General Response to Referees' Comments

Three anonymous referees have provided generally positive comments on our manuscript, with some constructive critiques that we plan to address as explained below (responses are written in *italic*; modified text in quotation marks). The three main comments are as follows:

- Reviewer #1: ambiguous definition of C-use efficiency (CUE) for organisms and communities. The reviewer correctly argues that CUE should be defined as 1-respiration rate/uptake rate. This means that biological products such as exudates should be accounted for in the CUE definition, differently from gross growth or biomass production efficiency in which net biomass increments only are accounted for. We will revise our definition according to the reviewer's suggestion.
- Reviewer #2: lacking discussion on human impacts on ecosystem scale efficiencies. This is an excellent suggestion as it prompted us to generalize the definition of C storage efficiency (CSE). We will include anthropogenic C fluxes in our definition of CSE and comment on the role of ecosystem management as a driver of change for CSE.
- Reviewer #3: lack of clarity in some definitions. We will revise the text to clarify ambiguous definitions, and change Table 3 to indicate which components of the C cycle represent inputs and outputs in each of the systems/scales considered.

Detailed responses are reported in the individual rebuttal letters.

Anonymous Referee #2

The manuscript submitted by Manzoni et al. is a review associated to a database analyse around the concept of carbon use efficiency and carbon storage efficiency.
The quality of the manuscript is very high and I particularly appreciated the effort of the authors to gather data from very different sources to have a broad view of the CUE/CSE concept. The writing is excellent and despite the complexity of the question the authors succeed to make a clear and easy to read document. I am convinced that this paper will be provide an important contribution to the literature and since it deals with data coming from plants, soil, ocean, etc. at different spatiotemporal scales it is of broad interest.
I may have few minor comments to try to make the manuscript even more attractive.

Thank you for the very supportive comments.

Section 3. Can you provide a bit more details on the methods used to collect the data (e.g. keywords used in ISIWEB).

Most of the datasets we used are already published. In this case we selected the most comprehensive published (and open-access) datasets that covered the widest range of ecosystems or organisms (see for details Table S1). We also collected specific data into new datasets to fill notable gaps. We aimed at having a representative sample of data, but did not perform a fully systematic data search as would be necessary in a meta-analysis, for two reasons:

1) *our goal was to only illustrate general patterns and report simple statistics (median, variability, range), not to perform a fully quantitative analysis*
2) *the enormous variability in terminology used across disciplines, and the fact that in many cases C-use or C-storage efficiencies were not reported in the papers, but only the C fluxes to calculate them were provided, made a systematic search not feasible. We therefore often followed leads from key papers (highly cited or identified by one of the co-authors) to find a selection of publications covering a given angle of C cycling and reporting enough information to calculate efficiencies*

For the new data compilations, we searched publications in the ISI Web of Science and in Google Scholar using various sets of keywords (refer to Table S1 for the following 'system' labels):

All plants: plant, "carbon use efficiency", growth AND respiration

Non-vascular plant communities: lichen OR bryophyte, respiration, temperature, "carbon use efficiency"; the compilation was based on existing synthesis papers (Porada et al. 2013, Lenhart et al. 2015)

Aquatic food chains: "food chain" OR "food web", "food chain efficiency" OR "carbon transfer efficiency"

Soils: soil, "organic carbon", "carbon sequestration efficiency", "carbon storage", "litter input" OR "residue input"

Catchments: "gross primary production", "dissolved organic carbon" OR "dissolved organic carbon export" OR "DOC leaching", "net ecosystem exchange", productivity, respiration

It should be noted that this was an iterative process, as we often started a search finding almost no relevant publication, only to later discover that in a specific sub-discipline different synonyms were used. Therefore, the search terms were updated accordingly, leading to a less structured search than we would have preferred. The result of this process is partly reflected by Table 2 in the main text, where all the synonyms found for CUE and CSE are listed.

To address this comment, we will add a paragraph in Section 3 "Data collection and analysis" that summarizes the above considerations:

"To compile the new data collections, we conducted an online search using ISI Web of Science and Google Scholar with keywords including various synonyms of CUE or CSE. We also gathered publications following relevant references in articles and books, and thanks to the expert knowledge of the authors. Due to the enormous variability in terminology used across disciplines, and the fact that in many cases CUE or CSE were not reported in the papers (but only C exchange rates to calculate them), a systematic search was not feasible. As a result, while not exhaustive, our selection of publications covers a broad range of conditions for each subset of data, and allows illustrating general patterns across disciplines and scales."

Section 4.1 You cite two studies as example but some methodological details are missing to fully understand your arguments (what kind of carbon added (litter, glucose...) or how long was the incubation for instance).

Details will be added in the main text to indicate the added compound used (glucose in both cases), and further clarifications will be added in the caption of Figure 4:

"Lower turnover rates were caused by lower mortality in the first 3 days of incubation compared to the day 112 (Ladd et al. 1992), or by lower grazing in the first two days of incubation compared to days 7-8 (Frey et al. 2001). Error bars indicate standard errors of the mean (variability is across three soil types in Ladd et al. (1992) and across replicates and soil types in Frey et al. (2001))."

We will also state for how long were the incubations performed to acquire the data shown in Figure 5c.

I missed some words on the anthropogenic effect on ecosystems CSE. In all the manuscript you compared different types of ecosystems but it may be interesting to compare systems highly managed like cropland or European forest and grassland with a substantial fraction of the NPP appropriated by humans (see Krausmann et al. (2013) for instance).

This is an excellent point. It is certainly possible to extend our definitions to systems that are heavily managed. We will first modify the definition of what are now referred to as "abiotic C exchanges", to accommodate anthropogenic intervention:

"The F_{in} and F_{out} are respectively C inputs and outputs occurring via abiotic exchanges of organic and inorganic C in natural ecosystems, but also account for anthropogenic inputs (e.g., manure) and outputs (e.g., harvested products) in managed ecosystems"

Second, we will refer more explicitly to anthropogenic C fluxes throughout the manuscript, and specifically add a paragraph in the discussion section 4.4 on human alterations of CSE:

"A large fraction of land surface and of marine systems is managed to extract food and fibre to support a growing human population (Krausmann et al. 2013). Management of ecosystems has two contrasting effects on CSE, depending on the balance of harvest removal, improved production, and organic amendments. On the one hand, extracting harvested products ($F_{out} > 0$) lowers CSE because a lower fraction of GPP remains in the system. For example, assuming a crop harvest index ranging from 25 to 50% of aboveground biomass (e.g., Unkovich et al. 2010) and a 30% allocation to roots, the percentage of NPP harvested and the corresponding reductions in CSE would range from 17 to 33%. On the other hand, management may improve CSE by increasing the production efficiency of vegetation (Campioli et al. 2015), or involve addition of organic C to fields ($F_{in} > 0$; e.g., manure or biochar). These C amendments increase CSE for given respiration and harvest rates, not only thanks to their direct effect through F_{in}, but also thanks to indirect effects when soil amendments promote plant productivity. However, this positive effect lessens as the amended organic C is respired and soil organic C reaches saturation levels (Stewart et al. 2007)."

As a modeller I have a very selfish request (but I guess it may help others). I appreciated the section 4.5 but I guess that the majority of the modellers using CUE concept are aware of the limitations presented here. Maybe one or two paragraphs with some concrete recommendations will be helpful. In particular, I am wondering if CUE or CSE at organisms or ecosystem levels should be considered as emerging properties of a given system and if yes it might become an interesting approach to evaluate model by comparing the CUE/CSE observed at the system level.

Yes, we agree that CUE/CSE are emerging properties of a given system and as such they integrate numerous processes and drivers. We also agree that some more specific recommendations may be helpful – to this end we will add the following paragraph to Section 4.5:

"In addition to the correct attribution of changes in CUE to processes or environmental conditions, it remains critical to match the definition of CUE used by empiricists with that implemented in models. Specifically, are the same biosynthesis components (e.g., biomass increment vs. exudate export) accounted for in both empirical estimates of CUE and in the model equations? Are abiotic C exchanges at the ecosystem scale both included in empirical estimates of CSE and described by models? As CUE and CSE represent emerging properties of organisms and ecosystems, they are appealing for model testing, but without a consistent definition, comparisons of model outputs and empirical estimates are not meaningful."

References

Campioli, M., S. Vicca, S. Luyssaert, J. Bilcke, E. Ceschia, F. S. Chapin Iii, P. Ciais, M. Fernandez-Martinez, Y. Malhi, M. Obersteiner, D. Olefeldt, D. Papale, S. L. Piao, J. Penuelas, P. F. Sullivan, X. Wang, T. Zenone, and I. A. Janssens. 2015. Biomass production efficiency controlled by management in temperate and boreal ecosystems. Nature Geosci **8**:843-846.

Frey, S. D., V. Gupta, E. T. Elliott, and K. Paustian. 2001. Protozoan grazing affects estimates of carbon utilization efficiency of the soil microbial community. Soil Biology & Biochemistry **33**:1759-1768.

Krausmann, F., K. H. Erb, S. Gingrich, H. Haberl, A. Bondeau, V. Gaube, C. Lauk, C. Plutzar, and T. D. Searchinger. 2013. Global human appropriation of net primary production doubled in the 20th century. Proceedings of the National Academy of Sciences of the United States of America **110**:10324-10329.

Ladd, J. N., L. Jocteurmonrozier, and M. Amato. 1992. Carbon turnover and nitrogen transformations in an alfisol and vertisol amended with ^{14}C[U]glucose and ^{15}N ammonium sulfate. Soil Biology & Biochemistry **24**:359-371.

Lenhart, K., B. Weber, W. Elbert, J. Steinkamp, T. Clough, P. Crutzen, U. Poschl, and F. Keppler. 2015. Nitrous oxide and methane emissions from cryptogamic covers. Global Change Biology **21**:3889-3900.

Porada, P., B. Weber, W. Elbert, U. Poschl, and A. Kleidon. 2013. Estimating global carbon uptake by lichens and bryophytes with a process-based model. Biogeosciences **10**:6989-7033.

Stewart, C. E., K. Paustian, R. T. Conant, A. F. Plante, and J. Six. 2007. Soil carbon saturation: concept, evidence and evaluation. Biogeochemistry **86**:19-31.

Unkovich, M., J. Baldock, and M. Forbes. 2010. Variability in harvest index of grain crops and potential significance for carbon accounting: examples from Australian agriculture. Pages 173-219 *in* D. L. Sparks, editor. Advances in Agronomy, Vol 105.