Proceedings

Carbon-Use Efficiency of Terrestrial Ecosystems under Stress Conditions in South East Europe (MODIS, NASA) †

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† Presented at the 2nd International Electronic Conference on Remote Sensing, 22 March–5 April 2018; Available online: https://sciforum.net/conference/ecrs-2.

Published: 22 March 2018

Abstract: Carbon Use Efficiency (CUE) is the ratio of net primary production (NPP) to gross primary production (GPP) and shows the capacity of terrestrial ecosystems to transfer carbon from the atmosphere to biomass. The aim of this study is to examine the CUE under the stress conditions using NPP/GPP data products from the MODIS (NASA) spectroradiometer for the period 2000–2014. The drought reduced the CUE by 10 to 20% and, as a result, the region has shifted from a carbon sink to a carbon source. The stress affects mostly forest biomes, which are the lowest effective. The most significant impact on terrestrial ecosystems productivity and CUE are five-months-lasting droughts in terms of SPEI drought index. Drought also increases the variation of CUE. The degree of CUE reduction depends not only on drought strength, but also on its duration and the time of year when it occurs (perhaps phenophase). Further research is needed to understand the mechanisms of dependencies between CUE and the combination of high temperatures and water deficit conditions in terrestrial ecosystems.

Keywords: remote sensing; carbon-use efficiency; NPP; GPP; SPEI biome; altitude; MODIS; South Eastern Europe

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1. Introduction

The net exchange of carbon between ecosystems and the atmosphere can play a key role in regulating the human-induced increase in CO2 and global changes. Carbon use efficiency (CUE), defined as the ratio between net primary production (NPP) and gross primary production (GPP), describes effectiveness of vegetation in storing carbon and is of significance for understanding carbon biosphere–atmosphere exchange dynamics [1,2]. At the ecosystem scale, CUE can be used as a measure, whether the terrestrial ecosystem is a carbon source or sink. In earlier studies, it was considered that CUE does not change [3,4] varies slightly from 0.4 to 0.6 over a wide range of plant functional types and environmental conditions. That is why in many terrestrial C-cycle models, it was assumed that CUE does not change. In recent years, there were obtained many results that argue that CUE is not constant, but varies with: ecosystem types, successional stage and stand age, geographical location, nutrient availability, and environmental conditions.

Droughts are frequently accompanied by strong heat waves. This combination complicates the understanding of the impact of drought on productive processes and respiration, consequently on CUE. Many studies on the impact of a single abiotic stress condition—such as drought or heat—have provided important information, but often they do not help us understand the effects of a combination of two stresses on plants. The response of plants to a combination of different abiotic stresses is unique and cannot be directly extrapolated from simply studying each of the different stresses applied individually [5].

In the period 2000–2014, South Eastern Europe was hit by four extreme events—in 2000, 2003, 2007, and 2012—characterized by high temperatures and water stress during the growing season. This posed the issue of the impact of extreme events resulting from climate change on the CUE of ecosystems. That is why the objectives of the current study were to: (1) map the carbon use efficiency in South Eastern Europe; (2) study dependents of CUE on extreme drought and temperature/heat waves; (3) study the dependence of CUE on main PFTs/biomes in the region; and (4) examine the CUE elevation profiles.

2. Data and Method

In natural ecosystems, carbon-use efficiency (CUE) is defined as the ratio of net primary production (NPP) to gross primary production (GPP) CUE = NPP/GPP = 1 − R/GPP, R—respiration.

In the present study we have used: 1-km annual GPP/NPP MOD17A3, v. 055 (MODIS, NASA) data sets over the period 2000–2014 [6]; MODIS land cover data product MOD12Q1 v. 4, representing the conditions in 2010 year; GLOBE Digital Elevation Model, 1-km spatial resolution. To determine the effect of drought on CUE of terrestrial ecosystems, the standardized precipitation evapotranspiration index (SPEI) [7] was used, based on precipitation and potential evapotranspiration.

The study region is part of MODIS (NASA) h19v04 tile, and covers a territory of 41411 km^2 in South Eastern Europe (Figure 1)—the Rhodope, Pirin, and Rila mountains; Aegean Thrace; and parts of the Greece's Macedonia province between the rivers Struma and Mesta.

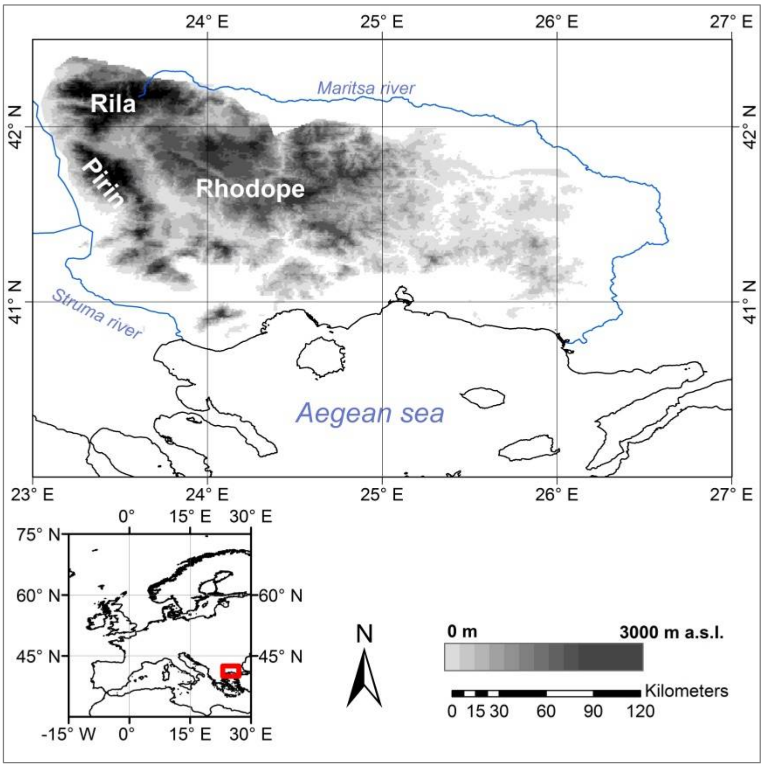


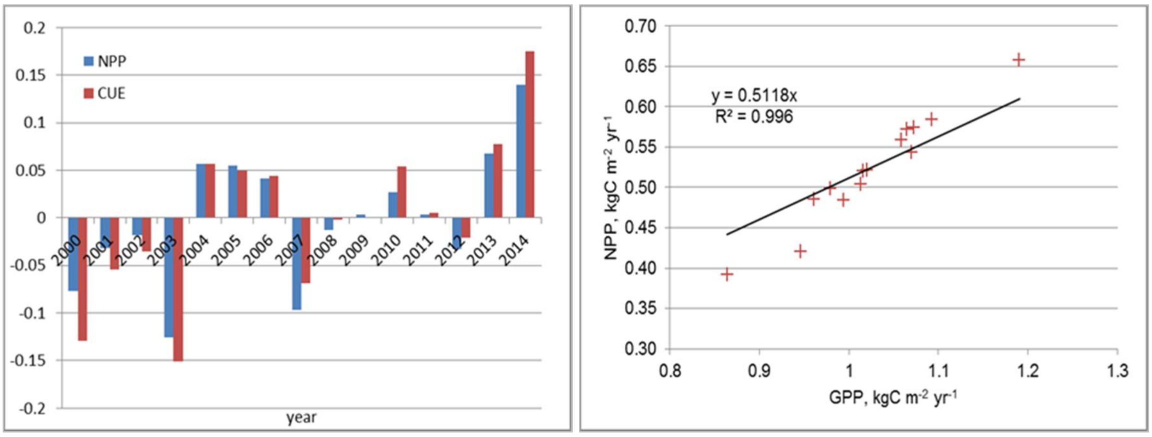
Figure 1. The Rila—Rhodope region and Aegean Thrace (South East Europe). ASTER GDEM2.

3. Results

3.1. Regional CUE

The mean NPP in the region from 2000 to 2014 was 0.516 kgC m^{-2} year^{-1}. During the extreme years (Figure 2a), negative anomalies of ecosystems' net productivity were 0.077 kgC m^{-2} year^{-1} (2000), 0.125 kgC m^{-2} year^{-1} (2003), 0.097 kgC m^{-2} year^{-1} (2007), and и 0.033 kgC m^{-2} year^{-1} (2012).

In the study period, GPP increased at a rate of 0.0064 kgC m^{-2} $year^{-2}$ ($R^2 = 0.45$, $p = 0.006$), but at the same time the respiration rate increased, but slower—0.0042 kgC m^{-2} $year^{-2}$ ($R^2 = 0.65$, $p = 0.0003$) kgC m^{-2} $year^{-1}$. The NPP values were plotted against the GPP values in Figure 2b, where a linear regression has been fitted to the data and so it was found mean CUE = 0.512. Annual mean CUE over the total territory varied between 0.444 and 0.552. During the anomalous years, ecosystem CUE was always less than 0.5, and it was 15% lower than that in the normal 2014—the year with maximum NPP. The least effective is the forests in the high parts of the mountains, especially the Middle and Southern Rhodope, South Pirin, and Pangaion Mountains at the mouth of the Struma River (Figure 3).



(**a**) (**b**)

Figure 2. (**a**) NPP (in kgC m^{-2} $year^{-1}$) and CUE anomalies; (**b**) Regression of NPP to GPP forced through the origin. The slope of the relationship is 0.5118 with a SE = 0.008.

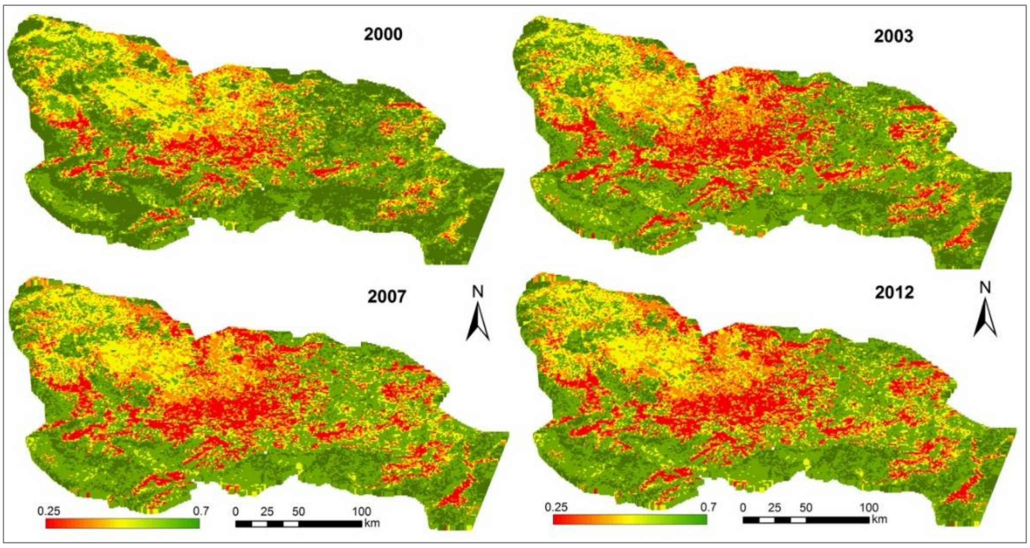


Figure 3. Carbon use efficiency in Rila–Rhodope region during 2000, 2003, 2007, and 2012 droughts.

3.2. Impacts of Droughts and Heatwaves on the Carbon Use Efficiency

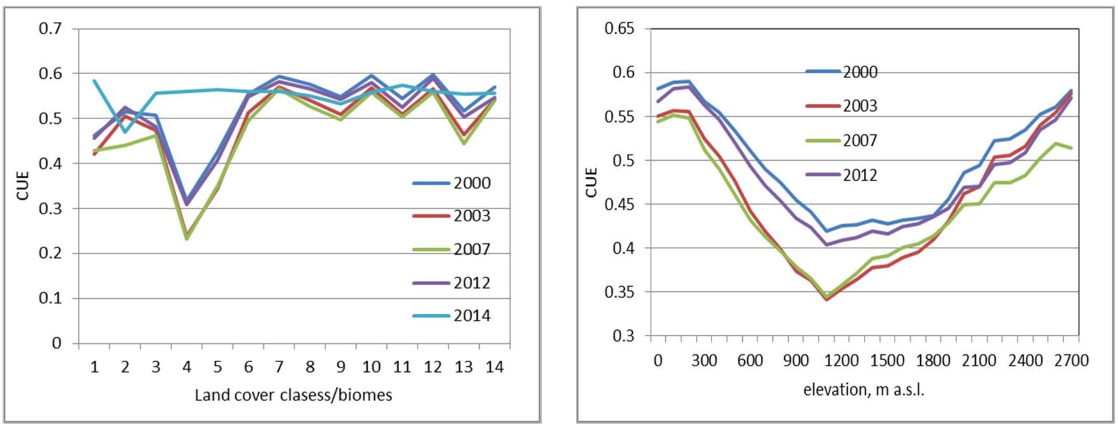
The drought is a multi-scalar phenomenon and depends on the time scale over which water deficits accumulated, and on the period of the year when the droughts appear. To determine the timescale suitable for exploring the impact of drought on plant productivity, we have studied the dependencies between NPP, GPP, CUE, and SPEI at time scales of 1 to 24 months. It was found that CUE, NPP, and GPP depend strongest by five months SPEI (SPEI_5), the correlation coefficients between CUE, NPP, GPP and SPEI_5 being 0.51 (CUE), 0.69 (NPP), and 0.75 (GPP). NPP and GPP correlate strongly and positively with $SPEY\_5_{July}$ ($r = 0.818$ and 0.830 respectively). $SPEY\_5_{July}$ has also a strong positive effect on CUE ($r = 0.684$). The drought period that most affects plant respiration was displaced one month earlier, i.e., the respiration depends strongest on $SPEI\_5_{June}$.

In 2000 SPEI_5 reached the highest value of (−1.75) in August. During the growing season April–August, the region was hit by a severe drought. The respiration and biomass accumulation processes compete at the same rate and NPP = 0.439 kgC m^{-2} $year^{-1}$ and R = 0.446 kgC m^{-2} $year^{-1}$. Despite extreme conditions and significant reductions in productivity (NPP and GPP), the region is not a carbon source as CUE remains at 0.497. Similar was the situation in 2012, when the NPP = 0.484 kgC m^{-2} $year^{-1}$ was of the same order of respiration R = 0.499 kgC m^{-2} $year^{-1}$ and CUE was 0.487, i.e., close to 0.5. However, in this case the drought started from July and was unusually strong, with $SPEI\_5_{November}$ reaching extreme values of −2.4. Although in both extreme years 2000 and 2012, CUE was about 0.5, the nature of droughts was different. In 2000, drought began as early as the beginning of February, with moderate dryness and at the beginning of March transformed into severe dryness, which continued to the end of the year with SPEI_5 between −1.5 and −1.7. While in 2012, we had extreme dryness conditions (SPEI_5 < −2) from June to the end of the year.

In 2003 and 2007, there was a strong reduction in CUE, CUE2003 = 0.453 and CUE2007 = 0.443 i.e., the efficiency was about 10% lower than in the other extreme years 2000 and 2012, although the drought was not that strong. In 2003, SPEI_5 reached a maximum negative value of −1.31 in September i.e., in the period of active growth May–September there were moderate dryness conditions. The better conditions during the growing season accelerated growth, NPP = 0.482 kgC m^{-2} $year^{-1}$, which led to an increase in growth respiration and hence to respiration as a whole, R = 0.510 kgC m^{-2} $year^{-1}$ and a corresponding decrease in CUE. In the winter of 2007, the drought was moderate, near extreme, $SPEI\_5_{April}$ = -1.46, which gradually weakened in spring and early June when SPEI_5 = -1.20. Low soil water content before the start of the active growing season and in the period of accelerated plant growth significantly reduced the NPP to 0.42 and increased the respiration to 0.52. This means that plants fail to acclimatize to the combination of rainfall and temperatures, resulting in a strong CUE reduction of up to 0.455.

3.3. CUE Dependence on PFT/Biome under Drought Conditions

In the anomalous years, CUE variation by PFT was stronger and ranged from 0.27 to 0.58, depending on the plant species. The most sensitive to droughts were the forest biomes, with the lowest CUE and the highest CUE variance (Figure 4a). The CUE of other biomes was higher and varied slightly over the years. Of the forest biomes, the deciduous broadleaf forests were the least effective and most susceptible to droughts. Under extreme conditions broadleaf forest (dominated by beech) CUE ranges between 0.23 and 0.32, and their average effectivity was 39% lower than in the normal 2014.



(**a**) (**b**)

Figure 4. (**a**) CUE of different biomes. 1—Evergreen needleleaf forest, 2—Evergreen broadleaf forest, 3—Deciduous needleleaf forest, 4—Deciduous broadleaf forest, 5—Mixed forest, 6—Closed shrublands, 7—Open shrublands, 8—Woody savannas, 9—Savannas, 10—Grasslands, 11—Permanent wetlands, 12—Croplands, 13—Urban and built-up, 14—Cropland/Natural vegetation mosaic; (**b**) CUE change with elevation (m.a.s.l.) in Rila–Rhodope region under 2000, 2003, 2007, and 2012 droughts, and 2014 (normal year).

3.4. CUE Dependence on Elevation (m.a.s.l).

Under drought conditions, in the lower parts of the mountains the CUE decreased linearly by −0.019 to −0.024, and at altitudes about 1100 m.a.s.l. it reached a minimum of 0.41 in 2000 and 2012 and 0.34 in 2003 and 2007 per every 100 m altitude increase (Figure 4b). In the zone above 1100 m.a.s.l., CUE change trends have some peculiarities. In 2003 and 2007 droughts, we had a positive efficiency gradient of 0.011 per 100 m. During 2000 and 2012 in the forest belt between 1100 and 1800 m.a.s.l., CUE increased by 0.002 and 0.004 per 100 m respectively, and over 1800 m.a.s.l. the efficiency gradient increased even more, and reached 0.015 per 100 m.

4. Discussion

The CUE exhibited a pattern depending on the main climatic characteristics such as temperature and precipitation and geographical factors such as latitude and altitude and PFTs. The regional CUE is not constant and varies from 0.444 to 0.552. CUE in 2000 and 2003 was lower than the global NPP/GPP ratio. In 2000 and 2003, CUE was 0.497 and 0.453, whereas then global CUE was 0.518 and 0.510, respectively [8]. However, the CUE of 0.61 for terrestrial ecosystems between 30° and 60° in the Northern Hemisphere was significantly higher than that for the same period in the studied region, located between 40.5 and 42.5° N.

It was shown in [9] that gross ecosystem productivity was ~50% more sensitive to a drought event than ecosystem respiration. The same result is confirmed in the Rila–Rhodope region, with the relationship between GPP and NPP, and SPEY_5 was significantly stronger than the impact of drought on respiration. So, droughts induced decreases in NPP and respiration to an average of -0.20 and −0.07 kgC m^{-2} $year^{-1}$ respectively, estimates being close to the global assessments [9], according to which the reduction of NPP and respiration is 16.6 and 9.3 gC m^{-2} $month^{-1}$.

The NPP/GPP ratio showed a significant variation depending on PFTs. In the Rila–Rhodope region, the mean CUE variation, depending on the type of biome, was 0.37 and was about two times higher than the estimate given in [10], according to which the variation of CUE between the different PFTs is about 0.19. Most sensitive to anomalies were the forest biomes, with the lowest efficiency and the highest CUE variance. The CUE variation in deciduous forests was strongest and its range was 0.080. This confirms the global estimate [8] that areas with a low CUE were largely occupied by forest ecosystems such as broadleaved evergreen or broadleaved deciduous forests. Heat waves and droughts lead to a reduction in CUE, which is strongest in deciduous broadleaf forests dominated by beech and significantly weaker in shrubs and savannas biomes, grasslands, and croplands.

On a global scale [8], evergreen forests have a lower NPP/GPP ratio than deciduous forests. While the CUE of evergreen needleleaf forests in the Rila–Rhodope region was greater by 0.17 than the CUE of deciduous broadleaf forest, whereas in the normal 2014 this difference was minimal (0.11) and in the extreme 2007 it was twice as big. Goetz and Prince [11] explored variability in carbon exchange, NPP, and light-use efficiency for 63 boreal forest stands in northeastern Minnesota using an ecophysiological model. The model was initialized with extensive field measurements of *Populus tremuloides Michx*. and *Picea mariana* (Mill.). They found that conifers seem to have substantially smaller CUEs than broadleaved tree species, perhaps owing to their larger foliage biomass [4]. However, in the Rila Rhodope region, the CUE of deciduous forests of oak and beech is lower than the CUE of coniferous forests dominated by *Pinus nigra*, *Pinus sylvestris*, *Picea abies*, and *Abies alba*. This distinction in CUE of deciduous and coniferous forests located in boreal and temperate climatic zones deserves to be studied separately, but we suppose it is due to different species composition and environmental conditions.

CUE depends both on the strength of drought and on its duration and time in the year when it occurs (perhaps phenophase stage). The most significant impact on CUE are five-month-long droughts, regardless of the time of the year when they occur. The present study shows that SPEI cannot fully explain changes in CUE. It turns out that in some cases the mechanism of drought formation is important. For example, in 2007 moderate dryness conditions (SPEI_5) are formed as a consequence of the sequential alternation of short periods of precipitation and drought, and the magnitudes in GPP and respiration reduction are comparable. So the positive effect of precipitation on CUE was offset by subsequent drought, and a determining factor on CUE remained the temperature that can increase terrestrial ecosystem respiration to 7% [12] and thus reduce CUE.

In the studied region, the CUE trend along altitude is more complex than the global one [8]. Starting from lower altitudes, the CUE declines with the increase of altitude, while global estimates show a rising trend. In the research region, the global trend is confirmed in the higher parts of the mountains, where the CUE trend is growing.

5. Conclusions

The present study shows that we need further research to understand the mechanisms of dependencies between CUE and the combination of high temperatures and water deficit conditions in terrestrial ecosystems.

Acknowledgments: This study was funded by Research Center at Agricultural University, Plovdiv, Bulgaria under the Project #13-16NIS AU.

Conflicts of Interest: The authors declare no conflict of interest.

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