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Carbon sequestration for different types of crops

Carbon emission of interventions for landslide risk

A global estimate of CO2 photogeneration by lake waters

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TABLE OF CONTENTS

Executive summary

This policy brief summarizes three complementary research projects focusing on CO_2 emissions or sequestration by different natural sources: crops, landslides, and lakes.

The first research line focuses on understanding how plants acclimate to climate variability and how new agricultural technologies can improve photosynthesis, especially under adverse climatic conditions, and help reduce carbon emissions and/or enhance its sequestration. It estimates technologies' effectiveness in enhancing crop photosynthesis and improving water efficiency. Experiments were conducted in controlled environments to measure CO_2 sequestration in various crops under variable water conditions. The acclimation of plants to temperature changes allows them to maintain efficient photosynthesis. However, drought poses a great challenge, especially as it increases with climate change. Agricultural practices significantly affect greenhouse gas balances through both emissions and CO_2 absorption. Emerging technologies, such as biostimulants and drought-resistant plant varieties, show promise for maintaining high photosynthetic rates and water-use efficiency under stress conditions, thus enhancing carbon sequestration and reducing chemical inputs. Experimental findings indicate that biostimulants can maintain high photosynthetic efficiency in drought: this suggest supporting drought-resistant crop breeding, promoting biostimulant use for water efficiency, and synchronising CO_2 absorption with emission patterns to maximize agriculture's role in climate mitigation.

The second research line focuses on developing a dynamic Landslide Susceptibility (LS) map for Italy that leverages Google Earth Engine (GEE) to enhance landslide risk management in a changing climate. By integrating satellite imagery, rainfall, and land cover data, GEE facilitates large-scale geospatial analysis at low computational cost, and it allows for temporal monitoring of environmental changes. The project proposes a framework that exploits a Random Forest (RF) algorithm trained on Italian landslide data. This LS map categorizes regions into six hazard zones. Additionally, the study explores the link between LS and soil organic carbon (SOC), finding that high SOC levels align with lower landslide hazards, contributing to insights on carbon storage’s role in stabilizing slopes. Moreover, an analysis following the Emilia Romagna landslides of May 2023 found significant SOC and above-ground biomass (AGB) losses: landslides may act as temporary carbon sources and human interventions, such as reforestation, could be essential in restoring carbon stocks post-landslide. The finding points to a need for sustainable management of SOC and AGB to maintain ecosystem resilience.

The third research line assesses the photochemical generation of CO_2 from organic sources in lake waters exposed to sunlight. Dissolved organic matter in lakes, particularly its chromophoric fraction (CDOM), absorbs sunlight, undergoing oxidation reactions that ultimately release CO_2. While photosynthesis typically offsets this CO_2 production, disruptions in lake ecology may result in a net increase in greenhouse gas emissions. Using a simplified model focusing on a single wavelength (410 nm) representative of sunlight-induced CO_2 production, the study considers over 70,000 lakes worldwide. Large northern lakes (30°N-60°N), like the Caspian Sea, account for about 50% of CO_2 emissions from lakes globally. Although the CO_2 produced by photomineralization is typically balanced by photosynthetic uptake, environmental changes could disrupt this balance. It is then important to prioritize large lakes for CO_2 monitoring.

1. Presentation and description of the research activity undertaken

1.1 Carbon sequestration for different types of crops

To improve the predictive capacity of climate models and orientate agricultural practices more effectively towards reducing emissions, it is crucial to deepen the understanding of the mechanisms of acclimation of plants to climate variations and to quantify the impact of new technologies on them and on the improvement of photosynthesis in adverse climatic conditions. This can enhance the role of agriculture in mitigating climate change.

This research aims to provide a first estimate of these technologies' effectiveness in improving crops' photosynthetic rate in difficult climate contexts. Furthermore, we analyze how they can optimize water usage, reducing dependence on water resources and external inputs. The presence of increasingly longer dry seasons even in temperate climates is currently the main factor in the ongoing climate crisis. The results obtained can be used within climate models and define how the use of these new technologies and the consequent efficiency of agricultural practices can contribute to the reduction of GHG emissions. To this end, experimental activities were carried out to measure the fixation and sequestration of atmospheric CO_2 in different crops in a growth chamber, in a greenhouse and in the field, modulating the environmental conditions, especially in relation to water availability.

Part of the results coming from these activities have already been published (or submitted for publication) by acknowledging GRINS funding in high-impact scientific journals or international conference proceedings (Patono et al., 2023b; Biglia et al., 2024; Cardinale et al., 2024; Gisolo et al., 2024, Maioli et al., 2024; Morabito et al., 2024; Visentin et al., 2024).

1.2 Carbon emission of interventions for landslide risk

Landslide Susceptibility (LS) maps are important instruments to manage landslide risk, especially in a climate changing environment. The goal of this research is to produce a LS map that automatically updates to account for the changes of the environment. We apply Google Earth Engine (GEE), a digital tool that integrates various datasets, including satellite imagery, DEMs, rainfall data, and land cover maps, for landslide susceptibility modeling. It offers geospatial analysis, machine learning algorithms, and statistical models, allowing for regional to global mapping at low computational costs. GEE is also a cost-effective and efficient solution for assessing landslide hazard at a national level. The research activity will not only share the result (i.e. maps), but the algorithm as well. This will encourage further research.

The framework proposed in this study includes:

(i) Collecting relevant data, such as satellite imagery, elevation data, soil type, precipitation, and any other relevant information needed for landslide susceptibility mapping;
(ii) Preprocess and prepare data for analysis using the cloud based vast repositories of GEE;
(iii) Develop a landslide susceptibility model using machine learning algorithms, such as Random Forest or Support Vector Machine, and apply transfer learning techniques;
(iv) Training of the model using landslide data based on Italian landslide inventories;
(v) Apply the model to the area of interest.

Some of the features used for LS mapping are also closely related to carbon emission and carbon stocks such as vegetation index (NDVI), land cover and land use. Since the algorithm uses open-source data that will be updated in the future, the model can be easily updated providing the most up-to-date results.

The LS map is further used to explore the spatial pattern between landslide hazard levels and natural carbon storage. A quantitative distribution of soil organic carbon (SOC) in each landslide susceptibility class is calculated based on the aforementioned model and open-source satellite data, showing that good levels of SOC are associated with lower hazards. We highlight how changes in carbon stock can affect landslides and the importance of implementing effective policies for protecting carbon stocks.

Finally, considering the extreme rainfall events that occurred in Emilia Romagna in May 2023, we computed the above-ground biomass available before and after the event, showing that in the landslide areas, one year after the event, the biomass decreased, thus landslides, at short term, act as source of carbon emissions. Human interventions may be necessary to improve vegetation recovery and restore important carbon sinks.

1.3 A global estimate of CO_2 photogeneration by lake waters

This research activity assesses the photochemical production/emission of CO_2 upon photomineralisation of organic matter in lake waters exposed to sunlight. Lake-water dissolved organic matter, and especially its chromophoric fraction (CDOM: chromophoric dissolved organic matter) absorbs sunlight (hν) and, as a consequence, undergoes a series of oxidation reactions in the presence of dissolved oxygen that initially produce oxidised/oxygenated compounds ($CDOM_{ox}$). Ongoing photooxidation of $CDOM_{ox}$ eventually yields CO_2, H_2O, as well as inorganic ions such as NH_4^+ and PO_4^{3-} from organic N and P species initially found in CDOM (Koehler et al, 2014).

$$\text{CDOM} \xrightarrow{h\nu} \text{CDOM}_{ox} \xrightarrow{h\nu} \text{CO}_2 + \text{H}_2\text{O} + \quad \text{inorganic ions} \qquad (1)$$

The CO_2 thus contributes to the overall emissions of GHG by lake waters (Cory et al, 2024), although this phenomenon is usually offset by photosynthesis that transforms CO_2 into organic compounds that are eventual sources of, among others, CDOM itself. However, possible alterations of biological processes in lake waters could turn reaction (1) into an actual source of CO_2. In this framework, this work has the goal of assessing which regions of the world and, ideally, which lakes contribute the most to CDOM photomineralisation, to set priorities for environmental monitoring of this process. To do so, we have combined global estimates of dissolved organic carbon in lake water (Toming et al., 2020) with an assessment of incident sunlight intensity over the lake surface. (Carena et al, 2023).

2. Relationship with the existing literature on the topic

2.1 Carbon sequestration for different types of crops

2.1.1 General framework

Climate change is profoundly influencing global ecological cycles, with significant impacts on forests, agriculture and other natural ecosystems. Among the processes most affected is photosynthesis, the mechanism through which plants absorb CO_2 from the atmosphere and transform it into energy for growth (Dutta et al., 2020). In addition to being critical for maintaining plant life, photosynthesis plays a crucial role in carbon sequestration, contributing to the reduction of greenhouse gas concentrations in the atmosphere. Terrestrial plants, by retaining CO_2 in plant biomass and soils, act as real "carbon sinks", mitigating global warming (Mercado et al., 2018).

However, the ability of plants to play this role is closely linked to climatic conditions. Each species has an optimum temperature within which photosynthesis occurs efficiently. Fortunately, many plants can acclimate to changes in temperature, regulating their physiological processes to maintain optimal photosynthetic efficiency (DaMatta et al., 2010; Lynch et al., 2021).

2.1.2 Acclimation and improvement of climate models

Through acclimation, plants can maintain higher rates of photosynthesis and respiration across a wide range of temperatures (Crous, 2019). This leads to greater carbon absorption and facilitates its storage in soils and plant biomass. Not taking acclimation into account in climate models risk overestimating the sensitivity of ecosystems to global warming, resulting in distorted predictions of carbon sequestration and mitigation strategies. Including acclimation in climate models therefore allows for more accurate projections of CO_2 uptake by terrestrial ecosystems, improving global estimates of the carbon cycle (Smith et al., 2015). However, if plants in temperate climates have a high capacity to acclimate to increased temperatures, they are less capable of responding to multiple stresses, such as events of drought during heat waves (Grossman, 2023).

2.1.3 The importance of studying agriculture in climate models

In climate models, agriculture plays a key role in the global greenhouse gas balance: it contributes both to greenhouse gas emissions and to the mitigation of climate change through the photosynthesis of cultivated plants. Therefore, on the one hand, cultivated plants absorb CO_2 via photosynthesis and on the other hand, agricultural practices – such as tillage, use of fertilizers and fossil fuels – generate significant emissions, including CO_2, methane (CH_4) and nitrous oxide (N_2O), which contribute to global warming (Lynch et al., 2021). Therefore, it is essential to analyze the contribution of agricultural practices to the emission of the aforementioned gases (Patono et al., 2023, 2023a) to develop targeted and effective mitigation strategies (Soares et al., 2023).

2.1.4 New technologies and climate mitigation in agriculture

Emerging technologies are revolutionizing agriculture, offering powerful tools to mitigate the effects of climate change. Biostimulants and new cultivated varieties, the result of advanced breeding or genetic engineering, represent promising solutions to increase the resilience of crops to environmental stress and improve photosynthetic efficiency (Balafoutis et al., 2017).

Biostimulants improve the resistance of plants to abiotic stresses such as drought and salinity, stimulating the physiological mechanisms of plants to maintain optimal growth even in unfavorable conditions. This, in turn, allows high rates of photosynthesis to be maintained, increasing the ability of crops to sequester carbon.

Furthermore, new plant varieties that are more tolerant of heat and drought, developed through genetic improvement, are essential for adapting agriculture to climate change. These plants require fewer water and nutrient resources: they can continue to sequester carbon while reducing fossil fuel consumption during agricultural practices (Johansson et al., 2023).

2.2 Carbon emission of interventions for landslide risk

LS evaluation models can be qualitative or quantitative, based on expert knowledge and computational tools. Qualitative methods include geomorphological analysis, heuristic approaches, and variable mapping. Quantitative methods include statistical analysis, machine learning methods, and deep learning. Different types of deep learning methods perform similarly well in prediction accuracy and evaluation. Considering a significant number of driving factor and work on large areas have always been challenging and computing-resources-consuming, but emerging cloud-computing resources offer new possibilities.
This research applies machine learning methods to develop a LS map for Italy considering 18 factors and it explores how GEE may offer a cost-effective and efficient solution for assessing landslide hazard on a national level. While previous research has employed GIS and satellite data for similar purposes, the national-scale utilization of GEE stands out as an innovative approach. In addition, a homogeneous LS map for the country is currently missing, as each regional authority applies a different approach.
Soil Organic Carbon (SOC) and Above Ground Biomass (AGB) are two of the most important carbon sinks, and they are threatened by different hazards such as floods, forest fires, and landslides. Landslides cause tree destruction and disrupt soil cover, resulting in various physical, chemical, and biological changes that may lead to the release of organic carbon stored in the soil and vegetation, contributing to increased atmospheric CO_2 levels (Shiels and Walker, 2013).
While it is well established that vegetation can improve slope stability, it is still not clear if landslides will increase or decrease SOC and AGB at different time scales. This research tries to give a contribution on this topic, although further developments are necessary.

2.3 A global estimate of CO_2 photogeneration by lake waters

Several studies suggest that the lower wavelengths of sunlight, especially UV, are most effective in inducing the photochemical generation of CO_2. This is quantified by the quantum yield of CO_2 photoproduction, which decays exponentially with increasing wavelength (λ) as $\Phi_{CO_2}(\lambda) = A\ e^{-B\lambda}$ (Vähätalo et al., 2000). Note that estimates for the A and B parameters relevant to lake-water CDOM are known from the literature (Vähätalo et al., 2021). The trend of $\Phi_{CO_2}(\lambda)$ is further exacerbated by the fact that the absorption of sunlight by CDOM also has an exponential decay with wavelength, as $A_{CDOM}(\lambda) = A_o\ e^{-S\lambda}$, where the parameters A_o and S are available from the literature as well (Vione and Scozzaro, 2019). At the same time, however, the intensity of sunlight has an opposite trend because it increases when passing from short UV wavelengths to the visible region (Frank and Klöpffer, 1988). Therefore, the sunlight wavelengths at which photomineralisation is faster depend on the interplay between CDOM absorption, sunlight intensity, and the mineralisation effectiveness of the absorbed sunlight photons at different wavelengths.

Previous measurements of CO_2 photochemical production have been carried out on several lake-water samples from different regions of the world (Vähätalo et al., 2021). Moreover, a nationwide assessment of the process is currently available in the case of Sweden (Koehler et al., 2014) In the same study an attempt has been made to extrapolate the Swedish results at a global level, but it had all the disadvantages of an extrapolation because it did not directly use data related to the global lakes. For this reason, it is very important to carry out such a global assessment based on DOC data for each relevant lake.

3. Research output

3.1 Carbon sequestration for different types of crops

To evaluate the increases in air temperature intrinsically linked to changes in carbon assimilation by plants, carbon assimilation measurements were carried out with temperature growth ramps in the range 22-42 degrees Celsius, parallel to light ranges 0-1700 PAR, mimicking the evolution of the growing season of plants in a temperate climate or the maximum daily excursion range of a summer day. While there are important variations for C4 plants (maize, model plant), the same cannot be said for C3 plants (grapevine, model plant) (Figure 1).

Our study therefore had the aim of studying the exchanges of CO_2 between plants and the atmosphere during drought phenomena, the main consequence of the thermal increase and ongoing climate change. In the study, the vine plant was used as a perennial plant model and the tomato plant as a crop model. Figure 2 shows how the assimilation rate (A), which coincides with the rate of absorption of atmospheric CO_2 by the plant, decreases strongly in conditions of water stress (>70%), while the plant respiration, and in this specific case of the root system decreases by a maximum of 40%, resulting in a clear decrease in the accumulation of net carbon in the plant (Figure 2).

Subsequently, the study demonstrated the possibility of using new agricultural technologies to reduce the water footprint of crops and improve their photosynthetic performance. Through the use of tomato genotypes resistant to water stress, we show that it is possible to reduce water consumption and allow the plant to overcome a period of drought without suffering high metabolic damage (Figures 3 and 4).

At the same time, the study demonstrated that using biostimulants can be equally effective, improving water use efficiency (WUE) even in the presence of drought stress. Biostimulants have shown the ability to drastically increase the rate of photosynthesis in adverse climatic conditions. The study quantified the overall water saving with the use of a biostimulant product in the study period and the absorption of CO_2 during drought (Figures 5 and 6).

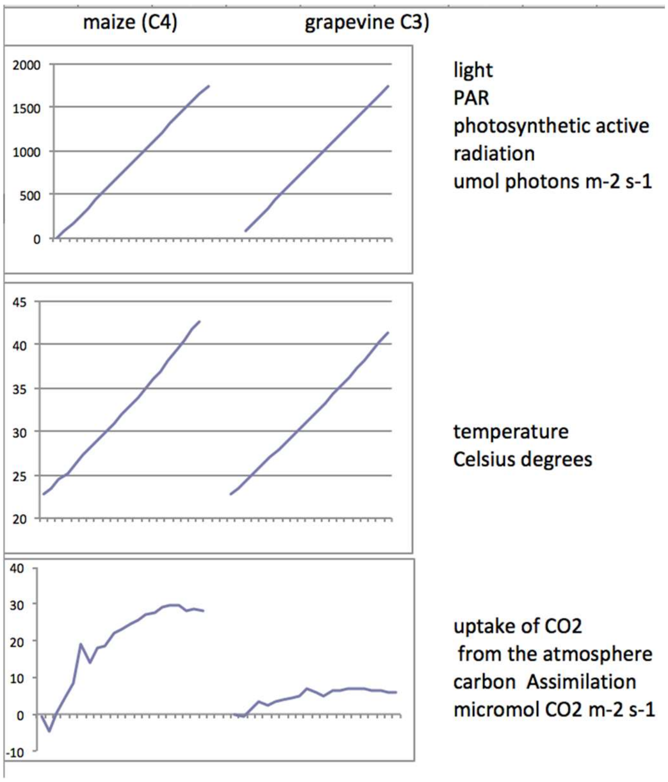

Figure 1. Experiment showing thermal and light variations mimic of a growing season and/or a summer day, demonstrating that in C3 plants, elevated thermal levels intrinsically lower carbon assimilative capacities, causing photo-respiratory processes to progress in parallel to photosynthetic ones.

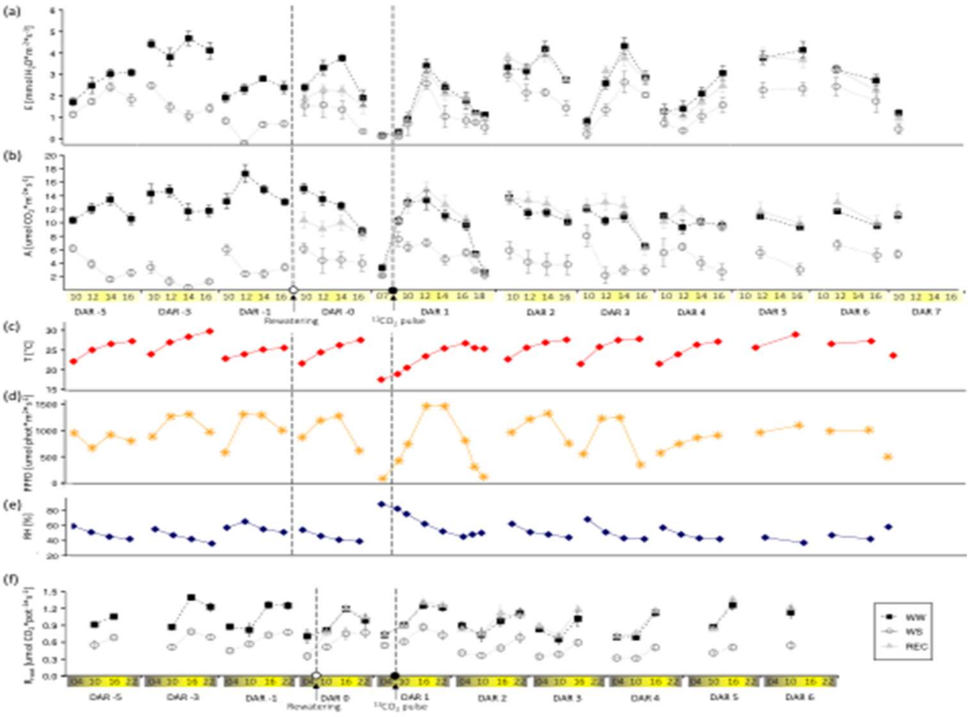

Figure 2. Experiment showing the rate of assimilation (A), transpiration (E) and respiration (Rroot) of grapevines in a drought condition (WS) compared to a well-watered condition (WW). As can be seen, the decrease in the rate of assimilation is proportionally reduced more than the reduction in respiration. At the same time, vine plants (REC) after a rehydration event following a period of drought, immediately resume maximum levels of respiration, while photosynthesis returns to maximum levels after a lag time.

Figure 3. Sldmr6-1 resistant genotype obtained with gene editing (gene involved in salicylic acid (SA) metabolism) and WT line compared during drought response tests. The image shows the growth of the plants in a greenhouse after 7 days of withholding, the resistant genotype presents maximum vitality and turgidity, while the WT line presents loss of turgidity and growth inhibition.

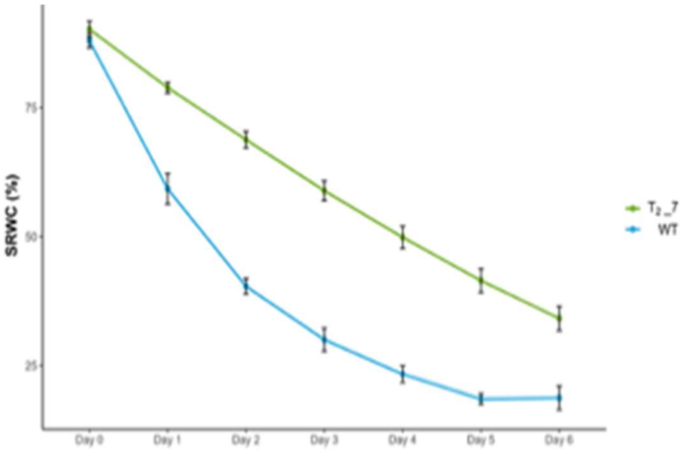

Figure 4. Soil relative water content (SRWC) of WT and Sldmr6-1 lines (T2_7) during the drought period. The resistant genotype shows less water consumption during the drought period, which is why the plant is able to overcome the period suffering less metabolic damage.

Figure 5. Grapevine plants during a biostimulant test.

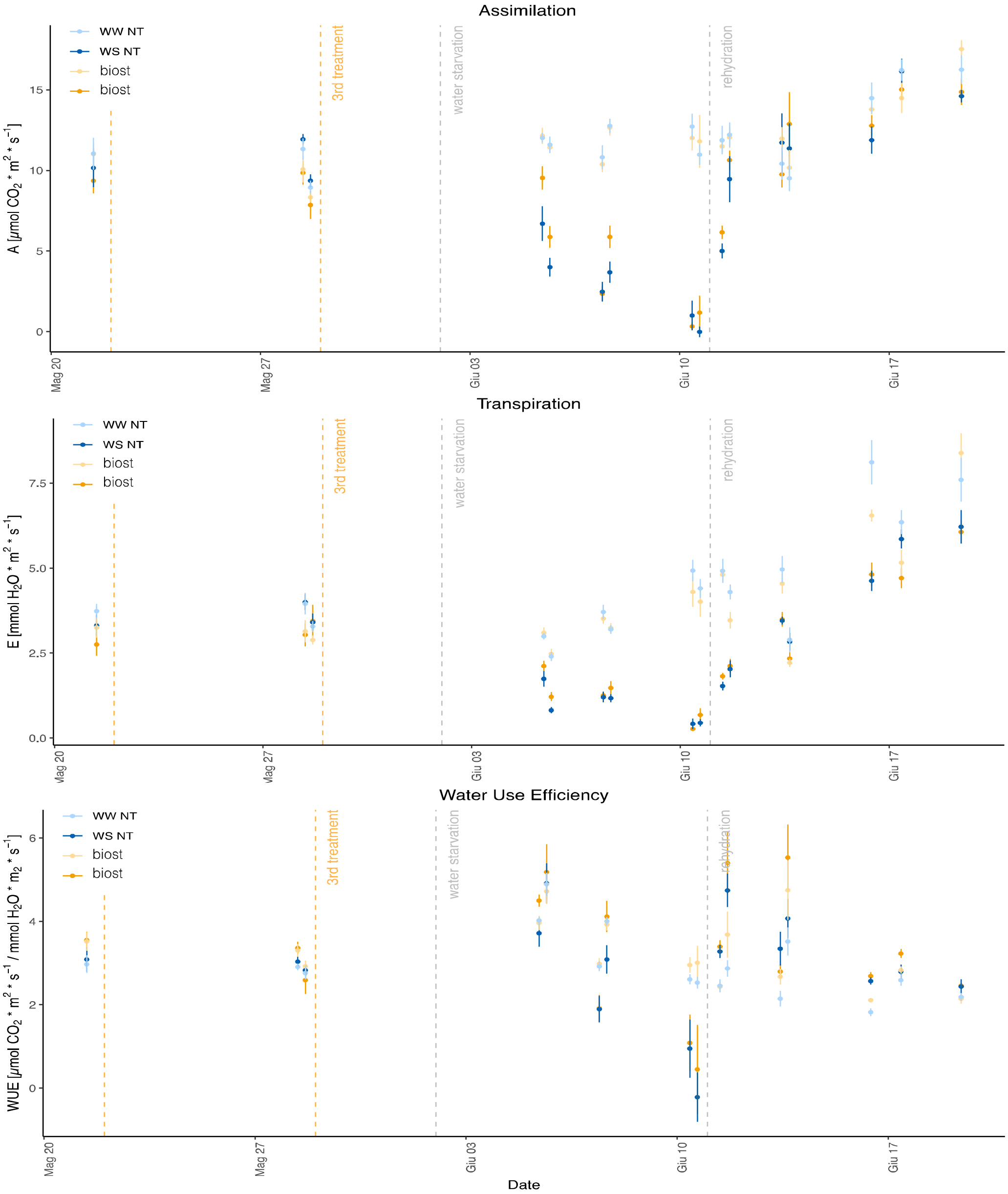

Figure 6. The graph shows how a biostimulant developed to improve the photosynthetic performance of plants during a period of water starvation (drought stress) allows the vine plant to preserve a high level of assimilation (absorption of CO_2 in the photosynthetic process). At the same time, in Well-Watered (WW) conditions, plants treated with a biostimulant product have a lower transpiration rate and therefore lose less water. This leads to better use of water and therefore the possibility of absorbing more CO_2 while consuming less water as seen in the graph showing the Water Use Efficiency.

3.2 Carbon emission of interventions for landslide risk

A LS map is prepared based on Machine learning Algorithm using cloud-based platform to deal with large scale data at national level and to serve as digital twin with the upgradation and addition of the new data. The parameters of the model are automatically loaded and elaborated from open-source databases. The model is trained and tested using two landslide inventories: the Italian Landslides Inventory (IFFI, https://www.progettoiffi.isprambiente.it/) and Italica (https://doi.org/10.5281/zenodo.8009366).

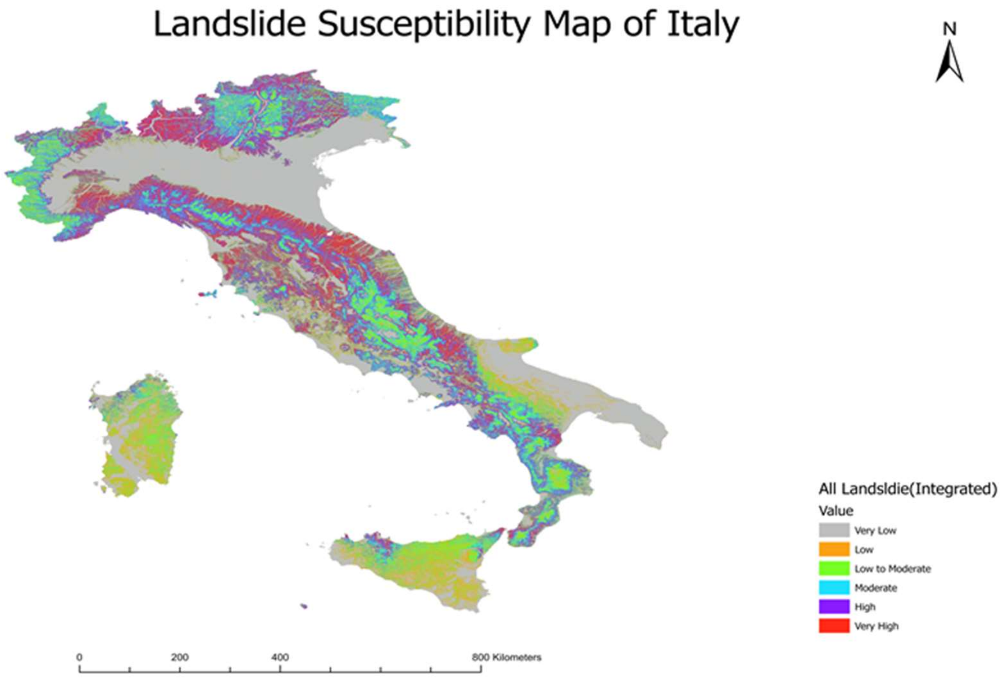

Figure 7 - LS map for Italy

The LS map divides area into six classes based on their likelihood of experiencing landslides: "Very Low," "Low," "Low to Moderate," "Moderate to High," "High," and "Very High" susceptibility. "Very Low" areas have stable geological conditions and minimal landslide history, while "Low" areas pose a slightly higher risk. "Low to Moderate" areas indicate a moderate increase in risk, while "Moderate to High" areas suggest a more substantial likelihood of landslides. "High" areas have steep slopes and unstable geology, and "Very High" areas present the highest risk due to extremely steep terrain and frequent landslides. These classifications guide land use planning, infrastructure development, and risk mitigation efforts in landslide-prone regions, helping to minimize potential damage and protect lives and property.

The Random Forest (RF) model is used with 18 parameters. Feature importance indicates the contribution of each variable to the accuracy of the model in predicting landslides or other phenomena (Fig. 2). Our results suggest that rainfall is the most influential variable in predicting landslides: this is reasonable, since water plays a significant role in triggering landslides. Following rainfall, we find the Normalized Difference Vegetation Index (NDVI), indicating its importance in assessing vegetation health and its potential correlation with slope stability. Elevation comes third, which is also logical since terrain elevation can influence slope steepness and soil moisture distribution. The HAND (Height Above the Nearest Drainage) variable follows it captures topographic features related to drainage networks, which affect soil saturation and landslide susceptibility. Slope, ranked fifth, is crucial as steeper slopes generally exhibit higher landslide potential. Soil density, occupying the seventh position, reflects the importance of soil properties in determining landslide susceptibility. Lastly, the shape index ranks eighteenth, suggesting it has the least influence among the variables considered.

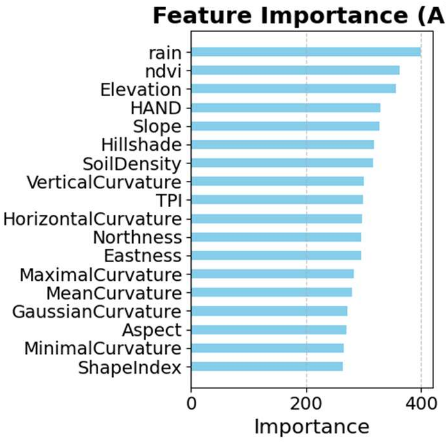

Figure 8 - Feature importance

Total and mean SOC for different hazard levels are computed. Low hazard levels (0 and 1) show limited mean and total SOC because these are typically urbanized and agricultural areas. Decreasing levels of mean and total SOC are observed for higher hazard levels (2 to 4), probably indicating that this factor may contribute positively to landslide hazard. At the same time, it is possible to observe that there is a significant amount of carbon stored in high or very high susceptibility classes which may become a carbon source if landslide occurs. However, the interpretation presented here is preliminary and necessitates further validation.

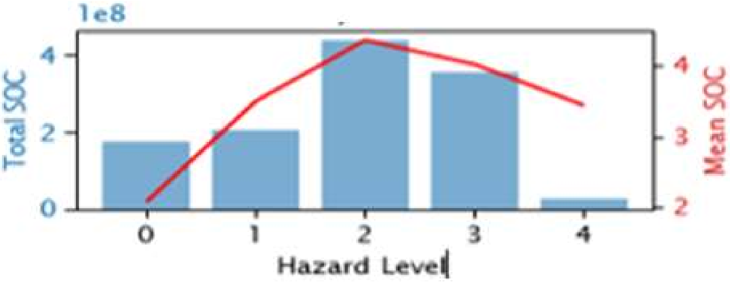

Figure 9 - Total and mean SOC for different hazard levels. Total Soil Organic Carbon is the sum of the organic carbon content in the soil across a specified area (Mg). Mean Soil Organic Carbon is the average organic carbon content per unit area in the soil (Mg/ha)

We investigate the impact of landslide events on carbon stocks, specifically SOC and AGB, using pilot case: the intense rainfall events that occurred in May 2023 in Emilia Romagna (Italy), causing more than 60 thousand landslides of different types. Results show that, one year after the event, the area experiencing a decrease in SOC (approximately 23 million square meters) is significantly larger than the area showing and increase in SOC (approximately 8 million square meters). Moreover, there is a significant loss of AGB: from 750,266.23 Mg in 2022 to 484,902.34 Mg in 2023. These quantifications should be considered preliminary, to be confirmed with field measurements.

3.3 A global estimate of CO_2 photogeneration by lake waters

The calculation of CO_2 photogeneration rate by a lake (R_{CO_2}) requires the use of a complex polychromatic equation that is difficult to manage when making global-scale assessments:

$$R_{CO_2} = A\, S_L \int_{\lambda} p^{\circ}(\lambda)\, e^{-B\lambda}\, (1-10^{-A_o\, DOC\, d\, e^{-S\lambda}})\, d\lambda \qquad (2)$$

where $p^{\circ}(\lambda)$ is the intensity of sunlight, DOC is the dissolved organic carbon of the lake water (the higher the DOC, the higher the content in organic matter), d is the lake depth, S_L is the lake surface area, while the quantities A, B, A_o, and S have been introduced previously. Given its complexity, equation (2) was simplified by considering the single wavelength that best reproduces the generation of CO_2 by the polychromatic system. As shown in Figure 10a, the wavelength λ = 410 nm (dashed curves) was very suitable to reproduce the polychromatic CO_2 generation (solid squares); moreover, a single-wavelength approach has the advantage of being much simpler and easier to be applied at a global scale. In particular, due to limitations in the equations used to describe the global behaviour of sunlight (Carena et al., 2023), we were able to assess its intensity in the latitude range going from 60°S to 60°N. The limit in the southern hemisphere is not a big issue due to the absence of land (except for the Antarctica) below 60°S. In contrast, many lakes occur above 60°N latitude but they receive relatively low sunlight throughout the year, which limits the possible extent of CO_2 photogeneration in such environments.

Figure 10b shows the estimated DOC values we used, relevant to approximately 70,000 global lakes for which such estimates are available (Toming et al., 2020), and limited to 60°S-60°N because of the lack of 410-nm sunlight intensity estimates outside that latitude range. It can be seen that the lakes that are richest in organic matter are located at elevated Nordic latitudes. This issue would be partially offset by the fact that the intensity of sunlight during the year at such latitudes is lower compared to sunlight intensity in the tropical belt.

Figure 11 reports the calculated values of CO_2 photoproduction (year averages) for each lake under study. First of all, it can be noted that the values of R_{CO_2} range between 10^3 and 10^9 g_{CO_2} day^{-1}, thus showing a large difference of six orders of magnitude between the least and the most photoproductive lakes. Another issue is that over 80% of CO_2 photogeneration would be accounted for by the lakes located between 30°N and 60°N latitude, which are more numerous than the lakes located between 30°N and 60°S.

However, by far the most important finding was that around 50% of the overall CO_2 emissions would be accounted for by just seven very large lakes: Caspian Sea (Iran, Azerbaijan, Kazakhstan, Turkmenistan, Russia), Lake Baikal (Russia), Lakes Superior, Michigan, Huron, Erie (USA, Canada), and Lake Malawi (Malawi, Mozambique, Tanzania). Very interestingly, six out of these seven lakes (i.e., with the single exception of Lake Malawi) are located between 30° N and 60°N latitude. The cumulated CO_2 generation by these lakes is $R_{CO_2} = 1.5\times10^{10}$ g_C $day^{-1} \approx 5$ Mt_C $year^{-1}$, which is for instance equivalent to ~2.5% of the total organic C load that is transported every year by the global rivers into the ocean, and that undergoes only very partial eventual mineralisation to CO_2 (CAI, 2011). This means that a huge amount of C is mobilised each year by the photochemical processes that cause CDOM photomineralisation in lake water at a global scale; however, the implications for net CO_2 emissions are usually much lower because CO_2 photogeneration is typically offset by photosynthetic uptake, even when taking into account the additional biological respiration of organic compounds to produce CO_2.

The risk that CO_2 production upon CDOM photomineralisation becomes a net greenhouse gas emission pathway depends on possible future imbalances between this process and the CO_2 uptake by the lake water upon biological processes. Possible signs of this concerning phenomenon could be DOC losses, especially during the summer season when CDOM photomineralisation is the fastest because of the peak in sunlight intensity (Buckley et al., 2024) while, usually, the DOC is maximum in summer because of the uptake of atmospheric CO_2 by photosynthesis (Massicotte et al., 2017).

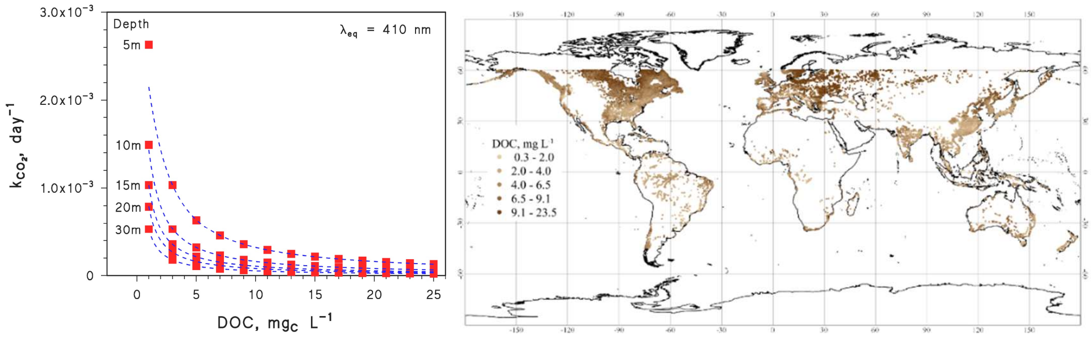

Figure 10. (a,left) Comparison between CO_2 generation ($k_{CO_2} = R_{CO_2}$ (d DOC S_L)$^{-1}$) as estimated by the polychromatic equation (2) (solid squares), and by a simpler monochromatic approach at λ = 410 nm (dashed curves). (b,right) Quasi global map (60°S-60°N) of the estimated DOC values in lake water.

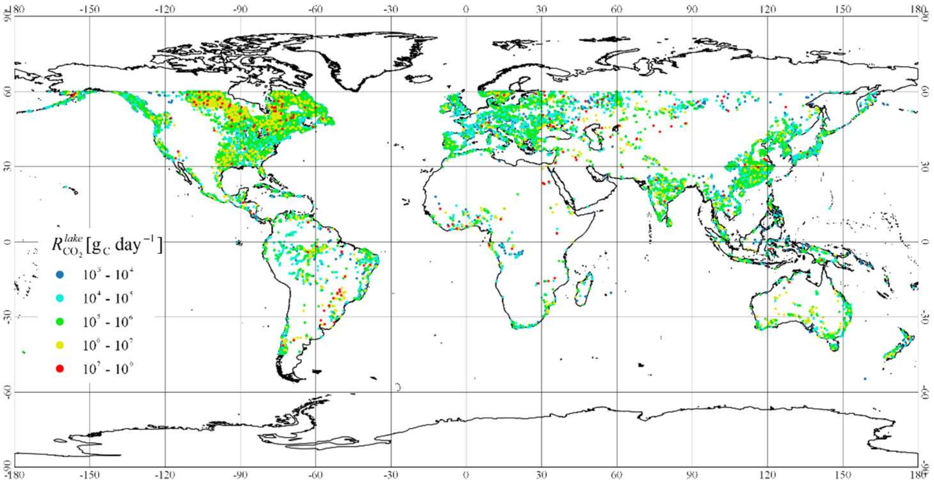

Figure 11. Photogeneration rates of CO_2 (year averages) in the global lakes located between 60°S and 60°N latitude. Note the differences by several orders of magnitude in the color-code scale.

4. Policy Implications

4.1 Carbon sequestration for different types of crops

Our study concludes that drought events favor respiratory metabolism compared to CO_2 assimilative metabolism; the use of a resistant variety allows crops to overcome the adverse period and immediately resume growth and high photosynthesis rates at the end of the drought, thus allowing the plant to increase its carbon stock; the use of biostimulants have the potential to mitigate climate change through the implementation of the photosynthetic rate of plants under drought conditions and the use of water, thus reducing inputs into agriculture and increasing the carbon stock potential of plants perennial.

Based on the aforementioned conclusions, we propose the following policy lines: aim at breeding crops with drought-resistant new varieties; use biostimulants aiming to optimize water and not to maximize carbon stocks (apparently a contradiction, but to date it is the only way, if one does not want/can engineer C3 plants by forcing them to C4 metabolisms that are extremely more advantageous for carbon fixation at high temperatures); synchronize the CO_2 assimilation seasons with the emission seasons either in time and/or in space (i.e. close to the emission sources: i.e. role of urban or suburban cultivations, cropping systems in CO_2-emitting territories, etc.).

4.2 Carbon emission of interventions for landslide risk

LS classifications help planners, engineers, and policymakers make informed decisions about land use, infrastructure development, and disaster risk reduction strategies in landslide-prone areas. The novelty of the research lays in the use of open-source satellite and DEM data that will be updated in the future, thus offering automatically an improved map. Another interesting feature is the possibility to exploit available time series: temporal trends in land cover changes, vegetation dynamics, and terrain evolution can be analyzed to assess LS and predict possible future scenarios. This is particularly relevant in a rapidly changing environment.

This study contributes to advance the current understanding of the relationship between different types of landslides, SOC, and the carbon cycle. This relationship has important implications for environmental sustainability and climate change mitigation efforts. The analysis reveals a pattern between landslide hazard levels and SOC accumulation. The overall trend indicates a decrease in SOC stocks with increasing landslide susceptibility, suggesting a correlation between environmental conditions and SOC accumulation, with higher susceptibility areas potentially experiencing lower SOC levels. This suggests that, on one hand, SOC may be beneficial for landslide hazard reduction, and on the other hand, there is a significant amount of SOC in highly susceptible areas, which may potentially become a source of CO2 emission if landslide occurs. While the study provides valuable insights, the authors acknowledge that the interpretations presented are preliminary and require further validation through field data collection, experimental studies, and the incorporation of additional environmental parameters.

The results on the relationship between landslide and carbon stocks show that, in the short term, landslides act as carbon emission sources. Natural recovery requires a long time, thus anthropic reforestation actions in landslide-affected areas may be necessary, together with the protection of existing carbon storage.

By safeguarding and enhancing natural carbon sinks, such as forests and healthy soils, we can contribute to climate change mitigation efforts while reducing the risk of landslide hazards. Sustainable management of these interconnected systems is crucial for achieving long-term environmental sustainability and resilience.

4.3 A global estimate of CO_2 photogeneration by lake waters

Our findings suggest that CO_2 production upon CDOM photomineralisation is a process, the quantitative proportion of which depends on the presence of a minority of large lakes that account for an important fraction of the overall water volume and surface. These lakes should thus be considered with priority, as they are the most important contributors to CO_2 production. In stable conditions the phenomenon is not a concern as a greenhouse-gas emission process, because CDOM photomineralisation is offset by biological CO_2 uptake (photosynthesis) to produce a steady configuration in the lake-water CO_2 budget. However, possible future imbalances could be spotted as DOC losses in lake water, most likely during the summer season, which can be highlighted by lake-water monitoring within routine measurement campaigns. Translating this global finding to the case of Italy, the most important environments from this point of view would be the large subalpine lakes such as, most notably, Garda, Maggiore, Como, and Varese.

References

Balafoutis, A. et al., 2017, Precision agriculture technologies positively contributing to ghg emissions mitigation, farm productivity and economics. Sustainability 9, 1339

Biglia, A. et al., 2024, Identification of drought-salinity combined stress in tomato plants by vegetation indices. Journal of Agricultural Engineering, https://doi.org/10.4081/jae.2024.1599

Buckley, S., Leresche, F., Norris, K., Rosario-Ortiz, F.L., 2024. Role of Direct and Sensitized Photolysis in the Photomineralization of Dissolved Organic Matter and Model Chromophores to Carbon Dioxide. Environ. Sci. Technol.

Cai, W.-J., 2011. Estuarine and Coastal Ocean Carbon Paradox: CO2 Sinks or Sites of Terrestrial Carbon Incineration? Ann. Rev. Mar. Sci. 3, 123–145

Cardinale, F. et al., 2024, Functional phenotyping of plant acclimation responses to drought stress: what constrains transfer from Arabidopsis to crops, and vice versa? Plant Cell, accepted for publication

Carena, L., García-Gil, Á., Marugán, J., Vione, D., 2023. Global modeling of lake-water indirect photochemistry based on the equivalent monochromatic wavelength approximation: The case of the triplet states of chromophoric dissolved organic matter. Water Res. 241, 120153

Cory, R.M., Ward, C.P., Crump, B.C., Kling, G.W., 2014. Sunlight controls water column processing of carbon in arctic fresh waters. Science (80-). 345, 925–928

Crous, K. Y., 2019, Plant responses to climate warming: physiological adjustments and implications for plant functioning in a future, warmer world. Am J Bot 106, 1049–1051

DaMatta, F. M., Grandis, A., Arenque, B. C. & Buckeridge, M. S., 2010, Impacts of climate changes on crop physiology and food quality. Food Research International 43, 1814–1823

Dutta, P., Chakraborti, S., Chaudhuri, K. & Mondal, S. 2020, Physiological Responses and Resilience of Plants to Climate Change. in 3–20

Frank, R., Klöpffer, W., 1988. Spectral solar photon irradiance in Central Europe and the adjacent North Sea. Chemosphere 17, 985–994

Gisolo D. et al., 2024, Evapotranspiration of an Abandoned Grassland in the Italian Alps: Modeling the impact of shrub encroachment. Journal of Hydrology, 635, 131223 https://doi.org/10.1016/j.jhydrol.2024.131223

Grossman, J. J., 2023, Phenological physiology: seasonal patterns of plant stress tolerance in a changing climate. New Phytologist 237, 1508–1524

Johansson, E., Muneer, F. & Prade, T., 2023, Plant Breeding to Mitigate Climate Change—Present Status and Opportunities with an Assessment of Winter Wheat Cultivation in Northern Europe as an Example. Sustainability 15, 12349

Koehler, B., Landelius, T., Weyhenmeyer, G.A., Machida, N., Tranvik, L.J., 2014. Sunlight-induced carbon dioxide emissions from inland waters. Global Biogeochem. Cycles 28, 696–711

Lynch, J., Cain, M., Frame, D. & Pierrehumbert, R., 2021, Agriculture's Contribution to Climate Change and Role in Mitigation Is Distinct From Predominantly Fossil CO2-Emitting Sectors. Front. Sustain. Food Syst. 4

Maioli, A., et al., 2024, Knock-out of SlDMR6-1 in tomato promotes a drought-avoidance strategy and increases tolerance to Late Blight. Plant Stress, 13, 100541

Massicotte, P., Asmala, E., Stedmon, C., Markager, S., 2017. Global distribution of dissolved organic matter along the aquatic continuum: Across rivers, lakes and oceans. Sci. Total Environ. 609, 180–191

Mercado, L. M. et al., 2018, Large sensitivity in land carbon storage due to geographical and temporal variation in the thermal response of photosynthetic capacity. New Phytologist 218, 1462–1477

Morabito, C., et al., 2024, The sucrose signalling route controls Flavescence dorée phytoplasma load in grapevine leaves. Journal of Experimental Botany, erae381 https://doi.org/10.1093/jxb/erae381

Patono, D.L., Eloi Alcatrão, L., Dicembrini, E., Ivaldi, G., Ricauda Aimonino, D., Lovisolo, C., 2023a, Technical advances for measurement of gas exchange at the whole plant level: Design solutions and prototype tests to carry out shoot and rootzone analyses in plants of different sizes. Plant Sci., 326:111505 https://doi.org/10.1016/j.plantsci.2022.111505

Patono, D.L., Said-Pullicino, D., Eloi Alcatrão, L., Firbus, A., Ivaldi, G., Chitarra, W., et al., 2022, Photosynthetic recovery in drought-rehydrated grapevines is associated with high demand from the sinks, maximizing the fruit-oriented performance. Plant J. 112, 1098-1111 https://doi.org/10.1111/tpj.16000

Smith, N. G., Malyshev, S. L., Shevliakova, E., Kattge, J. & Dukes, J. S., 2016, Foliar temperature acclimation reduces simulated carbon sensitivity to climate. Nature Clim Change 6, 407–411

Soares, P. R., Harrison, M. T., Kalantari, Z., Zhao, W. & Ferreira, C. S. S., 2023, Drought effects on soil organic carbon under different agricultural systems. Environ. Res. Commun. 5, 112001

Toming, K., Kotta, J., Uuemaa, E., Sobek, S., Kutser, T., Tranvik, L.J., 2020. Predicting lake dissolved organic carbon at a global scale. Sci. Rep. 10, 8471

Vähätalo, A. V, Salkinoja-Salonen, M., Taalas, P., Salonen, K., 2000. Spectrum of the quantum yield for photochemical mineralization of dissolved organic carbon in a humic lake. Limnol. Oceanogr

Vähätalo, A. V, Carena, L., Vione, D., 2021. Photochemical Reactions in Inland Waters, in: Reference Module in Earth Systems and Environmental Sciences. Elsevier

Vione, D., Scozzaro, A., 2019. Photochemistry of Surface Fresh Waters in the Framework of Climate Change. Environ. Sci. Technol. 53, 7945–7963

Visentin, I., et al., 2024 Strigolactones affect the stomatal and transcriptomic memory of repeated drought stress in tomato. Plant Stress, accepted pending minor revision