Dear Editor and reviewers,

Here as requested a point by point answer (in blue) on the observations and then actions taken to solve the critical points. I think that your comments helped to make the paper more clear, thanks for this.

COMMENTS FROM EDITOR

Both Jason Beringer (JB) and Bruno Marion promote important extensions of the Fluxnet data to commercial use and for forecasting which will be good to consider.

These and other suggestions received personally (from people that preferred to not use the discussion channel) have been implemented in the new version of the manuscript

But I am more concerned with the main comments from both JB and Joshua Fisher (JF). While clearly encouraging the discussion that Dario Papale has initiated, there is also a clear dose of skepticism, and a sense of "wishful thinking" (e.g. direct on-line data use, or the expectations with imposing a new world order on clusters). I concur with these concerns.

I was somehow expecting some scepticism, probably also due to a lack of clearness in some part of the paper. I need to underline that the paper has been submitted as "Ideal and perspective", so a personal view based on the past experience in FLUXNET and actual needs that I see. It is clearly not a tentative to impose anything to anybody, I considered this implicit (I can only decide on my personal work). I tried to clarify this in the new version. I think also that probably the fact that in the last 15 years I co-coordinated the FLUXNET synthesis activities introduces a kind of bias in the evaluation of a personal view. This is a problem and I think that exactly what I propose in the paper can help reducing the "personalization" of FLUXNET.

In fact, I was expecting much more community discussion of this 'Discussion Paper' and I, in fact, made a significant effort to get more reviews on board. Failing in both expectations maybe consistent with the concerns raised by the reviewers.

I personally do not agree with the link between number of reviewers and evaluation of the paper. If you look at all the papers in BGD and the amount of comments, the interesting system developed by Copernicus that allows everybody to add comment is (unfortunately) not yet used as we all would like. I also sent emails to FLUXNET and other networks to stimulate discussion and presented the idea in virtual conferences always suggesting to submit their view through the system. However, I received a number of comments personally, from people that did not want to post them publically. I tried to implement also these in the new version.

It seems to me that the comments center on two main arguments. First, the sort of “if it’s ain’t broke, don’t fix it” nature. After all, Fluxnet has been a formidable and enormously successful project (to which author has greatly contributed, and I have been a happy member of for 20 years).

This is true, but also that if there is nothing to fix it does not mean it does not need to/can evolve… The current system worked well because there has been the possibility to invest from single groups for huge efforts in the organization of synthesis activities. The risk is that to see future FLUXNET collections it will be needed to wait a lot of time. In fact, dataset from many people are currently not included in the FLUXNET2015 and there are no plans currently to initiate a new collection. I also think that the proposed system has not so many risks. I tried to revisit the text to make this more clear and analyse them.

The second, seems to suggest “evolution” over the “revolution” of the type proposed, noting some of the dangers, such as losing the data sharing nature of the current system, the complications that can arise from going “continental”, and the inability to impose, control, or manage such complicated and totally voluntary system.

The changes proposed would not affect so much the single station that would continue to collect data, submit and get involved, I recognize this was probably not very clear in the paper. It is something affecting more the regional databases that will have to develop more competences and take some of the workload if they are interested to keep FUXNET ongoing. To better clarify this and the fact that it is an evolution and not a revolution I added a new section and a table with the summary of the old vs new tasks for PIs and Regional networks.

The motivation for proposing changes is clear when it comes from someone who invested tremendous efforts in the current system of periodical data compilations. But it might require less committed, done-deal type presentation and more exploration of some alternatives, with more pros and cons.

Here I find some difficulties to find a balance. As said before, this is an Idea and perspective paper, not a formal proposal to other networks or anything forcing anybody. I think I should be free to present my personal view of this based also on the “tremendous efforts” invested and the problems in seeing this as a standard procedure. But see also the two answers below that can contribute to clarify this (I hope)

For example, it could be useful to add a Table comparing the functioning of the existing regional networks, highlighting the good the bad and the missing.

Thanks for the suggestion, I added this and I think it is useful to have a clear picture. It also highlights that the seed for the shuttle is somehow also operational as test case.

It might be good to present some gradual steps that can be taken from the good old system (see both JF and JB major comments) before breaking up to independent clusters. Consider how to gradually expand the already exiting cluster services, but keep the non-aligned sites active partners. Perhaps consider if it would be feasible to maintain the current system and shuttle the responsibility for the periodical data compilation among the sub-networks every few years (an alternative concept to the proposed “Fluxnet Shuttle”?)

Thanks for the suggestion; I added a completely new section on this to propose a possible transition scheme. It does not follow the suggestion of a periodic compilation because, in my opinion, it would not solve the problems and answer the needs (periodic and not continuous, not updated, need to additional resources for the current system, less engagement by the networks) but I tried to suggest a smooth transition path

And so I recommend major revisions of the paper seriously considering the critical (!) comments of the reviewers, going beyond the responses posted so far that are, arguably, not sufficiently convincing. I am confident that a revised version will deserve more response and discussion.

I hope that the revisions are answering the questions and moved the paper more in the suggested direction. All the changes are highlighted in the marked-up manuscript.

COMMENTS FROM REVIEWER 1 (ADDITIONAL TO THE ONE ALREADY SUBMITTED)

Isn't this already the *old* organization? I know what you're trying to say here, but it doesn't come across clearly (essentially, those pillars aren't always under the same ceiling, and so it takes some moving of those pillars around in the syntheses, which is time consuming).

I tried to make this more clear adding text and a table, highlighting where are the differences respect to the current system and why these are proposed.

Is it really a new proposal? Hasn't this been proposed for years?

As already said it was not proposed before in these terms, there have been discussions on the need of standardization but not as tool to evolve FLUXNET. I added an example to better clarify where we are now in this process, with the activities in AmeriFlux and ICOS and what is still not discussed and implemented.

Overall, the paper is somewhat light on specific details of how everything would work. I would guess that people are mostly on-board in theory. But, the practical systems engineering could perhaps be flushed out a bit more. Perhaps an additional figure could be useful that would reflect this.

I added a figure and a table to better clarify the data flow. I also added a paragraph where I suggest that all the technical details should be discussed by the networks once/if they agree to implement it (or a different system). This also because as answered above the decisions on implementation and technical and should be defined by the participants (and experts in the specific aspect). I added a reference to activities where these tools are under development.

Are there analog data networks that could be discussed for failures/successes?

I'm not aware of a network with a similar structure (diffuse bottom up initiative without funding) that implemented a similar scheme of coordination; I added a sentence to say that this could be in fact an example for others.

I wonder if FLUXCOM is the best example to justify the proposal. Adding new data to FLUXCOM at this point changes it very little, as far as I would expect, and it moves without real time eddy flux data based on globally gridded inputs. I guess the justification might be better if it were for FLUXCOM-like new initiatives; or, new members to FLUXCOM.

I added a more detailed description on why also for FLUXCOM this is very important and which opportunities could open, being a system that needs continuous recalibration.

I'm trying not to be biased, though I definitely am, but a good example for the remote sensing need was published in Fisher et al. [2020] for the ECOSTRESS mission… ….We're going to continue to have new missions that would benefit greatly from the proposed global standardized network…

As I already said in the first answer these are very important activities that can benefit from a more accessible and updated FLUXNET and could also strategic for the FLUXNET sustainability. I added references and text on this.

It would be good to include a statement of justification for Continental clusters. (Also, continents are not always consistently defined across the world).

I changed the term and removed the word Continental, changing also the figure and adding a second to better clarify this. I also added a SWOT table to better clarify the benefits.

COMMENTS FROM REVIEWER 2 (ADDITIONAL TO THE ONE ALREADY SUBMITTED)

In addition to the demand for real time data that you have outlined, there is also an emerging area of ecological forecasting, for example, The EFI-NEON Research Coordination Network that is an NSF project to create a community of practice that builds capacity for ecological forecasting using NEON. There is also potential demand from data assimilation of flux tower data into short range weather forecast (e.g. https://doi.org/10.1175/MWR-D-19-0370.1). Also real-time agricultural monitoring should be possible. Finally, data can also be used to generate regional real time evapotranspiration estimates using a fusion of flux tower, remote sensing and modelling all of which have potential for use by the public.

Thanks, I added a paragraph to include also these other potential users and applications that are very important and relevant.

With respect to the proposed re-organisation from a single large database into sub collections. On the one hand this helps make the network more sustainable by delegating work and responsibility to continental clusters so that not all the work is being done by a small group. On the other hand this will require continental clusters to be functional, accessible and have open data sharing policies. I would be concerned that many clusters may not have capacity to do this…

I added a section on the transition phase and also clarified how also few clusters could be sufficient to start the implementation of the system. I also removed the word “continental”, so that it is clear that this is geographically independent.

…or there may be a difference in data sharing between groups and individuals…

I tried to better clarify with text and a figure that the data policy of individual sites and Regional network doesn’t have to change. The point is to agree on the standard once they start to be shared in FLUXNET through the sharing system proposed.

…such that individual sites that may want to contribute are unable because of the inability of the cluster to participate for technical, personnel or other reasons.

I hope this is also more clear now, with the transition phase and the possibility to have a generic entrance for unaffiliated sites under the responsibility of one of the networks (that should provide the funding for this)

Following on from this I can see that there could be many, many sites (even some that were not part of FLUXNET2015) that want to contribute to FLUXNET but they are unable too because they don’t have a functional continental cluster. It will be crucial to make sure there is a mechanism for them to contribute.

I added a more clear statement on the importance to get all involved and the proposal for a generic entrance to the system for sites that are not part of any network (although I think that all the sites could and should have a network of reference, because networking with colleagues also regionally is important)

I’m not entirely sure for the rationale and need to move away from a large centralised data base to Continental cluster collections? There has been a lot of effort gone into making the database and I’m not sure if it is broken in some way or has reached its capacity technically. It seems to add another layer of complexity to have Continental cluster collections and a shuttle they queries each of them. It then relies to the ability of the clusters to maintain the data in real time in these clusters. Why not just have a continually updated big database where data is added at any time (daily or annually as it becomes available). You then rely on sites and clusters to push the data continually rather than calling and hassling for sites to submit data (current model). Users can query the data anytime too. We could build a set of tools that allow data to be accessed and queried in more sophisticated ways.

To try to summarize the advantages I added a SWOT table in the new version. I also made more clear that the current system requires resources that don't exist at the moment (organization of a FLUXNET synthesis and the organization of the distribution as it is now cost quite a lot, it should not be charged to only one network or group if we want to raise the level of quality and be robust…).

I like the idea of a persistent identifier (PID) or something similar. I would envisage that initially the processing would follow the FLUXNET2015 (i.e. ONEFLUX) pipeline and the PID would reflect that. But processing methods do evolve and a Fluxnet steering group could endorse any changes to the pipeline and periodically the PID would change to say FLUXNET2025 for example. It is probably important to think about changes in processing and reprocessing the whole database. This may well happen in the future if we have a new pipeline and you would want to apply the new pipeline retrospectively across all the data I presume? This would be manageable under a single large database but may be difficult under Continental cluster collections.

I added explicitly this example (the large massive reprocessing) to explain why the new system would work better and what we can do in case single networks or clusters are not able to do the task.

Ideas and perspectives: enhancing the impact of the FLUXNET network of eddy covariance sites

Dario Papale[1,2]

[1]DIBAF, University of Tuscia, Viterbo, 01100, Italy
[2]Euro-Mediterranean Center on Climate Change (CMCC), Lecce, 73100, Italy

Correspondence to: Dario Papale (darpap@unitus.it)

Abstract. In the last 20 years, the FLUXNET network provided unique measurements of CO_2, energy and other greenhouse gases exchange between ecosystems and atmosphere measured with the eddy covariance technique. These data have been widely used in different and heterogeneous applications and FLUXNET became a reference source of information not only for ecological studies but also in modeling and remote sensing applications. The data are in general collected, processed and shared by regional networks or by single sites and for this reason it is difficult for users interested to analysis involving multiple sites to easily access a coherent and standardized dataset. For this reason, periodic FLUXNET collections have been released in the last 15 years, every 5 to 10 years, with data standardized and shared under the same data use policy. However, the new tools available for data analysis and the need to constantly monitor the relations between ecosystems behaviour and climate change, require a reorganization of FLUXNET in order to increase the data interoperability, reduce the delay in the data sharing and facilitate the data use. All this keeping in mind the large effort made by the site teams to collect these unique data and respecting the different regional and national networks organization and data policies. Here a proposal for a new organization of FLUXNET is presented with the aim to stimulate a discussion for the needed developments. ~~, where t~~In this new scheme, the regional and national networks become the pillars of the global initiative, organizing clusters and becoming responsible for the processing, ~~and~~ preparation and distribution of datasets that users will be able to access real time and with a machine-to-machine tool, obtaining always the most updated collection possible but keeping high standardization and common data policy. This will also lead to an increase of the FAIRness (Findability, Accessibility, Interoperability and Reusability) of the FLUXNET data that would ensure a larger impact of the unique data produced and a proper data management and traceability.

1 Introduction

The FLUXNET network is a self-organized network of eddy covariance sites managed by scientists that share data, ideas and competences across the globe (Baldocchi et al. 2001). The eddy covariance technique (EC) (Aubinet et al. 2012) allows a direct and not-destructive measurement of greenhouse gases (GHGs) and energy exchange between surface and atmosphere at ecosystem scale (500m to 1km around the measurement point) and typically half-hourly time resolution.

Since the first examples of year-long measurements (e.g. Black et al. 1996, Valentini et al. 1996), the use of EC data became more and more common not only to study single ecosystems from an ecological and physiological point of view (e.g.

Reichstein et al. 2007, Law et al. 2002, Mahecha et al 2010, Luyssaert et al. 2007, Besnard et al. 2018) but also as ground observations in modelling development and validation and remote sensing applications (e.g. Bonan et al. 2011, Friend et al. 2007, Williams et al. 2009, Balzarolo et al. 2014, Jung et al. 2020). The large range of possible applications and the wide interest in these measurements, led first to the creation of regional and continental networks such CarboEurope (Dolman et al. 2006) and AmeriFlux (Novick et al. 2018) (followed by other continents for example with AsiaFlux, OzFlux, LBA and ChinaFlux, see Yamamoto et al., 2005, Beringer et al., 2016, Restrepo-Coupe et al., 2013 Yu et al., 2006) and then to the organization of the FLUXNET network-of-networks where all the regional networks contribute with a variable number of sites and years of data.

In the context of FLUXNET there have been different initiatives to facilitate discussion and cooperation across networks with specific conferences and meetings (starting in 1995, see Baldocchi et al. 1996) and the preparation of FLUXNET synthesis data collections with the aim to make the data available to wider communities. The main FLUXNET collections were produced in 2001 (Marconi dataset, Falge et al. 2005), 2007 (LaThuille dataset) and 2016 (FLUXNET2015 dataset, Pastorello et al. ~~2017~~2020), including an always larger number of sites-years (97 in Marconi, 965 in LaThuile and more than 1500 in FLUXNET2015) and providing standardized data ready for a large range of heterogeneous applications. These collections were needed because each regional network applies its own processing and formatting scheme (including different variable names and units) and this prevents an easy use of data across sites in different continents. In the last years AmeriFlux and the European networks worked toward a standardization that also highlighted the uncertainty introduced by the data processing (Pastorello et al. 2020) but this still not sufficient to replace ~~a~~ global initiatives. ~~The~~ However, the preparation of a FLUXNET collection requires a large effort that involves data collection, data policy agreement, common data quality controls, feedbacks with the site owners for corrections, processing and finally preparation of the products and their distribution, including the maintenance of the web-services for the data distribution, users tracking, updates of information etc.. All this considering that FLUXNET per se is not a funded initiative, there are no structural funds to maintain its operation and the synthesis dataset were created on initiatives of single groups often in the context of specific research projects. This is why 6 and 9 years passed between one FLUXNET synthesis collection and the following one.

The heterogeneity across regional networks is however something difficult to avoid. These networks are in fact based on general goals and scientific aims that can be different and can require specific design and processing. For example, the NEON network was planned using a hierarchical system to represent different ecoregions (Schimel et al. 2007) and the sites are highly standardized in terms of setup. Also in ICOS (Integrated Carbon Observation System) the stations are highly standardized but the design is driven by the single country decisions and priorities. In AmeriFlux, instead, an open participation is possible and everybody can register their sites in the network, without an overall design or standardization of the towers setup but allowing diversity and bringing under the same network sites designed for specific and heterogeneous research projects. In addition, single sites can be linked to other national or regional initiatives that could impose specific ways to prepare and distribute the data collected. Finally, but often one of the most important aspects, there are different views, sensitivities and readiness respect to the data sharing and data use policies, often linked to the need of visibility (of both the single sites and the Regional networks) that ensure proper funding to sustain the activities. These are key aspects, fully justified and difficult to change at global level in a short or medium period, which therefore need to be considered in a re-organization of the FLUXNET network structure

2 New needs and the role of FLUXNET

The need of ground observation data is increasing continuously and there are new examples of modelling and synthesis applications that require (or would require) direct measurements updated frequently. One example of such activities is the FLUXCOM initiative (Jung et al. 2020), where satellite and meteorological spatialized data are used as input in a machine-learning (ML) ensemble to predict Net Ecosystem Exchange, Gross Primary Production, Ecosystem respiration and other energy fluxes at continental and global scale. These data represent often a link between the observations in FLUXNET and the large scale modelling initiatives. The ML algorithms need observations for their parameterization and the FLUXNET data have been successfully used in the training (e.g. Tramontana et al. 2016). Although the relations between drivers and fluxes can be "learned" by the ML also using past data, the availability of new stations is crucial to improve the quality of the predictions and reduce their uncertainty.~~, in particular when covering~~ This is particularly relevant if new data cover under-sampled areas (Papale et al. 2015), extreme climatic events (Mahecha et al. 2017, van der Horst et al. 2019),~~ and more recent years that represent the recent climate variability and~~ different land management ~~effects~~practices, and in general the effect of the climate pressure on ecosystems (Anderegg et al. 2020)~~ would be important to improve the quality of the predictions and reduce their uncertainty~~. An annual production of these bottom-up empirically upscaled estimations could for example be used as additional input in the Global Carbon Project (www.globalcarbonproject.org) annual report (e.g. see Friedlingstein et al. 2019) on the carbon balance of the globe, where currently the FLUXNET data are in general not sufficiently used. The provision of a standard, continuous and global dataset of surface-atmosphere exchanges of GHGs is also a fundamental step to include the eddy covariance fluxes in the list of the Essential Climate Variables (ECV) define by GCOS for the empirical observation of processes related to climate change (Bojinski et al. 2014).

The same is valid for the remote sensing community that needs ground validation data frequently and with high quality standards, like in case of the Ground-Based Observations for Validation (GBOV) of Copernicus Global Land Products (https://land.copernicus.eu/global/gbov/home/) or the CEOS Land Product Validation (LPV) subgroup (https://lpvs.gsfc.nasa.gov/) that already cite FLUXNET as potential source of data but currently can not find a valid contribution because the data do not overlap in time with the most recent sensors (e.g. the Sentinel constellation).

Remote sensing community is also developing new tools that requires almost real time data (or with minimal delay) for the validation of their products that can also be of interest for the FLUXNET community. An example is the ECOSTRESS initiative for the evapotranspiration estimation where FLUXNET data have been already used (Fisher et al. 2020) but additional missions requiring a set of rapidly and directly available flux data will probably appear in the near future (e.g. Sun induced fluorescence or radar based products on soil moisture and canopy structure).

Finally, there is a set of potential new fields and applications that today are only partially using the FLUXNET measurements but would benefit from a more strong interaction with the eddy covariance community. These include, for example, the near-term ecological forecasting (Dietze et al. 2018), the use of FLUXENT data in weather forecast models (Boussetta et al, 2013) or the near-real time monitoring of agriculture.

If we want to have the FLUXNET data more used and integrated with other scientific disciplines, also to start new cross-disciplines collaborations based on recent or even near real time data, we need to change the way in which the data are shared in order to make their use more easy and suitable for new applications. In particular, we need to work to ensure fast updates of the collection and easy and direct machine-to-machine data access and data use capabilities, with a clear and easy to apply data use policy. Unfortunately we are not yet there and the use of an updated and standardized set of data still requires and extra effort (and a set of competences) that only few users are able to afford. For example Fisher et al. (2020) in their paper present very clearly the list of issues to address to create a usable collection, that span from a largely heterogeneous data format (more than a dozen), processing level, collection mechanism to the need of an additional reformatting, processing and QAQC before the data use.

The characteristics of a dataset to ensure a machine findable and readable format and a clear rule for its use have been described by the FAIR principles (Wilkinson et al., 2016) and a new scheme should move in this direction (e.g. Collins et al. 2018). In particular, following the FAIR principles, the FLUXNET data should be easy to find (Findable) through common metadata searchable by a tool; easy to access (Accessible) also through a machine-to-machine system and with a common and clear data use policy; processed in the same way and distributed in the same format in order to simplify the merging and synthesis (Interoperable); and clearly identified and permanently referenced in order to allow multiple uses and reproducibility of the studies and results (Reusable). All this, keeping the system robust and sustainable and for this reason not dependent on the capabilities and resources of a single network or group (as it has been until now).

The FLUXNET members would also benefit from a system able to process, standardize and distribute their data rapidly and in a clear and traceable way. The site teams would obtain a set of products as output of the centralized processing, that in some cases could be difficult and time and resources consuming to apply individually. In addition, and more important in my opinion, a FLUXNET network with these characteristics would provide new opportunities to the FLUXNET members for collaboration and joint activities, facilitating synthesis studies at continental and global scales. For example, the ICOS community promptly prepared and shared a collection of in situ measurements from 52 sites in Europe (www.icos-cp.eu) that are used to analyse the effect of the 2018 European drought (e.g. ~~Bastos et al. 2019~~Graf et al. 2020, Fu et al. 2020) on terrestrial ecosystems. This fast data release however was possible only thanks to an extra effort for the data processing by ICOS (in addition to the effort by the site teams to collect and share the data) and it is difficult to imagine this as standard way to proceed in future and globally. In fact, ICOS was created and funded as Research Infrastructure designed to sustain an organized observation network with prompt data delivery but this is not common across all the regional networks that compose FLUXNET.

3 A new FLUXNET organization

In order to answer the new needs and opportunities described above, a new FLUXNET organization is necessary, that should start from the experience and development achieved ~~must~~ and take into consideration the complexity of the system and peculiarities of all the participants. The solution should involve all the regional networks participating in order to increase the robustness and sustainability and, at the same time, keep their autonomy and internal flexibility needed to answer additional specific research questions, respect the organizational and political structures governing them and answer specific needs in terms of data processing, format and sharing.

For this reason, a new FLUXNET organization should be based on an agreement among the different regional networks, in order to ensure redundancy of competences particularly important in case of limitations in the resources. In the proposed scheme, the networks are grouped in ~~Continental~~FLUXNET clusters that agree to share data following a common procedure when the participating networks and the single sites are ready, interested or available to share (Figure 1).

With this organization, the ~~Continental~~FLUXNET clusters become the pillars of the FLUXNET system, coordinating the participation and data sharing in FLUXNET by different national and regional networks. In order to ensure the needed standardization in terms of processing, format, accessibility and data policy, the ~~Continental~~FLUXNET clusters must agree to prepare and maintain a specific database structure (the “FLUXNET ~~version”~~ baskets” in Figure 1) where a common and agreed data product (including all the needed metadata and versioning information) are loaded and made available. The main change respect to the current system is in the role of the Regional network databases and processing centres that would need to organize and run the cluster (Table 1). For the sites instead the system remains similar to the current organization (Figure 2), with the addition that it is not needed to organize double submissions of the same data (to the Regional network and for FLUXNET synthesis) but it is sufficient to decide when, for a given dataset, it is time to share in FLUXNET. In fact the Regional networks can continue to distribute data according to their specific data policy and move to the FLUXNET cluster only the dataset that can be shared under the common open data policy.

The FLUXNET product creation requires also that all the participating networks agree on the characteristics (for example minimal requirements about the variables, standard processing to apply, (meta)data format, common data policy, mechanism for data access etc.) and contribute to the development. However, we do not have to start from scratch: in the last years, for the preparation of the FLUXNET collections, standards have been already defined and implemented also at regional level (e.g. AmeriFlux, the European Database and ICOS produce already the same output). These include format, units, processing schemes and codes that are openly accessible, like in the case of the ONEFlux suite (Pastorello et al. 2019 and 2020).

Clearly the methods, standards and the needs evolve in time and for this reason it is important to discuss and agree on a plan and strategy to coordinate the efforts and define the common set of rules to apply in the ~~Continental~~FLUXNET clusters. FLUXNET worked well as bottom up initiative, community driven and without rigid and formal governing bodies, allowing people to participate, propose and use the FLUXNET organization in a democratic way. To keep this spirit, a light coordination committee constituted by Regional networks and ~~Continental~~FLUXNET clusters representatives that work directly on data processing could serve as tool for the process governance in the definition of the new standards to apply and new products to introduce.

It is also important to define a strategy to evaluate and decide on implementation of changes or additions to the standards. In general, there is no reason to change established methods and formats if not motivated since this has an impact on the users that have to adapt their tools (in particular users interested to continuous data uses). For the processing the requirements could be, as in the last FLUXNET releases, that the processing tools should be at least 1) published in peer-review journals, 2) available to be easily applied to large and heterogeneous dataset, 3) with the implementation codes open source and 4) different enough from what is already implemented to justify their addition to the processing flow (it is crucial to find the right balance between completeness and usability, too many options lead can lead to confusion).

The regional and national networks and single sites that are part of a ~~Continental~~FLUXNET cluster can continue to keep their specific databases and interfaces if needed (the Data portals in Figure 1) to distribute their data. This could be needed in case of different formats (e.g. when linked to other observation networks with different standards) or in case of different processing (e.g. additional variables calculated centrally from raw data, or products of regionally specific processing tools). It should be noted that standard processing has the advantage of making all the data more comparable but at the same time it is possible that in specific conditions or sites it fails and an ad hoc specific processing is needed and results could be shared in the network Data portals. Differences in the data policies applied to specific sites or specific portions of the database can also be handled through regional data portals that can define licenses different respect to the common used in FLUXNET. Then, when a dataset become ready to be shared in the FLUXNET system, it is processed also following the agreed FLUXNET standard and loaded in the FLUXNET ~~version~~ basket.

The FLUXNET collection is then not any more a large dataset stored in one location but a set of sub-collections stored in the FLUXNET ~~version~~ baskets of the different ~~Continental~~FLUXNET clusters and accessible visiting all of them to get the last version available. The access can be implemented through a common query system (the FLUXNET shuttle in Figure 1) that points automatically to the different FLUXNET ~~version~~ baskets and, using standardized metadata that include versioning information, gets the last version of the ~~Continental~~FLUXNET cluster collections to create an updated FLUXNET collection for the user. In this way, each single user could create at any time (on demand) a collection that is built using the most recent data provided by the FLUXNET network, allowing applications that requires updated collections. At the same time, the system gives the possibility to promptly correct possible errors if needed and to include continuously new sites as soon as they are ready to share, making FLUXNET even more inclusive. In order to help scheduling of the work of the teams responsible of the sites, fixed "FLUXNET shuttle" runs can be scheduled for the main operational activities, e.g. before a FLUXCOM training or periodically when satellite products validation tasks are scheduled.

Clearly one of the requisites to have the FLUXNET shuttle working correctly and the users able to use the data is a common and clear data policy. The ~~Continental~~FLUXNET clusters must agree on a common data licence that should simplify and promote the use of the data. With the aim to have FLUXNET used and promoted by different communities, standard data licenses should be considered because common across disciplines and for this reason well know. Currently most of the monitoring networks are moving to the Creative Common CC-BY 4 license (https://creativecommons.org/licenses/by/4.0/) that ensure attribution and promote data use. All this, however, must also considered the need of recognition and advantages for the scientists working at the sites that are discussed below.

4 Advantages and risks of the proposed new organization

The proposed FLUXNET scheme would have a number of advantages. First, the users will not have to wait for releases of datasets every 5 or 10 years but can get the most updated version of the shared data in real time. This would stimulate the use of data by scientific communities that need recent measurements (e.g. in early detection of anomalies). The data would increase also their level of FAIRness, improving their Findability through the use of standard metadata across the ~~Continental~~FLUXNET clusters, their Accessibility through a common open data policy and a single tool to retrieve all the data (the FLUXNET shuttle), their Interoperability thanks to the standardization. With a system that creates a new (and potentially different) collection at every user's request, it is crucial to clearly identify the data included (and the versions) also to ensure reproducibility of the results. This is achievable through a specific persistent identifier (PID) that users should always report and that will improve the data Reusability in case of studies reproduction and verification.

In terms of robustness, sustainability and flexibility, the proposed system would also substantially improve the current situation thanks to the overlap of data processing capacities and responsibilities among the ~~Continental~~FLUXNET clusters. In fact, sharing of workload will stimulate collaboration across networks and promote interchangeability of roles since each ~~Continental~~FLUXNET cluster could process the data of another cluster if needed. This crucial aspect is missing today; if for example one network or FLUXNET cluster has difficulties in a certain period (lack of funding, key people moving etc.), the other FLUXNET clusters can support the common processing so that the network with difficulties could dedicate the resources only to internal discussion with the sites and data collection. This could be particularly relevant in case a big changes in the processing scheme (that will inevitably happen) and that will require a massive data reprocessing. In this case, a mutual support of the FLUXNET clusters or also an investment on a common and shared computing resource for the standard processing would help the sustainability for all the networks.

~~This~~ The capacity to process the data following the same standard method and the alignment in terms of code versions can be periodically tested though a verification system similar to a "round-robin test" where all the clusters will have to process the same set of data with the standard procedure and results are compared. ~~In addition, the Continental clusters could also invest on common and shared computing resources where all the data are processed with the same codes.~~ All this keeping the full flexibility of each single network to decide what to share and when in FLUXNET and the possibility to distribute different formats and versions through their Data portals.

It is however important to analyse the concerns that a new FLUXNET organization like the one here proposed could raise. In particular, there is the risk of losing the control of the data (who accessed, where they are used etc.) and this is directly linked to a crucial aspect: the visibility of the people. The large amount of work and investment done by single stations and networks participating to FLUXNET must be fully recognized and should have an effect on the funding to continue the work and data provision and on the career of the people involved. The contribution of data to FLUXNET is in most cases on voluntary bases so the proposed system would not force participation. It is however important to try to get as many people and networks as possible engaged and the analysis of the benefits that data sharing can brings is the natural step to take a decision. Although this has been discussed in different frameworks (e.g. Papale et al. 2012) and studies demonstrated that people sharing data get more recognition due to the collaborations established (Bond-Lamberty, 2018; Dai et al., 2018), it is out of scope here to enter in the details on the benefits and convenience of data sharing.

What a reorganized and truly international FLUXNET system can do is to ensure a full traceability of data access and data uses, to allow each data owner to have an exact quantification of the use of the data shared. From a technical point of view, the compilation of a list of downloads per site it is something that can be easily implemented using the FLUXNET Shuttle and can provide important information about the use of the data. However, this is not enough: it would be important to have in all the papers that use these data the citation of the datasets so that the impact and usefulness of each single site can be quantified and recognized. This would require the help of the journals that should request, during the review, to clearly cite the DOI or PID of the dataset used, and this should not be affected by the limitation in the number of citations often imposed. In this way it would be possible to evaluate and show the importance of the data collected and distributed by FLUXNET and which are the communities using them. Finally, a new and more robust, sustainable and fast organization could stimulate the interaction with the private sector that is currently missing (except for the instrument manufactures). Private users interested not only to use but also to contribute to the measurements could increase the FLUXNET visibility and attract the needed resources to growth and strength the link with the stakeholders (Marino 2020).

5 Moving toward the implementation

A change in the FLUXNET organization, although based on the existing capacities and experiences of the site teams, regional networks and past collections leaders, can only be gradual with a transition phase that must allow all the interested groups to adapt and organize their role and work. During this transition phase, it is important to keep present the overall aim and final structure but the activity can start from few initial groups that, for historical reasons or contingent situations, are ready to start prototyping the system. For example, ICOS and AmeriFlux are already distributing data processed using the same software (ONEFlux, Pastorello et al. 2020) in their respective portals (ICOS: https://meta.icos-cp.eu/collections/ueb_7FcyEcbG6y9-UGo5HUqV, AmeriFlux: https://oneflux-beta.ameriflux.lbl.gov/). The access is still individual and the policy different but it is a first step in the direction of a distributed preparation and access to a common product.

During the transition phase it is important that FLUXNET remains inclusive, giving the possibility to everybody to get involved and have data processed and shared, without the risk to feel isolated or excluded. This can be ensured by a cross-networks support system, where clusters ready to process and distribute can temporary offer to do the activities for other networks or individual unaffiliated sites with, and here it is a difference respect to the current system, the agreement that in parallel all the networks work in the direction of the establishment of a reference FLUXNET cluster. It is also clear that a single Regional network could act as FLUXNET cluster autonomously, this is possible and it is only a matter of optimization in the use of resources.

It is also needed to discuss and agree on all the technical details, which can start from the experiences already done in the context of the FAIR principles applications and development and prototyping of specific tools (e.g. see https://envri.eu/home-envri-fair/). The choices regarding the organization of FLUXNET clusters, the technology to use, the timeline for implementation and all the other technical details need a general discussion where all the regional networks should be involved independently of their readiness in the actual implementation.

6~~5~~ Conclusions

The main differences between the current FLUXNET organization and the new proposed structure are the shared workload and overlap of competences among a number of organizations (FLUXNET clusters) that can ensure the needed robustness and the real time distribution of new data available. All this without scarifying the visibility and role of the Regional networks that remain crucial for their role of organization, support, guidance and scientific development linked to the local networks. ~~A reorganization of FLUXNET following the line presented here would lead to a~~The main ~~number of~~ benefits would be~~:~~ 1) an increase of robustness of the global network thanks to the sharing of workload and responsibilities, 2) a strength of the collaborations ~~and links~~ among networks and colleagues across the world and 3) an increase of visibility thanks to the continuous~~ly~~ availability of updated products that can lead to more users and resources. There are clearly also risks like in all changes that however can be handled with a smooth transition phase and a real spirit collaboration (Table 2). The solution is also scalable once implemented, giving the possibility to include new measurements (e.g. new GHGs like CH_4 or N_2O, see Knox et al. 2019, Nemitz et al. 2018) or new processing also starting from raw data. In fact the development of new tools by a ~~Continental~~FLUXNET cluster, already designed to be generally applicable, can be made available to all the others easily and without duplication the efforts. The proposed scheme would also move FLUXNET in the direction that was already defined 20 years ago, developing a collaborative, self-organized and bottom up network, able to answer to new requests thanks to the continuous updates. This can works also as example for similar distributed observational networks that could benefits from the experience done in reorganizing FLUXNET. The evolution of the regional networks toward more organized and stable infrastructures, the large number of eddy covariance people that are now sharing data and collaborating in FLUXNET and the new spirit of collaboration among regional networks, are solid bases to do this step.

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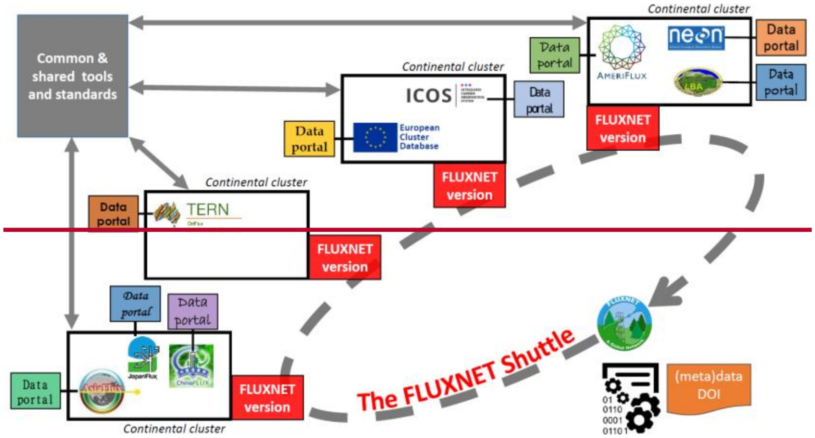


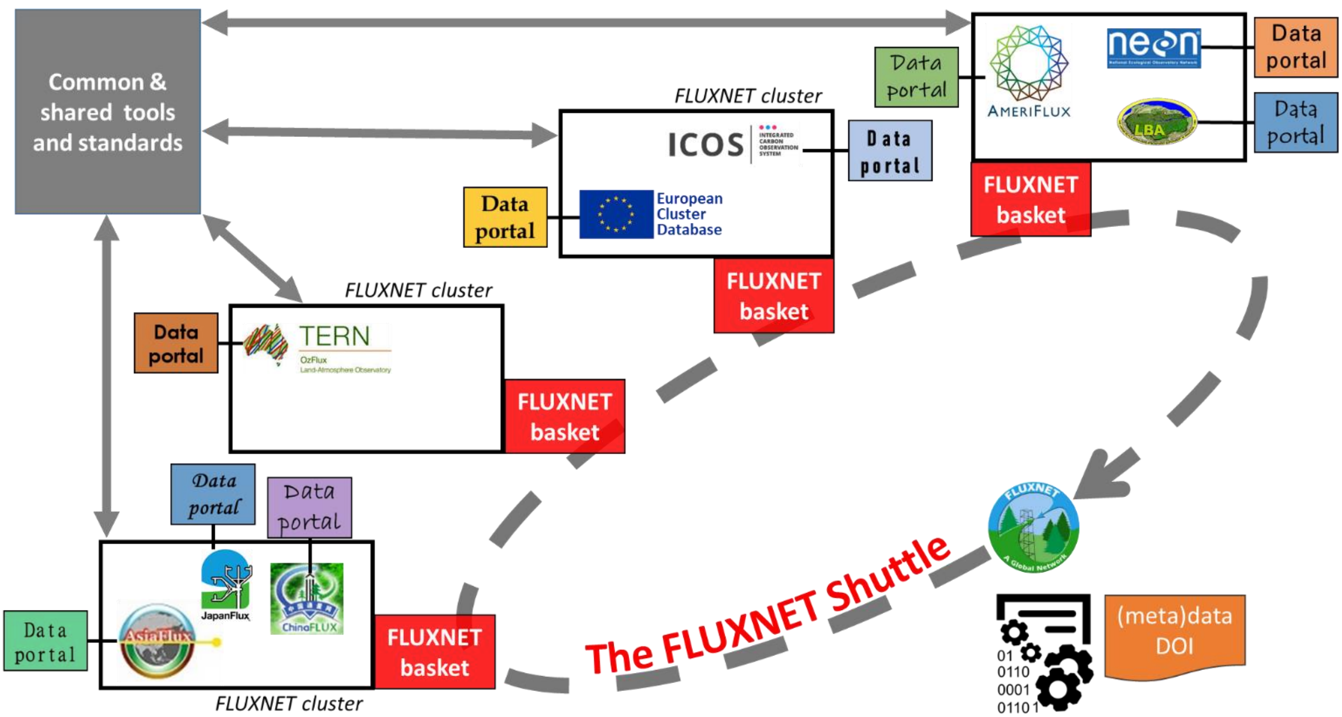
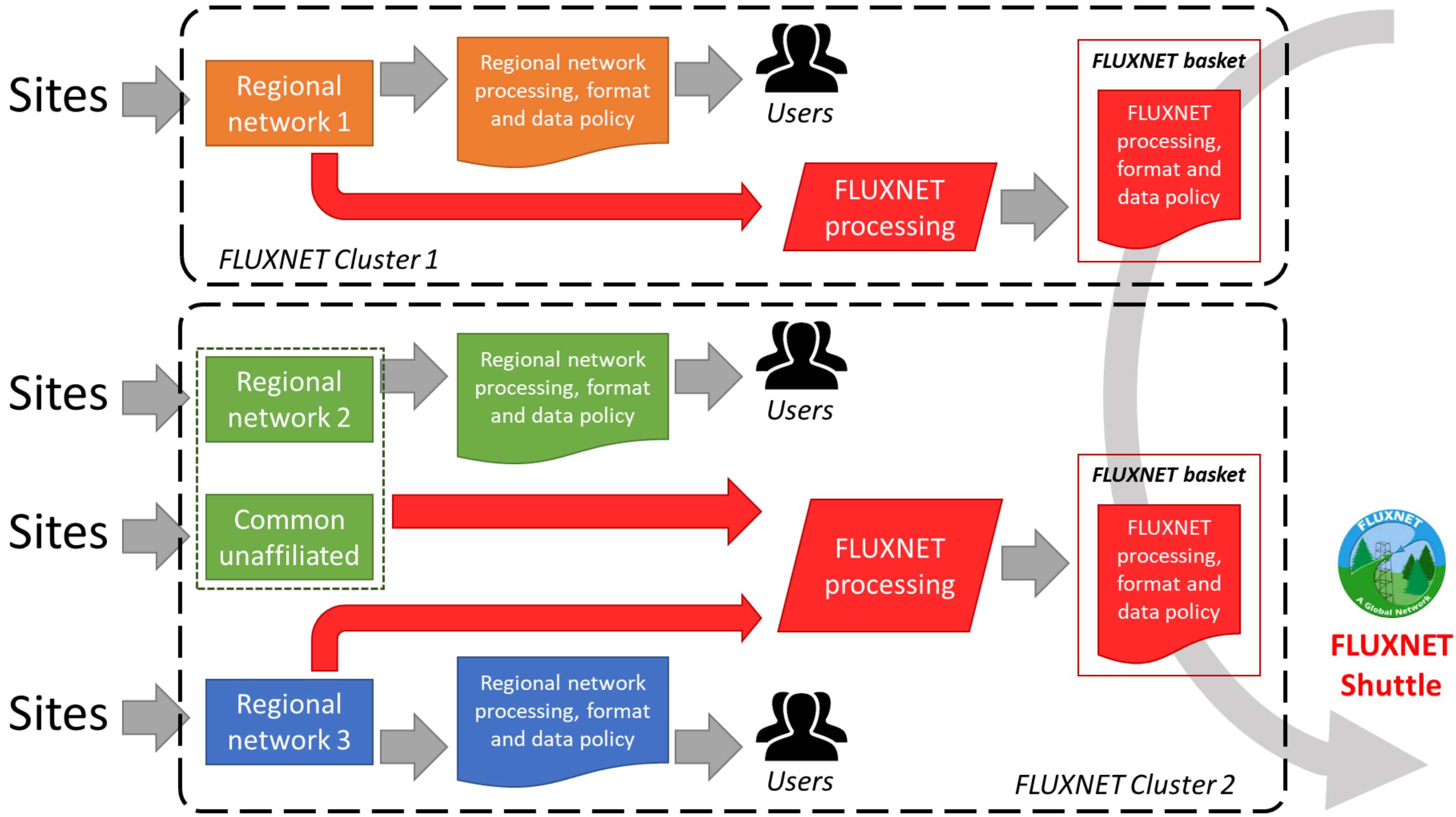


Figure 1: scheme of the proposed new organization of FLUXNET for data collections preparation (see text). "Data portal" boxes represent the regional/national network databases, all potentially different in terms of data processing, format and data policy. The black boxes grouping regional/national networks are the "~~Continental~~<u>FLUXNET</u> cluster", the framework under which a set of national networks coordinate their participation in FLUXNET and where a common processing is applied. "FLUXNET ~~Version~~<u>basket</u>" red squares are the ~~common "baskets"~~<u>database sections</u> for FLUXNET data to share, where common format of data and metadata are loaded whenever ready and distributed under the same and common data policy. "FLUXNET Shuttle" is the tool to access the data across the ~~Continental~~<u>FLUXNET</u> clusters that is run on-demand by the users and provide a dataset (including metadata) and a PID or DOI for the exact citation and reconstruction of the dataset used.



510 **Figure 2: data flow from the sites to the FLUXNET Shuttle. The sites submit the data to the Regional networks where they are associated or, may be for a temporary period, to a common system for unaffiliated sites that is managed by one of the Regional networks (in the figure the Regional network 2). Each Regional network can organize its own data processing, data policy and data distribution system. Part of the data are then also processed using the standard FLUXNET processing and then shared in the FLUXNET basket where the FLUXNET shuttle can collect for the user on request. The data shared in the FLUXNET shuttle are defined by the data owner. Note that the clusters can be also composed by a single Regional network (like for Regional network 1 in**
515 **the figure) if the resources are sufficient to maintain it.**

Component	Action	Current system	Proposed system
Sites	Data submission date	*After a call for synthesis, respecting a deadline*	*As soon as ready or interested*
	Data submission method	*To the people initiating the synthesis*	*To the Regional network (temporary if needed to a common platform)*
	Data policy	*Two or three options to select*	*One policy, common for everybody*
Regional Networks	Data collection	*Some networks collect from their sites*	*Data collection for all the sites participating*
	Data processing	*none*	*Contribute to the FLUXNET Cluster*
	Data storage	*Original data*	*Original data and FLUXNET products*
	Data distribution	*Original data*	*Original data and FLUXNET products through the FLUXNET Cluster*
FLUXNET Cluster	Data collection	*not existing*	*none*
	Data processing	*not existing*	*Apply standard FLUXNET data processing*
	Data storage	*not existing*	*FLUXNET products*
	Data distribution	*not existing*	*Organize and maintain FLUXNET basked for the sharing through the shuttle*
FLUXNET Synthesis team	Data collection	*Collect from all the sites and Regional Networks*	*Collaborate through the Regional Networks and FLUXNET Clusters*
	Data processing	*Apply standard FLUXNET data processing*	*Collaborate through the Regional Networks and FLUXNET Clusters*
	Data storage	*FLUXNET products*	*Collaborate through the Regional Networks and FLUXNET Clusters*
	Data distribution	*Organize and maintain a FLUXNET server for distribution*	*Collaborate through the Regional Networks and FLUXNET Clusters*

Table 1: main changes for the different actors between the current FLUXNET synthesis system and the one proposed in this paper. The FLUXNET Cluster does not exist in the current organization and it is the key new component proposed.

Strengths	Weaknesses	
	Point	**Corrective action**
Distributed workload that ensures sustainability and robustness	Investment done until now is not used	The competences will migrate in the new system
Continuous updates of the collection	Risk that the data policy is not followed	The new system make all more engaged to ensure proper data citation
Easy data access and clear policy	Feeling that the data control is lost	The FLUXNET Shuttle will have to register all downloads and provide PIDs
Increase visibility of the Reginal Networks and engagement of the regional communities	Sites could be not ready/interested to adopt the standard open policy	The Regional networks can continue to distribute the data under their policies

Opportunities	Threats	
	Point	**Corrective action**
Attract more users and interests	Only few Reginal Networks able to organize this	Other Regional Networks could help
Stimulate participation also from less represented areas	Distributed processing could affect standardization	Periodic tests using a "Round robin" method
Increase visibility and international collaboration	Readiness of the Regional networks not homogeneous	Transition phase where a general FLUXNET Cluster is also active
Get more stable funding from other organized users	-	-

Table 2: SWOT (Strengths, Weaknesses, Opportunities, Threats) analysis of the new proposed system. For the Weaknesses and Threats possible corrective actions are also reported.