Chapter 6    Synthesis

6.1    Introduction

The work presented in this thesis covers two closely related topics in Earth system sciences. One is the estimation of global cropland GPP (gross primary production) and NPP (net primary production). The other investigates soil moisture constraints on terrestrial ecosystems and the carbon cycle. In this synthesis, integration of the findings of the work in this thesis and other related studies are presented in section 6.2. After that, a discussion of existing limitations and future perspectives is given in section 6.3.

6.2    Research purposes and main findings

6.2.1    Cropland GPP and NPP estimations

In chapter 2 and 3 of this thesis, we focused on cropland GPP and NPP estimates, essential components in the terrestrial carbon cycle. The light use efficiency (LUE) approach, a well evaluated empirical method developed by Monteith (1972), was used here. Usually, empirical methods require look-up tables of key parameters to quantify the diversity of ecosystems. Therefore the maximum light use efficiency approach ($\phi$) was evaluated and a look-up table was generated for 26 crop types. A new monthly global cropland GPP dataset was created based on this look-up table and a more sophisticated LUE model.

The objective of this study was to improve GPP estimates. GPP is the largest carbon flux in the terrestrial carbon cycle and provides the main carbon input into terrestrial ecosystems, ranging from about 120 to 150 Pg C yr$^{-1}$ (Beer et al., 2010; Welp et al., 2011). About half the GPP is used by plants for maintenance (autotrophic respiration, $R_a$), the remainder being available for plant growth as net primary production (NPP). Because direct field measurements are far from sufficient to generate global GPP and NPP due to large variability in plant species and growth, a sophisticated modelling approach is required. Current global GPP and NPP estimates mainly rely on model results, observations, model fusion methods and atmospheric isotopes changes (Field et al., 1995; Knorr and Heimann, 1995; Potter et al., 1993; Ruimy et al., 1994; Zhao et al., 2005; Ryu et al., 2011; Koffi et al., 2012; Beer et al., 2010; Welp et al., 2011). However, considerable differences exist among various studies. For example, global annual GPP is estimated at 123±8 Pg C yr$^{-1}$ versus 150-175 Pg C yr$^{-1}$ suggested by Beer et al. (2010) and Welp et al. (2011) respectively.

The light use efficiency (LUE) approach (Monteith, 1972; Monteith and Moss, 1977) and carboxylation rate calculation (Collatz et al., 1991; Collatz et al., 1992) are the two main methods used to estimate GPP and NPP in biogeochemical or land surface models. The LUE approach was developed realizing that growth of plant biomass is directly
proportional to absorbed solar radiation. These observations suggest that environmental variables, such as radiation can be used to estimate plant productivity circumventing the complicated calculation of detailed biochemical processes (Field et al., 1995; Knorr and Heimann, 1995; Potter et al., 1993; Ruimy et al., 1994, 1996, 1999; Prince and Goward, 1995). LUE-based models are relatively easy to apply and are still under development with more and more proxy data becoming available to drive models (Goerner et al., 2011; Jin et al 2013).

The LUE method is an effective empirical approach, therefore, parameter evaluations have been widely applied across global different plant types, and this kind of work will continue in the future. Currently, using flux tower measurements to evaluate LUE models is becoming the standard way of model evaluation. There are several widely used LUE models or algorithms, such as Moderate Resolution Imaging Spectroradiometer Primary Productivity (MODIS MOD17 product, Zhao and Running, 2010), Carnegie-Ames-Stanford Approach (CASA, Potter et al., 1993), Vegetation Photosynthesis Model (VPM, Xiao et al., 2005). Evaluation using eddy flux towers at site level (about 1km²) has been applied across various plant types worldwide although large biases were found. Turner et al. (2006) showed that MODIS GPP products had no overall bias over 9 sites covering several plant and land use types. However, more evaluation work suggests the $\phi$ of MODIS GPP should be adjusted to better estimate GPP for local ecosystems. For instance, after testing MOD17 products with eddy flux tower measurements over 12 African sites, Sjöström et al. (2013) suggested $\phi$ were underestimated in 10 savanna or grass land sites. Wang et al. (2012b) validated MOD17 products at 10 flux sites in northern China, and also found that site based $\phi$ values were larger than that used in MOD17. The work in Chapter 2 and the first part of Chapter 3 used similar methods to evaluate $\phi$ of cropland globally based on flux tower records and remotely sensed vegetation index.

Although the empirical characteristics of the LUE method requires plant type specific parameter values, only less than 20 vegetation type globally were separated (i.e. MODIS MOD17 product; Zhao and Running 2010) and many studies even set $\phi$ constant globally (Potter et al., 2007). In addition, cropland usually is treated as one vegetation type, using a constant $\phi$ in consequence in these models. However, among these main vegetation types globally, the bias is particular large over croplands (Sjöström et al., 2013; Wang et al., 2012b). The results in this thesis demonstrated a clear underestimate of model default $\phi$ values over 8 crop types, which is in consistent with previous results. An important improvement presented in this thesis is the large number of crop types that were studied independently. $\phi_{GPP}$ ranged from 1.21 g C MJ⁻¹ (Other perennial) to 2.96 g C MJ⁻¹ (Cassava). Parallel studies found similar results which led for example to modifying the cropland $\phi_{GPP}$ value of the MOD17 product to 1.044 g C MJ⁻¹ (Zhao and Running, 2010) compared with the previously used value of 0.68 g C MJ⁻¹ (Heinsch et al., 2003).
Based on previous studies and the results in this thesis, $\varepsilon_{\text{GPP}}$ in croplands exhibits a very large range. The $\varepsilon_{\text{GPP}}$ value used in models usually try to represent the global average conditions, making the results at that scale match or look reasonable. An inevitable problem is then the bias at local scales or site level. Some efforts have been made to separate C3 and C4 plants in the models, for instance in the global production efficiency model (GLO-PEM; Prince and Goward, 1995). This is however, still far from an evaluation based on site measurements. A key question is to determine how many crop types are needed for an overall credible global result. Distinguishing hundreds of crop types in global models is unrealistic. Separating some main crops, like maize, wheat, rice and so on to cover the most important crop types is suggested in this thesis. Using both previous site results and the $\varepsilon_{\text{GPP}}$ values calculated in chapter 3, maize has a larger $\varepsilon_{\text{GPP}}$ value than most other crops. It is also suggested that the range of maize $\varepsilon_{\text{GPP}}$ is much smaller than that of all crop types. Therefore, it is possible, and effective, to separate some widely cultivated plants rather than treat global croplands as a whole.

The creation of a new dataset of global cropland GPP is the direct consequence of the parameter valuation executed in this study. There are several widely used LUE models, however, only a few of them have publicly released their outputs. MOD17 GPP and NPP datasets are evaluated worldwide as illustrated previously in this synthesis. NPP based on CASA model is still being updated (Potter et al., 2012), and CASA is also used to further calculate fire emissions (van der Werf et al., 2010). As discussed above, to improve the dataset using LUE method, separating more plant types is an efficient way.

In addition to separating more crop types, information on the extent of different crop types is crucial to create a new cropland GPP map. Portmann et al. (2010) created such a crop type map, separating 26 crop types. This dataset was used in Chapter 3 along with a newly developed look-up table of $\varepsilon_{\text{GPP}}$ combining several input data sources. The spatial resolution is 1/12 degree, which is higher than most of other current models.

A look-up table of $\varepsilon_{\text{GPP}}$ for these 26 crop types is the first main task. Only 8 types could be evaluated directly using flux tower measurements as shown in Chapter 2 and 3. Fortunately, croplands are the most studied plant category previously and hundreds of $\varepsilon$ values are available by measuring dry matter, either only above ground or total dry matter. Because these $\varepsilon$ values cannot be used to build the look-up table directly, a conversion method was created in chapter 3 to convert $\varepsilon$ to $\varepsilon_{\text{GPP}}$ based on the assumption that environmental stresses could be ignored for well watered croplands. As a result, a global look-up table of 26 crop types was created based observational records.

A dataset of global cropland GPP in the year 2000 was created in Chapter 3 at monthly temporal and 1/12 of a degree spatial scales. There are still evaluations needed in the future to further validate this dataset. Currently, its performance over North America was confirmed by comparing with harvest based estimate (Lobell et al., 2002). Importantly, this work may also contribute to resolving an outstanding issue. Usually, $\varepsilon^*$ values in LUE-based models are much smaller than field-based values (Lobell et al., 2002;
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Potter et al., 1993; Zhang et al., 2008). This dataset only uses observational \( \epsilon^*_{GPP} \) values. Global cropland GPP was estimated to be 11.05 Pg C yr\(^{-1} \), falling in the middle of previous studies indicating 14.2 Pg C yr\(^{-1} \) by Beer et al. (2010) and 8.2 Pg C yr\(^{-1} \) by Saugier et al (2001). This suggests how to merge the difference between field-based \( \epsilon^*_{GPP} \) and that in models.

The main conclusions of chapter 2 and 3 can be summarized as follows:

- The light use efficiency (LUE) approach is very suitable to estimate cropland GPP and NPP.
- FLUXNET-based \( \epsilon^* \) values are comparable to previous values reported by field measurements based on dry matter measurements.
- Cropland \( \epsilon^* \) at field level, including FLUXNET-based and literature-based in this thesis, are substantially higher than used in most vegetation models.
- A more accurate description of cropland distribution (crop types and growing periods) and sophisticated parameterization for individual crop types, will help to better use field based \( \epsilon^*_{GPP} \) in vegetation models.
- A dataset of global monthly GPP in the year 2000 was developed at a spatial resolution of 1/12 degree yielding a global cropland GPP of 11.05 Pg C yr\(^{-1} \).

6.2.2 Soil moisture constraints on vegetation

In chapter 4 and 5 of this thesis, we focussed on the soil moisture related impacts on vegetation, using both a drought index and remotely sensed soil moisture. A global analysis of SPEI (standardized precipitation evapotranspiration index) and NPP was presented to complement previous studies of spatial patterns of the relationship between anomalous dry or wet conditions and NPP. The Köppen climate classification was used to classify the spatial pattern into some main categories. Besides, a very prior attempt was made in chapter 5 to quantify the relationship between observational soil moisture and vegetation.

The objective of this study is to contribute to the knowledge of vegetation response to climate change, which is crucial in understanding and predicting future terrestrial carbon cycle behaviour. The spatial distribution of ecosystems as well as their growth is mainly determined by climatic factors, including water availability, solar radiation and temperature (Churkina and Running, 1998; Nemani et al., 2003; Stephenson, 1990). Water availability is a primary constraint compared to radiation and temperature (Heimann and Reichstein, 2008). Drought events impact terrestrial production and reduce the sink strength at (sub) continental scale (Ciais et al., 2005; Reichstein et al., 2007a, 2013; van der Molen et al., 2011). More importantly, since the occurrence and severity of drought are likely to increase or at least continue in the future (Dai, 2013, but see also Sheffield et al., 2012), there is a clear need to further evaluate the relationships between soil moisture and vegetation.
Reichstein et al. (2013) reviewed the impacts of climate extremes on the terrestrial carbon cycle and pointed out that drought and storms have the potential to cancel the expected increase of terrestrial carbon stocks. As mentioned above, usually this kind of studies focused on some typical extreme cases, such as the 2003 heat wave in Europe (Ciais et al., 2005; Reichstein et al., 2007a) and 2005 drought in Amazon (Phillips et al., 2009). These kinds of case studies have made robust conclusions by comprehensive analysis. In addition, some others tried to investigate the globally integrated effects of dry/wet conditions on vegetation (Gobron et al., 2010; Zhao and Running, 2010). Previous studies found that on a global scale, drought and NPP are strongly related in a positive way. It is easy to expect some spatial differences to occur, however, details of the spatial patterns of this relation are not clear. Therefore, in chapter 4 of this thesis, the spatial patterns of the relationship between SPEI and NPP are presented. Also, the rules governing those spatial patterns are key to understand. As a further step, the Köppen climate classification was used here to categorize the spatial pattern successfully. As a result, this study provides a stronger regional focus than previous work.

Drought indices have their advantages in application because usually precipitation and temperature data used to calculate drought indices are relatively well known. Drought indices are powerful tools to describe intensity, duration and spatial extent of droughts and have been widely used in analytical applications. Additionally, soil moisture data are still being developed and remarkable achievements have been reached using satellite derived indices (de Jeu et al., 2008; Dolman and de Jeu, 2010; Liu et al., 2011, 2012). Therefore, firstly, a drought index was used in chapter 4 to make a global analysis. The work in chapter 5 uses remotely sensed soil moisture directly, but on a more regional scale.

Soil moisture is an essential component in understanding the climate-soil-vegetation system both in space and time, and is directly associated with the dynamics of plant photosynthesis and respiration. Remote sensing based data are able to measure large-scale surface soil moisture continuously (de Jeu et al., 2008; Owe et al., 2008). In the last few years, near-surface soil moisture from space borne passive and active microwave instruments provided robust estimates of surface soil moisture at regional and global scales. Blending passive and active microwave soil moisture retrievals from various satellites has led to a long-term improved product with better spatial and temporal coverage than previous data sets (Liu et at., 2011, 2012). These remotely sensed soil moisture estimates offer the opportunity to evaluate the relationships between water availability and vegetation.

Global scale application is still limited due to data gaps in the time series. Therefore, a first attempt was made focusing on mainland Australia because the soil moisture data there have been well evaluated with ground-based measurements (Draper et al., 2009). Several statistical methods were used to perform a comprehensive analysis between remotely sensed soil moisture and vegetation index (i.e. NDVI).
The main conclusions of chapter 4 and 5 are summarized here:

- Drought indices, such as SPEI, are an effective and useful way to estimate the impact of drought on vegetation.
- The strong positive relation between SPEI and NPP that exists on a global scale is the result of a generally positive relation in dry regions and a coherent NPP decline with intensive drought event in humid regions, whereas NPP and SPEI were negatively related in most boreal regions.
- The spatial patterns of drought impact on NPP could be analysed using the Köppen climate classification, which suggests that the adequate prediction of vegetation in the different climate zones may be crucial to the quantification of the behaviour of the future terrestrial carbon cycle.
- Remotely sensed soil moisture is positive related with NDVI in mainland Australia.
- NDVI typically lags behind soil moisture by one month and this indicates a typical scale of vegetation response to soil moisture shortages.
- Dry regions with low vegetation density are more sensitive to soil moisture for the high end of the distribution of NDVI than moist regions, suggesting that soil moisture enhances vegetation growth in dry regions and in the early stage in wet regions.

6.3 Limitations and future perspective

6.3.1 LUE application in GPP estimation

As discussed previously, improvements of GPP estimates using the LUE methods depend on the parameterization of $\varepsilon^*$ and model structure to present vegetation conditions and environmental stresses more accurately. Several aspects are included, such as evaluation of $\varepsilon^*$, environmental stress description, vegetation index and the model’s spatial and temporal resolution. Several vegetation indices and descriptions of environmental stresses are used in different models (Goerner et al., 2011; Jin et al. 2013; Potter et al., 1993; Zhao and Running, 2010). Usually water and temperature condition are the two main factors. These models generally perform well in evaluation studies while large uncertainties still exist. Currently, all these aspects are requiring further work.

In this thesis, the global cropland GPP dataset created in chapter 3 highlights the importance of crop type separation and parameterization in dataset environments. Here, the limitations of the current work are obvious. For example, the survey data that could separate crop types over croplands was only available for the year of 2000 (Portmann et al., 2010). Croplands were separated into 26 crop types. However, not all the $\varepsilon^*$ values were estimated directly using flux tower measurements. Even a combination of FLUXNET-based and literature-based $\varepsilon^*$ values could not cover all the 26 crops. More direct field estimations of $\varepsilon^*$ with crop type information are thus needed. Besides, irrigated and rainfed croplands should be separated in the future as natural water stresses can be larger for the rainfed croplands.
6.3.2  Soil moisture constraints on vegetation

Both model and field measurement confirmed that drought could reduce vegetation production significantly. However, on large scales (regional to global), the relationships between drought and NPP are also determined by the accuracy of the modelled NPP and the data used to calculate drought index. For example, NPP values in rain forests still have great uncertainties, partly related to the low sensitivity of satellite productivity data in highly productive areas (Samanta et al., 2011; Zhao and Running 2010).

Besides the calculated drought index, soil moisture observations are in principle a better and more robust way to quantify water availability. However, the remote sensing approach also has its inherent shortcomings. Passive remote sensed soil moisture data have large errors over regions with high vegetation density (Parinussa et al., 2011). Therefore, semi-arid or arid regions were chosen where soil moisture data are more reliable to evaluate the relationships between soil moisture and NDVI. A further complication is that only the surface layer soil moisture content can be obtained by satellite observations, not that of the full root zone. Thus, currently, the analysis in this thesis could only quantify the surface hydrological cycles and its impact on vegetation. However, the shallow depth observations can be representative for soil moisture dynamics at the root zone layer. This was clearly demonstrated by Rebel et al. (2012) where they found high correlations between the satellite product and modelled root zone soil moisture.

In the future, more work on several aspects of this study is needed. The work in this thesis only quantifies the relationship between remotely sensed soil moisture and NDVI over mainland Australia. It is a typical region and a clear global conclusion in general cannot be reached yet. Extending similar work over other regions is needed, but this also depends on the data quality. Filling gaps is a precondition over many regions, and is still under development (Wang et al., 2012a). In addition, remotely sensed soil moisture offers observational records of soil water condition. Both soil moisture-NPP and precipitation-NDVI relationships have been established. Further comparison work is required to demonstrate whether there are some advantages using soil moisture than precipitation under specified conditions.

6.3.3  Integration

The amount of global GPP is not a constant but changes with time, although there are still large uncertainties in the estimate of annual average GPP. In a foreseeable future, the concentrations of atmospheric CO₂ will continue to increase due to anthropogenic carbon emission. It is clear that greenhouse gases have caused global warming, based on the latest IPCC report AR5 (Stocker et al., 2013). Due to the fertilization effects of atmospheric CO₂, modelled GPP and NPP would exhibit significant increase in the future as shown by Free-Air CO₂ Enrichment (FACE) experiments (Piao et al., 2013). Climate change will lead to different environmental stresses on plant photosynthesis processes.
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The proportions of vegetation types will also change due to vegetation adaptability. Land surface cover change could be caused by both natural and anthropogenic changes. For instance, herbaceous vegetation would replace woody vegetation in some tropical areas in the future (Sitch et al., 2008). But importantly, this might also occur due to human activities, known as land use or land cover changes, such as deforestations and croplands extensions (Houghton et al., 2012). Therefore, due to human activities, croplands will contribute more to global terrestrial GPP. To improve the estimate of global croplands GPP could become more and more important.

Meanwhile, agricultural activities primarily rely on water availability, particular the case for rainfed agriculture. Even irrigated croplands are constrained by vulnerable ground water conditions. Therefore, integrating the analysis of global cropland GPP and soil moisture constraints on vegetation is a necessary next step. Current estimate of croplands GPP only focuses on the one year due to the data limitations. It is possible to extend its temporal scales, for example, using history crop areas records during 1700 to 2007 (Ramankutty and Foley 1999). If these trends continue, the prediction of cropland GPP could be also based on some designed scenarios. How well to quantify the environmental stresses on GPP needs be based on the knowledge of soil moisture constraints on vegetation. Therefore, the two topics in this thesis are closely related and will contribute to the future understanding of terrestrial carbon cycle in a combined way.