect of human uses on forest is also evidenced by the non-linear relationships between the sampled sites and the distance to the nearest roads. All these results suggest a number of things. The first is that through this method it will be possible to identify communities where carbon levels are well below those that could be expected. The most relevant thing about this method is that it can be carried out for the landscapes of different communities, using only variables derived from digital elevation models, which are freely available for download in Mexico and many developing countries.

However, none of the models produced high correlations, which means that the results are not directly useful as such for planning REDD+ interventions at the community level. The main value of the exercise carried out in Paper 1 (Chapter 4) was identification of which factors are overall the strongest in the explanations of regional AGB patterns, and can therefore be used in developing models at regional scale. The second paper builds on the findings of Paper 1 to create better models, which are spatialized and which provide a higher level of prediction, and therefore have much more value in this context.

Unraveling the factors that explain field levels of AGB is a challenging task, but in short, to answer sub-research question 1, I found that from a large range of candidate variables related to topography which were initially included in the analysis, only a few were shown to be significantly related to biomass levels as measured in the field. Elevation and slope consistently appeared as the most important explanators. The effect of elevation is probably not only related to underlying differences in temperature, but also to the availability of diffuse sunlight. On the other hand, slope is a primary determinant of the human activities which change biomass levels. Of the two directly measured human factors that were included in the analysis (distance from settlements and distance from roads), only distance from roads was significantly related to AGB.

7.3 SUB-RESEARCH QUESTION 2:

To what extent can spatial prediction of standing aboveground biomass (AGB) help to identify the locations within community territory that are most suited to the establishment of carbon enhancement projects? (Fig. 7.2)

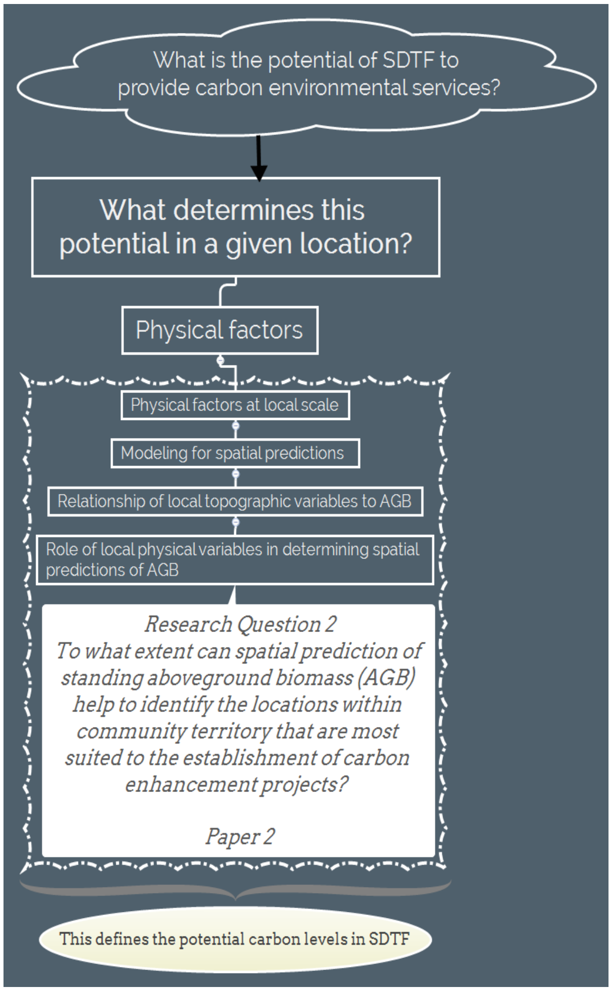


FIGURE 7.2 Elements of the overall diagram which relate to question 2

This sub-question addresses the conditions within the territory of each rural community, at local scale, that is to say not just up and down the slope as was the case in Chapter 4, but across the whole landscape. At this level of analysis I used a method for finding sites within the communities where biomass levels are below levels of their biological potential, i.e. areas in which enhancement could in theory be achieved. This analysis was carried out for four rural communities in the area of study: Agua Hedionda, Ayutita, Chiquihuitlan and Zenzontla. For these four communities I analyzed a very large number of alternatives (48,960 models) and selected the Bayesian geostatistical models that best predict biomass in each of the communities. These models are a combination of 15 models that incorporate four topographic covariates as well as spatial components. Notably, the selected models contain variables that relate water movement and accumulation in the surface of the territory. Topographic wetness index, tangential curvature of terrain and slope were the significant variables that were included in the models for the four communities. The tangential curvature of the terrain, which indicates concavity and convexity of the sites, was the variable with the greatest effect on standing biomass when this is viewed not in two dimensions, as was the case for the analysis done in Chapter 4, but in three dimensions. Essentially this variable is an indicator of soil water availability; concave sites tend to accumulate water, which is a key limiting factor for plant growth in these dry zones. The selected models had prediction accuracies for AGB of between 65% and 85%. AGB predictions for Chiquihuitlan were the best at 85%, followed by Ayutita, Agua Hedionda and finally Zenzontla with an accuracy of 65%.

Many studies have shown that topography and soil properties strongly influence soil water availability (Borchert 1994, Oliveira-Filho et al. 1998, Segura et al. 2002), and that the spatial distribution of water availability in SDTF remains relatively stable over long periods of time (Murphy and Lugo 1986, Ceccon et al. 2006, Nath et al. 2006). Although nutrient heterogeneity may cause part of the observed differences in standing AGB in SDTF, the relative effect of soil water availability is much larger (Bullock et al. 1995, Oliveira-Filho et al. 1998), as my study showed, because functioning of SDTFs is more limited by physical constraints such as water availability and topography (Bullock et al. 1995). Pulses in availability (sudden increases and slow reductions) drive water availability in SDTF. With the onset of the dry season, soil water availability decreases at a slow pace. This allows concave areas to retain water longer than convex ones. These patterns in water availability are clearly recognised by farmers, who know from experience which portions of the landscape are too wet or too dry for agriculture; however, the concave areas are ideal for higher levels of natural AGB, while convex areas will never be able to reach such high AGB levels (Scholten et al. 2017). Using the topographic wetness index, curvature of terrain and slope as indirect measure of the spatial distribution of wetness conditions in field I found that together they had significance in explaining AGB levels.

These findings provide a clear answer to sub-research question 2: the sites which offer highest potential for forest enhancement projects within any one community will be those areas which are concave and which currently have low biomass levels because of human uses. This is regardless of other variables such as elevation and slope, since these variables are of only secondary importance in explaining AGB densities. Degraded forest in concave sites may therefore be selected and targeted under REDD+, for example by ensuring that they are not accessible to cattle, or by removing shifting cultivation to other sites. This simple rule may help the efficiency of REDD+ planning at community level, allowing normal farming activities to go on as usual in other parts of the landscape but protecting these sites in particular, where natural regeneration will proceed fast and result in a high level of biomass and thus of carbon storage.

7.4 SUB-RESEARCH QUESTION 3:

Following this insight, this sub-research question (Fig. 7.3) deals with possibilities for intervention. Give that shifting agriculture is considered by many to be the major cause of lowered biomass levels (degradation), if not of deforestation in the area, it asks: *what is the impact of shifting cultivation on carbon stocks and how can cultivation cycles be optimized to promote carbon sequestration ?*

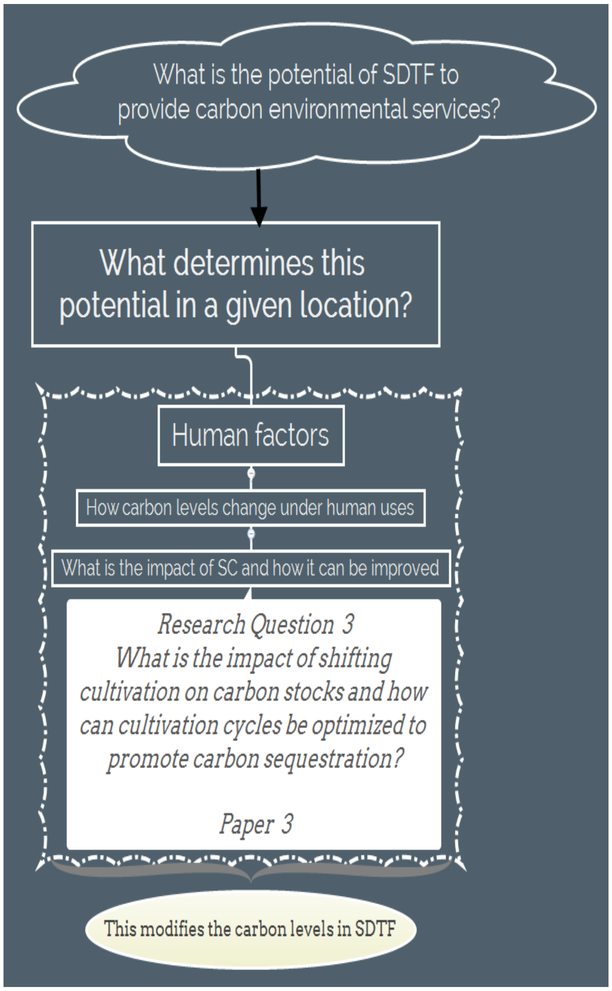


FIGURE 7.3 Elements of the overall diagram which relate to question 3

This question was dealt with in depth in Paper 3 (Chapter 6). First, it was established that in the area of concern, shifting cultivation does result in degradation of the SDTF and associated lowered carbon stocks, but that it does not result in deforestation (defined as permanent clearance of land, i.e. where forest does not return within 20 years).

To quantify the impact of shifting cultivation on carbon stocks, I performed an analysis of variance to examine differences in carbon storage at two levels; first between main land-use categories and then between these same categories and the different phases of the shifting cultivation cycle. Five land uses were identified: old growth forest (OG); old-fallow forest (OF, i.e. sites which have been under fallow for more than 20 years); pasture lands (PL); permanent agriculture (PA) and shifting cultivation agriculture (SC), which was divided into different stages, i.e. cultivation period (CP) and fallow phase (FP), which itself was divided into three periods (FP1:3-6 years, FP2 7-9 years and FP3 10-20 years). Two different carbon pools were measured; aboveground carbon and soil carbon; calculations were also made for total carbon (the sum of above ground and soil carbon).

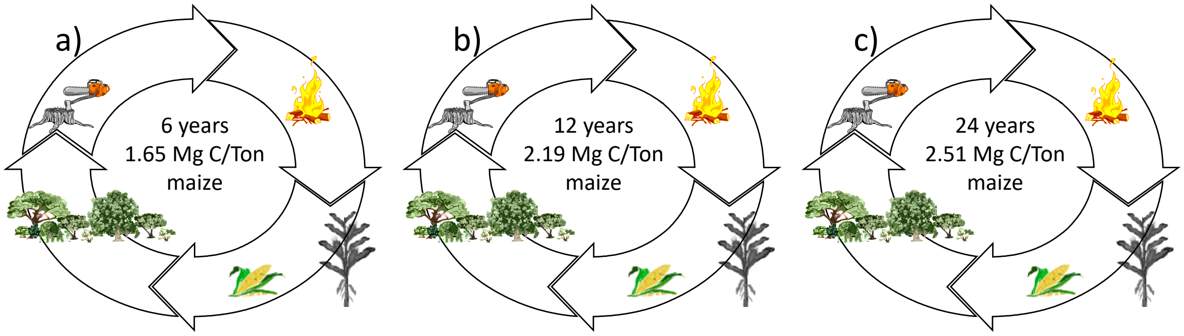
I first identified carbon stocks by land use category. OG has the highest levels of AGB and hence of above ground carbon (AGC), PA has the least (it is assumed to have zero carbon stock in its above ground parts, as there are almost no trees associated with this land use). On average, sites with SC (taking into account the full cycle of cultivation and fallow) had 30% less AGC than OG sites, and 40% less AGC than OF sites. There is more soil carbon in FP2, FP3, CP and PL than in permanent agriculture. There was on average about 10% more soil carbon in sites under the SC regime than in OG, indicating that the process of SC brings about additional carbon sequestration in the soils.

The categories with highest and lowest total carbon were FP3 and PA, respectively. When comparing total carbon between categories, CP and PL had higher levels than PA. The fallow periods (FP) pooled together had much higher levels than PA. The average amount of total carbon stored in SC areas is 14% lower than those values in OG sites and 16% lower than that of OF sites. Hence while it is clear that shifting cultivation lowers stocks, on average this reduction is less than 20% compared to forested parts of the study area which are conserved as forest.

Any interventions in this cultivation system, for example under REDD+, to maintain or increase carbon stocks need to take into account the fact that shifting cultivation is primarily a system designed to produce food (maize) and that simply eliminating it will displace the demand to other places or to other forms of production. I therefore made some calculations relating to carbon emissions per ton of maize production for the two agricultural systems in the study area aimed to produce maize (i.e. comparing permanent agriculture versus shifting cultivation).

I first made an estimate of the carbon balance for the production of 1 Mg of maize in a SC system and in a PA system for comparison. I started by calculating the carbon impacts of a SC system of 12 years (2 year cultivation and 10 of fallow), against those of PA. Secondly, because the duration of the SC cycle in the study area has been shortened recently to 2 years of cultivation and 8 years of fallow as a result of agricultural subsidies, I made calculations also for this cycle. I then looked at two different future scenarios, to estimate the impacts that would occur if different kinds of changes were introduced. The first illustrates the effects of policy changes that are based on the idea that degradation is occurring because the shifting cultivation cycle has been shortened; the solution is therefore to lengthen the cycle. An underlying assumption is that there is no growth in demand for land *per se* and that the demand for maize remains constant. To test this policy, I compared a long cycle length (24 years), a 12 years length cycle and a shortened cycle length (6 years), in each of which there is only 2 years of cultivation, the rest of the land being fallow at any given point in time. The second group of scenarios considers what happens if the crop cycle is being shortened in response to land pressure, that is, the need to produce more food from the same area, for example as a result of population growth, but using the same technology. To model this, I assume that the number of farmers operating on the territory increases by a factor of four. This scenario assumes a 6-year cycle (2 years cultivation, 4 years fallow); the land what would have been in long term fallow (as in the first scenario) is all taken up by short term shifting cultivation, in this second scenario.

For the comparison of emissions between SC and PA, the carbon emissions for the 12-year SC system are 0.63 Mg C/year for the production of 1 ton of maize, while permanent agriculture loses 2.19 Mg C annually, considering the same window of time (and this does not include carbon losses as a result of use of inputs such as fertilizers and fuel for the machinery). In the scenarios that compare reduction in the length of the cycle without land pressure, I found that the shortest cycles retain the highest carbon stocks (476 Mg C). Carbon emissions for Mg of maize produced were 1.65 Mg/year in the 6-year cycle, 2.19 Mg/year in the 12-year cycle and 2.51 Mg/year in the 24 year cycle (Fig. 7.4 a, Fig. 7.4 b and Fig. 7.4 c). This is because with shorter cultivation cycles, much more of the territory remains unused, and rapidly develops secondary woodlands. Lengthening the shifting cultivation cycle under these conditions would result in higher, not lower emissions. However, if the cycle is shortened as a result of increased demand for land and more food (4 tons maize instead of 1) is produced in the same area (scenario 2), (Fig. 7.4 d and 7.4 e), then indeed this results in higher carbon emissions for scenario 2; 1.65 Mg of carbon yearly per ton maize. The calculations are shown in schematic form in Fig. 7.4



d) Land dedicated to shifting cultivation without land pressure

-At any one time 0.6 ha will be in cultivation
and 6.6 ha in fallow o untouched forest.
Yield= 1 Ton of maize
Emissions= 1.64 Mg/Ton maize/year

e) More land dedicated to shifting cultivation due to pressure on land

-Every year four plots of 0.6 ha (2.4
ha) will be in cultivation and 4.8 ha in
fallow.
Yield= 4 Ton of maize
Emissions= 1.65 Mg/Ton maize/year

FIGURE 7.4 Comparison of carbon emissions from scenarios evaluated: a) 12 years length cycle, b) 12 years length cycle, c) 24 years length cycle, d) without land pressure and 3) increased demand for land. For everyone there is only 2 years of cultivation. The rest of the land being fallow at any given point in time in a, b and c. Untouched forest is present just in a and b, but with different proportions.

These scenarios present information about the carbon impacts of shifting cultivation and permanent agriculture and therefore fuel the controversy around which of these production systems is more environmentally friendly.

There is an on-going debate about the relative merits of land sparing (which implies intensifying agriculture so that large forest areas can be kept intact) and land sharing (which envisages more extensive farming with less ´conserved´ forest but with agricultural production that is less dependent on industrial inputs). Land sparing is gaining ground in related policies that seek to reduce carbon emissions from forestlands. This scheme was proposed in the Regional Strategy for REDD + in the Yucatan Peninsula (ECOSUR 2012) and was recently supported by a scientific article (Williams et al. 2017). This evaluated the impact on carbon stocks from a combination of various land uses, from highly productive to non-productive habitats, in order to develop land sparing and land sharing scenarios. The authors found higher levels of carbon stocks in land sparing scenarios with spatially segregated land uses. The authors of the article leave implicit the idea that this strategy has less environmental impacts than other strategies, mainly in biodiversity terms. However, the authors did not consider that this proposal might generate unexpected negative results. They did not consider that by increasing the efficiency by which a resource is used, the consumption of this resource is more likely to increase, rather than decrease, leading to increases of the total consumption of the resource in the land sparing scenario, which is known as the Jevons paradox. The essence of this paradox is that by obtaining greater production of commodities per unit area due to an increase in production and technology intensity, the production of commodities will increase, needing more area to produce, thus the incentive to convert forest to permanent agriculture would become stronger, in a rebound effect, which has been documented in several studies (Meyfroidt and Lambin 2007, Angelsen and Kaimowitz 2001, Byerlee et al. 2014, Ceddia and Zepharovich 2017).

To provide a short answer to sub-research question 3, my study indicates that shifting cultivation does have an impact on carbon stocks. But taken at the landscape level, i.e. taking into account the large areas of fallow that accompany the plots that are in cultivation at any one time, carbon levels in the SDTF landscape of the study area are not nearly as low as might be expected. After comparing shifting cultivation carbon densities against those of other land uses, I found that they are only 14% and 16% lower than old growth forest and fallowed sites older than 20 years, respectively. In terms of emission per ton of maize produced, I found that lengthening fallows would increase emissions, for a given level of maize production, as more forest would be disturbed, but I also show that more maize could be produced in a given area without significant increases in emissions.

7.5 SUB-RESEARCH QUESTION 4:

Sub-research question 4 asks how the findings of this study could be used to help communities in SDTF areas to pursue forest enhancement projects under REDD+ (Fig. 7.5).

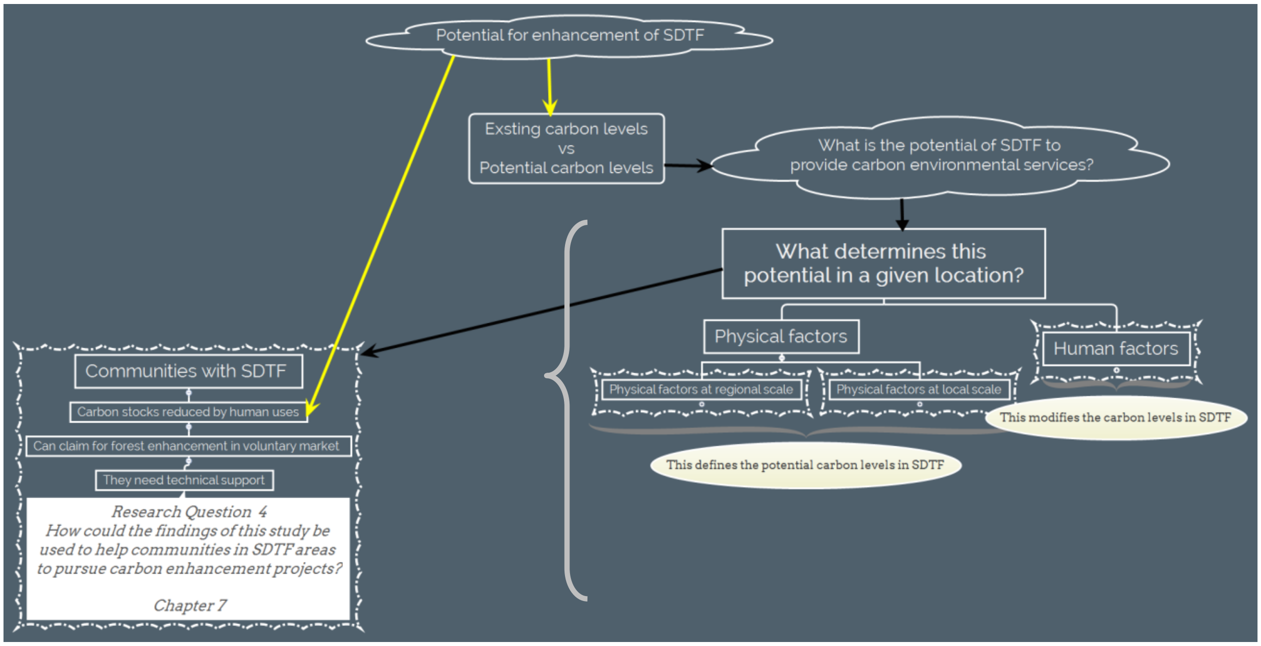


FIGURE 7.5 Elements of the overall diagram which relate to question 4

In undisturbed state, SDTF has a relatively low carbon stock compared with other forest types in Mexico and has often therefore been ignored in the context of REDD+. However, much of it is highly degraded (Trejo and Dirzo 2000). There exists therefore considerable potential or ´room to grow´ though natural regeneration, which in REDD+ terms is referred to as forest enhancement. In Mexico´s REDD+ policy, the state will not claim carbon credits for enhancement, only for reduced deforestation, see Chapter 2. Communities with SDTF could however play a very important role with regard to climate change by starting projects aimed at increasing forest carbon stocks, for which they may be rewarded in the voluntary carbon market. Indeed in this type of tropical forest with low carbon levels, it may make more sense to pursue projects to improve carbon stocks, rather than to avoid deforestation: 1) because in these areas there is ´room to grow´, i.e. carbon stocks could be increased by enabling natural regeneration to take place in degraded forests, 2) because this may be more feasible and cost-effective than attempting to stop deforestation, and 3) because under Mexican law, the land owner is the owner of any gains in biomass, but not of any reductions in emissions (CONAFOR 2017). The underlying rationale for this policy, as explain in Chapter 2, is that increased carbon in vegetation as a result of incorporation of CO_2 from the atmosphere represents ´fruits of labour´, assuming that the increases in forest carbon are the result of certain positive actions taken by the owners, such as fencing to keep cattle out, or changing the shifting cultivation regime. This makes sense since Mexican forestry law specifies that the ownership of any forest resources (i.e. trees) lies with the land owners within whose property the natural resources are located (CONAFOR 2017). In short, communities own increases in biomass, and may claim for credits for forest enhancement, although they do not own, or have rights, to emission reductions. The IRE (CONAFOR 2017) states clearly that communities may apply for credits for increased carbon stocks through any voluntary market or agency they choose.

Hence communities and individuals with land rights may participate in the voluntary market for any proven gains in their forest biomass, but not for reduced emissions.

Having established the legal right of communities to participate independently of government programmes in forest enhancement under REDD+, the question is how they could do so. Firstly, it is clear that communities will not be able to pursue such a path on their own; they will need technical support, such as is already provided by most of the agencies in the voluntary carbon market. Many of these agencies are environmental NGOs. The findings of this thesis (Chapters 4, 5 and 6) could be used by such agencies in order to develop a decision-making scheme for community carbon enhancement projects. This scheme may first select within the whole REDD+ intervention area the communities where activities to increase carbon forest stocks have the most potential. Then the scheme can draw the attention to areas of highest REDD+ forest enhancement potential *within* communities. Spatial models could be made of the hypothetical amount of carbon that could be held in these forests and then compared with independent datasets to identify sites in the territory with carbon levels well below this potential. After identification of these sites, the cause of their forest degradation would have to be identified, in order to decide whether it is feasible to intervene in these places and how.

Accurate assessment of increases in carbon levels over the project period generally requires intensive ground level forest surveys at different points in time. The methodology is based on standard frequentist statistical procedures, in which first AGB in a small number of plots is measured, from which the standard error is calculated. This is then used to calculate the total number of sample plots that will be needed to achieve a predetermined confidence level (99%, 95%, 90% etc), in each sampling period. These plots are then laid out across the forest area and measurements are taken in each one. This methodology is described in numerous forestry manuals, including McDicken (1997), and forms the basis for the recommendations given in the IPGG guidelines (IPCC 1996).

The drawback of this kind of intensive ground level forest survey is that to achieve acceptable levels of accuracy and confidence, a large number of sampling plots are required, given the fact that biomass levels vary enormously within forests of a given type. For example, in the SDTF Mexico, this variation in biomass in SDTF results from variation in water availability, which is itself influenced by elevation, aspect and type of slope (as shown in Salinas-Melgoza et al. 2017, i.e. Chapter 3 of this thesis). Taking measurements in such large numbers of plots is tedious and expensive. I argue that a Bayesian approach like the one presented in Salinas-Melgoza et al. (forthcoming, i.e. Chapter 4), could provide a basis for a more efficient use of data, through sequential procedures which could, in part, replace intensive ground-level forest while still arriving at acceptable levels of uncertainty, by using prior information available from previous time periods.

The proposal that I am making, therefore, is that instead of carrying out full scale inventories, the modelling approach that I have presented in this paper, based on topographic analysis and calibrated with data from a few sampling plots, could be used to determine not just the baseline, but also the carbon estimates at Time 1, Time 2, etc. using Bayesian logic with prior information to increase the accuracy of estimates.

I suggest that two different procedures, carried out at the same time, and repeated over time could be used in developing community forest enhancement projects; the advantage is that the model parameters can be updated when new measurements are acquired, using Bayesian statistics. These procedures are: a) first, a procedure to improve estimates of aboveground carbon and to reduce uncertainty (IP) related to this and b) a procedure to measure and claim for carbon enhancement, on the basis of improved estimations (CE) (Fig. 7.6), after project activities start. To summarize the reasoning behind this approach: Bayesian statistical methods rely completely on the specification of *a priori* model parameters, which are updated as new data become available, obtaining an updated model, see Fig. 7.6. Both procedures begin when project starts at Time 0. At the beginning of the project, a data set from field measurements of AGB number 1 and there is no prior information at this stage (Prior 1) are used as input to the modeling procedure. The model of standing carbon (Model T1), a map of estimated AGB levels

(MapT1) and information that can be used as prior information in following time period (Prior1) are obtained as outputs.

This could be used throughout the life of the forest enhancement project (Time 1, Time 2, Time 3,.... Time n+1) by making use of its REDD+ monitoring scheme after project implementation (Fig. 7.6), with a relatively small number of plots. Time 1 has the peculiarity that the prior information used does not actually exist, as is the first time, leaving the data obtained in the field (M1) to speak for themselves. The modeling process implies that inputs and outputs will be available at each time interval. Inputs include field measurements (M) and information from previous period (Prior n-1), both of which will be used to improve carbon predictions (MapIPn). In addition, in order to make a comparison for evaluating the project's performance at a given time, the map (MapTn+1) of AGB for evaluation time of carbon enhancement (Time n+1) uses the same "prior" information used to obtain the map of improved carbon predictions of the previous time period, but this time including new measurements. The map of carbon enhancement (CE) is obtained by comparing the differences between the map with improved predictions of carbon stocks of the previous time period (MapIPn-1) and the new map (MapTn+1). In other words, to claim for carbon enhancement each time (Time 1,… , Time n+1), estimations of carbon gained in time n-1 (MapIPn-1) are subtracted from MapTn+1 (Fig. 7.6).

Thus, the Bayesian approach for forest enhancement projects proposed could provide a way of evaluating stock changes over time. The accuracy of my estimations of AGB using Bayesian methods are between 65 to 80%, which fall well within the range of accuracy of those in many studies that have estimated AGB using remote sensing methods (Mitchard et al. 2015).

The final answer to the question of how the research findings might help communities in SDTF develop forest enhancement projects is therefore two fold. First, I have shown that despite the fact that potential total stock levels are not as high in these forests as in some others, the high level of degradation of SDTF means there is plenty of ´room to grow´, and this message could be useful in promoting the idea of forest enhancement for communities. Secondly, I believe that the Bayesian methods I developed could be used as tools by the NGO groups supporting such a movement, for more efficiency in planning at the local level.

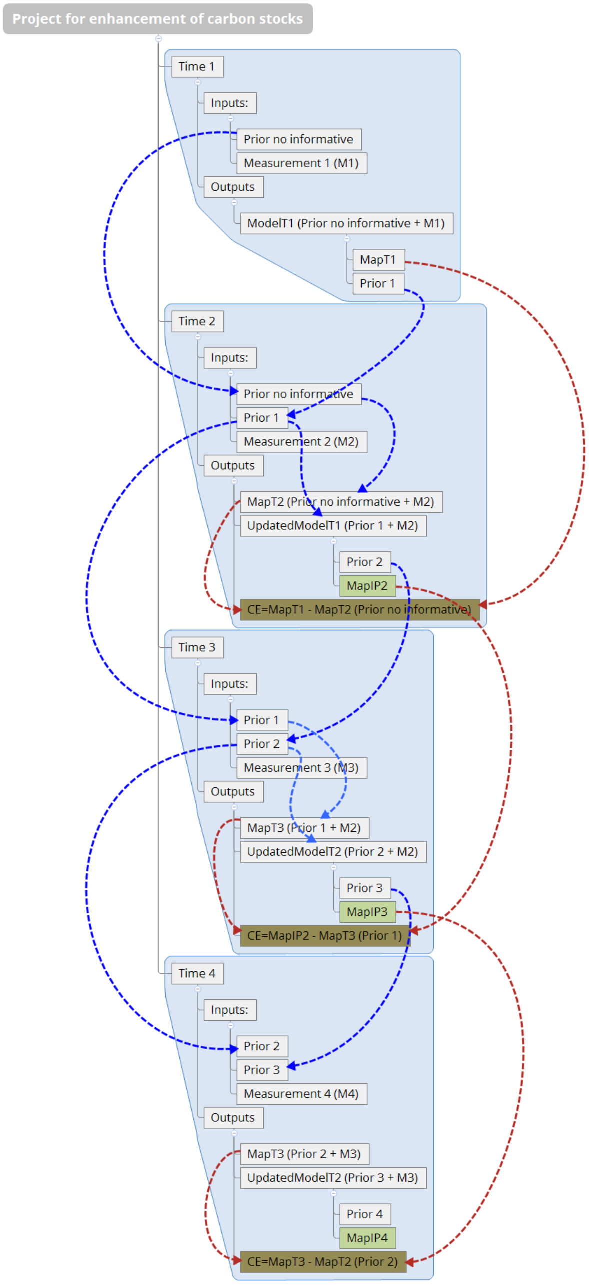


FIGURE 7.6 Flowchart of both procedures for improvement of predictions and evaluation of carbon enhancement achieved throughout life of a carbon enhancement project. It is shown here from the beginning of the project and up to three re-measurements during project monitoring, but it might continue (Time n+1). Inputs, inputs used in modeling procedure; Outputs, expected product from modeling; Prior, prior information; CE, indicates when the carbon enhancement is performed; comparing map with predictions of time n-1 and map with predictions of time n+1. Blue arrows show how prior information is borrowed at different times for IP and CE. Red arrows indicate how maps of AGB predictions are used to calculate CE. Green boxes are the map with IP for Time n. Brown boxes are the map with CE for Time n.

7.6 CONTRIBUTIONS TO KNOWLEDGE AND POLICY

In this section I address the main contributions of this thesis to scientific knowledge and its practical implications in establishment of REDD+ projects and targeting REDD+ action in the ground. The present study started from the understanding that the amount of biomass, and hence of carbon, in a landscape is strongly influenced both by topography and by the human uses that are present.

7.6.1 SCIENTIFIC CONTRIBUTIONS

The physiognomic structure of tropical forest has been studied by many scholars (for an early mention, see Richards 1952), who have shown that there can be large variations in structure and density in different regions and localities, and at different sites within these areas. This uneven distribution of forest structure has been related both to topographic factors such as elevation, slope and concavity and convexity of the terrain which affect growing conditions, and to human influences such as shifting cultivation, grazing, and extraction of building materials, firewood and pole for fences, which result in lowered biomass levels, at least temporarily. It has also been shown that these activities human themselves in seasonally dry tropical forest (SDTF) in Mexico often follow topographic features (Morales-Barquero et al. 2015). For example shifting cultivation is carried out at particular positions along the slope, although the intensity may differ from community to community. Free range grazing is typically found on the steepest parts of the slope which is less suited to shifting cultivation, and affects forest structure and carbon density in other ways. Hence an important contribution needed is elucidating how the human and natural landscape features combine to modify forest forms and carbon levels along the catena. This study was designed to contribute on this issue by determining in what extent aboveground biomass (AGB) in a human modified SDTF in Mexico is affected by the conditions along the hillslope or catena (Chapter 1).

The first contributions of this thesis to scientific knowledge enhance our understanding of AGB determinants in SDTF. I found that, as expected, AGB levels in the human modified SDTF of Ayuquila are determined by topographic and human factors. I found that the topographic factors showing a significant relationship with AGB in the SDTF were elevation, slope, terrain curvature and a topographic humidity index, elevation at regional level and terrain curvature at local scale. This is not new, but I obtained the relative contribution of predictors to explain total variation on AGB for the SDTF. I suggest that this combination of variables contributes to the movement and accumulation of available water in the soil, which in turn is very important in biomass accumulation in SDTF. The results of this thesis also help to gain insight into the role of the spatial relationships of the topographic variables within the rural communities, which determines to some extent the levels of AGB.

Secondly: the role of shifting cultivation in GHG emission by human activities has been debated for a long time. In this thesis I was able to make a calculation of the emissions related to shifting cultivation compared to those of permanent agriculture. I found that the former were higher, although this did not take into account the high amounts of carbon emissions associated with inputs used in permanent agriculture. Also I contribute to the idea that shifting cultivation should not be considered a leading cause of deforestation.

The third contribution of this thesis to scientific knowledge is a number of models obtained from the empirical research that provide new insights into the role of physical features in determining AGB. These models suggest ways of looking at empirical data on AGB-topography relationships in a tropical forest modified by humans.

Another contribution of this thesis to scientific knowledge is a fresh perspective in the land sparing and land sharing debate, discussing how shifting cultivation regimens might simultaneously provide food and carbon ecosystem services. Land sparing and land sharing are idealized as the opposite extreme of a continuum; higher yields on a smaller area of land vs lower yields in a large area, but when considering strategies to deal with climate change, they had not been well addressed. This point is discussed in more detail below under contribution to policy.

The selection of SDTF as the tropical forest type of concern in this regard is also innovative. SDTF – also known in Mexico as ´selva baja caducifolia´ - has in the past been considered by foresters as the poor cousin of other forest types such as pines, oaks, and the rain tropical forests as found for example in the Yucatan peninsula. There have been far fewer academic studies in SDTF, and its characteristics are much less known to the public, even though it represents a big proportion of all forest in Mexico. This is mainly because SDTF does not have much value in terms of timber development. However, it is one of the richest biomes within Mexico in terms of biodiversity (Dirzo et al. 2011), and it is essential not only in terms of carbon storage, but also for the provision of other important ecosystem services to surrounding populations, such as water. Hence this thesis aims to highlight the importance of SDTF, particularly in terms of reduction of carbon emissions.

7.6.2 POLICY CONTRIBUTIONS

The practical implications of this thesis should make an important contribution to policy intervention (for example under REDD+) which aim increase carbon stocks at the local level. The first practical implication involves the re-assessment of shifting cultivation as a source of carbon emissions. Shifting cultivation in these areas is carried out by sedentary farmers, who use the areas available in a cyclical manner, such that a period of several years of fallow follows every few years of cultivation. This agricultural system yields a mosaic landscape of forests of different ages, in a continuum of forest succession. Shifting cultivation has been vilified since colonial times as being the destroyer of forests, but the thesis shows that in terms of carbon emissions, it is a relatively carbon efficient means of food production, since on average carbon density in fallow areas is higher than in most permanent croplands (Houghton and Goodale 2004, Pelletier et al. 2012). This finding has bearing on the debate on ´land sparing´ versus ´land sharing´, as I show that shorter cycles in shifting cultivation do not necessarily result in higher emissions, indeed the contrary is true. It all depends on what drives the shortened emissions. In the study area, farmers have gone for shorter fallow periods because of the structure of agricultural subsidies, not because of pressure for land. But even where shortened cycles are the result of land pressure, and more of the total landscape is taken into cultivation, emission levels are only slightly higher than in systems with longer fallow. However, there is some room for maneuver here. I elaborate in Chapter 6 the idea that this traditional form of maize production could be optimized in order to reduce carbon emissions even further. This rests on the idea that shifting cultivation keeps the forests young, and young forests tend to grow rapidly, thus giving rise to the possibility of promoting net ‘carbon sinks’ or landscape level ‘carbon banks’, with greater ´sinking´ potential than mature forest landscapes. Moreover, I show that carbon stocks in the soil, which represent two thirds of the carbon stock in this ecosystem, are much better preserved under shifting cultivation than under permanent agriculture.

The second contribution of the thesis with practical implications for policy is related to showing to how forest enhancement may be better included in the REDD+ mechanisms. Forest enhancement is one of the five UNFCCC identified REDD+ activities, but it is hardly considered in most national REDD+ plans. As explained in Chapter 1, forest enhancement – understood here as assisting degraded forests to regain higher levels of biomass by managing them in a way that encourages natural growth - has hardly been discussed, as popular concern is with reducing deforestation. The argument I have developed in this thesis is that SDTF in most parts of Mexico is very badly degraded due to a variety of human uses and to lack of care from the forestry sector. I argue that a major potential for REDD+ in these forests is forest enhancement rather reduced deforestation, and that it may well be a more cost-efficient strategy for carbon mitigation, although economic calculations for this proposition are beyond the scope of this thesis.

The third contribution which this thesis makes with practical implications is showing how practice on forest enhancement could be better developed in Mexico. Mexico is conducting efforts to prepare for REDD+. It recently published its National Strategy or REDD+ Action Plan 2017-2030. ENAREDD+ (CONAFOR 2017), and a proposal called the Initiative for Reducing Emissions from Deforestation and Degradation (IRE), has been submitted for funding to the Forest Carbon Partnership Facility (FCPF) of the World Bank. The IRE is based on an idealized model which is being tested in five states of the country: Campeche, Chiapas, Jalisco, Quintana Roo and Yucatan (otherwise known as ´Early Action Areas). These states will serve to test different kinds of interventions to reduce emissions, as well as the effectiveness of the results-based approach on which international REDD+ is based. These interventions will not be aimed only at climate change mitigation, but will also promote integrated landscape management in general, by aligning public policies and programmes for sustainable rural development and providing additional funds to carry out integrated landscape management at the community and landowner level.

I believe that forest enhancement options under REDD+ could be dealt with best using a kind of landscape approach; not the approach recommended by Minang et al. (2014) which envisages complete coverage for carbon accounting purposes of all land areas within a territory, but a landscape approach based on the characterics of landscape geometry and applied to forest areas in which there are mosaic patterns of shifting cultivation and secondary regrowth. This landscape geometry approach allows predictions to be made not only of the basis of physical characteristics of the landscape but also to some extent of the human uses likely to be associated with these different physical characteristics. My study is a scientific effort to gain insight through so called ‘use-inspired basic research’ (Clark 2007) to the issue of landscape approach, that is to say, the search for advancing both in fundamental understanding and in taking informed action.

In this, one of the contributions is that the vocabulary used in my landscape approach is in the language that people commonly use to describe a landscape. This language that never going to change, it is understood and is shared between all stakeholders: Regular people as well as scientists refer to different parts of hillslope that can easily be distinguished in the landscape; the flattest area, the highest area in a hillslope, the bottom part of this hillslope, etc. Those units in the landscapes are material and well perceived by stakeholders. The use of the geometry of the landscape not only makes quantitative modelling of carbon stocks feasible, but can also help in communication with local people, when plans are made for implementing REDD+ activities. Furthermore, the geometry of the terrain can indicate how natural and human patterns and process are interlinked, using a number of indicators that people will easily understand; for example, here are fewer hard wood trees in the lowlands because it is easier to extract poles from the flatter areas than from the steeper ones, which everyone will acknowledge. Water moving on the surface is trying to reach sea level due to gravity and geometry of the landscapes play a key role in how water moves, which people will also recognize. I argue that the geometry of the landscape is a starting point through which the intimate relationship between man and nature and the use of the landscape might be presented in plain English (or Spanish!).

The landscape approach I am proposing also provides fuel for the debate on land sharing versus land sparing, as the geometry of the landscape used in this thesis allows us to think more in real landscape terms, i.e. highlighting the micro-variations in landscape which make land sharing a rational approach in many situations. It also allow a focus on the carbon emissions of the land sparing/land sharing, a factor which is hardly considered by supporters of either position (Grau and Aide 2008, Perfecto and Vandermeer 2010) though both claim they are aiming for sustainability.

Finally, the thesis contributes through the development of a practical methodology which would allow the identification of areas within communities or landholdings, which have high potential for carbon enhancement; i.e those areas which are currently well below their natural carbon potential, and the same methodology could potentially be used to construct spatially explicit baselines for forest enhancement projects.

7.7 LIMITATIONS OF THE STUDY AND FUTURE RESEARCH

This thesis draws together various findings regarding the effect of topography and human activities on AGB. It would however be interesting to understand how topographic factors act on variability of AGB *without* the presence of human activities, as this could provide information on the maximum potential of SDTF to provide carbon ecosystem services. However, this thesis did not investigate the variation of AGB in untouched forest. Studies on this would provide relevant insight for some REDD+ activities, specifically with those that aim to increase forest carbon stocks. The forest of the study area has been under human management since colonial times and untouched forest is hardly found in the study area. This is true for most SDTF in Mexico, as pointed out in Chapter 3; this forest type is the most highly degraded of all forest types in Mexico, and much has been deforested to make way for agricultural crops. I did make an attempt to find the least degraded forest in the study area. Two communities were suggested by the JIRA crew in this regard. I visited those communities, but after several day of field work, marihuana cultivation patches were detected within the forest. I found these conditions were not ideal for field work, as our own security would be threatened and I therefore decided to not establish sampling plots within these comunities. It is of course no coincidence that the most untouched forest is in areas where drugs gangs are operating: not only researchers, but also ordinary farmers are afraid to enter these areas.

This limitation in my research however opens the opportunity for future research in areas devoted exclusively to conservation. There are also areas in Jalisco, but outside Ayuquila, which are conserved as a result of protective policies, most notably areas in the Chamela-Cuixmala Biosphere Reserve. Data on AGB was available to me on these areas, but after consideration, I did not feel that I could compare my AGB levels with those of the Chamela sites, because Chamela is much lower lying, with quite different microclimatic conditions.

A further limitation of the study concerns the sampling strategy. The predictive models developed in this thesis and their performance can be sensitive to the size of the sample. There are two sides to this coin. On the one hand, those models presented in Chapter 5 with small training sets could be prone to low performance predictions (Breiman 2001). On the other hand, using large sample sizes can have a prohibitive monetary and operational cost. This issue illustrates the compromise that must be found between effort needed for sampling versus a very good precision and low variance in prediction.

The sampling plots used in this thesis are from three different datasets from different sources. The combination of these three datasets increased the size of the sample used. On the one hand, I recognize the limitations of one of the datasets used in Chapter 4, which was obtained by preferential sampling and was not very well defined; this set of data could be more strongly autocorrelated with environmental variables than the other datasets. On the other hand, in Chapter 5 the ability to assess AGB spatial variation depends on the spatial arrangement of the sample plot; the sampling plots used in this chapter used a strategy that selected sites randomly, which is appropriate for this purpose.

The take to home message of these drawbacks is that, if I were to do it all again, I would improve the sampling design in order to get a more representative sample, minimizing the risk of drawing the wrong conclusions from sample data. This could be done by randomly locating samples in forest conditions that represent small proportions of the landscape. Since the data analysis did not include many sample point of SDTF in conserved conditions without human influence, my findings cannot be applied to forest under those conditions.

Finally, I would like to clarify why my thesis has the phrase “connecting the dots” in the title. Connecting the dots originated from a game of connecting numbered dots to reveal a picture or drawing. I´m using connecting the dots as a metaphor about grasping a pattern and understanding how different underlying physical factors and human uses are connected, in order to make a big picture of aboveground biomass patterns in Seasonally Dry Tropical Forest. After doing my fieldwork and sitting down to analyze the information obtained, I realized that trying to detect such hidden relationships was really difficult. Now I realise that connecting the dots means that I found a common thread that structures biomass patterns in the human modified tropical dry forest. This thread is the topography, which to some extend determines the human activities found in a given location as well as the naturally occurring biomass levels. For me, the sampling plots were the “dots”, which I tried to connect to make a picture through which the hidden relationships can be seen.

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ABOUT THE AUTHOR

Miguel Angel Salinas-Melgoza was born in Uruapan, Michoacan, Mexico. He did his bachelor´s degree in Morelia at the Universidad Michoacana de San Nicolas de Hidalgo. In his bachelor´s thesis he evaluated the spatial patterns of tropical tree species populations and possible causal factors for them in the Chajul region of the Lacandona tropical rain forest, Chiapas, México. Subsequently, he enrolled in the MSc program in Biological Sciences at UNAM (Centro de Investigaciones en Ecosistemas-CIEco), evaluating surrogate methods to measure biological diversity in the state of Colima, Mexico. He practiced as a professional biologist for eight years in his home country. He has collaborated in various projects of different study areas, mostly focused on the sustainable development of Mexico's forests. These projects have provided useful information for natural resource management from the perspective of population and community ecology, restoration and conservation, as well as biotic inventories for diversity assessments. For five and a half years he worked at Mexican commission for protected areas (CONANP) supporting the process of establishment of new protected areas and elaborating protected areas management programs, technical opinions for environmental impact evaluation, and also contributed to the territorial planning of municipalities and regions in which various protected areas are located. His daily work has many times made him aware of the need for information related to improvement of social and environmental conditions in Mexican tropical forests. The knowledge he gained during during his professional career encouraged him to enroll in projects aimed at providing information on the potential of Mexican forest to provide carbon environmental services. In January 2011, he started to work on his doctoral research as part of the PhD programme in Innovation and Governance for Sustainable Development at the Twente Centre for Studies in Technology and Sustainable Development (CSTM), now Department of Governance and Technology for Sustainability – Institute for Innovation and Governance Studies (IGS) - University of Twente, in The Netherlands. The research was performed under the supervision of prof. Dr. Jon C. Lovett, Dr. Margaret Skutsch and at the end of this journey, Hans Bressers. His PhD position and research costs were fully funded by the Netherlands Organisation for Scientific Research (NWO). He is interested in continuing with problem-driven research dealing with the interactions between human and environmental systems, which some researchers call 'use-inspired basic research', and others ´the Pasteur quadrant´ to improve the well-being of present and future generations.

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