Workshop Report: Remote Sensing and Fluxes Upscaling for Real-world Impact

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Executive Summary

The "Remote Sensing and Fluxes Upscaling for Real-world Impact" workshop, held on July 9-10, 2024, at Lawrence Berkeley National Lab, was a collaborative effort led by the AmeriFlux Management Project, NEON, and the Carbon Dew Community of Practice. The event brought together over 200 registrants and approximately 100 attendees each day, including leading experts, researchers, and practitioners. The primary focus was on bridging the gap between cutting-edge research and practical applications in environmental monitoring by integrating remote sensing and flux data. Key themes included the importance of site-level measurements for validating remote sensing products, providing nature-based climate solutions, and addressing challenges such as instrument costs and the need for standardized methods. At the regional scale, discussions centered on addressing spatial heterogeneity and using high-resolution remote sensing and machine learning methods to enhance data interpretation. Global scale challenges included data consistency, gap filling, and accurate emission source identification, with opportunities for international collaboration and standardized practices to improve global carbon budget assessments. The workshop emphasized the critical need for integrating data across local, regional, and global scales through explicit scale-matching and developed a workflow for scaling flux data using "straight shot" and "explicit nesting" approaches. The event highlighted the importance of connecting scientific research with real-world applications in carbon, energy, and water management, ensuring that advancements translate into tangible societal benefits. These insights will guide future research, technology transfer, and collaboration, maximizing the potential of environmental fluxes to address real-world challenges.

Introduction

The "Remote Sensing and Fluxes Upscaling for Real-world Impact" workshop, held from July 9-10, 2024, at Lawrence Berkeley National Lab in Berkeley, California, was a collaborative effort organized by the AmeriFlux Management Project (AMP), the National Ecological Observatory Network (NEON), and the Carbon Dew Community of Practice (CarbonDew). This event built upon discussions and insights from the AGU Fall Meeting 2023 and the AmeriFlux Annual Meeting 2023, aiming to bridge the gap between cutting-edge research and practical applications in environmental monitoring and analysis.

With a focus on integrating remote sensing and flux data, the workshop sought to foster future collaborations and syntheses toward tangible societal benefits. Over 200 people signed up for the workshop, with approximately 100 attendees each day. The participants included leading experts, researchers, and practitioners at various career stages in the fields of remote sensing and flux data analysis.

Main Themes

Local Scale

At the local or site scale, the workshop emphasized the importance of in-situ data for validating remote sensing products and parameterizing models. Site-level measurements are crucial for providing nature-based climate solutions, carbon credit verification, and agricultural management practices. However, the scalability, representativeness, and mass and energy continuity of these measurements remain significant challenges.

Key discussions emphasized the importance of incorporating additional ground-level in-situ measurements alongside the eddy covariance technique to better understand the factors driving fluxes. Comments were made about the need to capture critical fluxes, such as N_2O, in addition to CO_2 and other more common greenhouse gasses. The cost of instruments and the need for standardized methods and protocols were identified as barriers to increasing the number of flux/sample sites in synthesis efforts. Innovative approaches and technologies, such as Unmanned Airborne Systems (UAS) and knowledge-guided data integration, were proposed to bridge the gap between site and regional scale observations.

Regional Scale

The regional or landscape scale presents its own set of challenges and strengths. A key strength is that regional assessments can smooth out noise from site-level data, and high-resolution remote sensing imagery enhances data accuracy and frequency. However, spatial heterogeneity challenges the representativeness of flux measurements, and quality measurements can be difficult under certain conditions, such as cloud cover or high albedo.

Discussions focused on how optical indicators from high-resolution remote sensing imagery (e.g., Planet Scope, MethaneSAT) can be used as proxies for characterizing landscape processes like land use and land change, thus enhancing flux data interpretation at this scale. Participants highlighted advancements such as the integration of drone and aircraft remote sensing, new indices, models, machine learning methods, and computational tools that improve the scaling and interpretation of flux data.

There was also an emphasis on the need for fine-resolution data tailored to different sectors, including commercial and government, to effectively address specific sectoral needs. Regional measurements are crucial for evaluating the effectiveness of policy interventions, and standardized large-scale programs and high-resolution imagery provide significant benefits. However, the trade-off between the cost of high-precision instruments and the wider deployment of cheaper sensors was noted, along with the importance of standardization and legal considerations in reducing uncertainty.

Global Scale

Global upscaling involves integrating remote sensing and flux data on a much larger scale, presenting challenges such as data consistency, gap-filling, and accurate identification of emission sources. Workshop participants were interested in global upscaling for various reasons, including supporting Earth system modeling, better understanding global carbon dioxide and methane budgets through the development of new upscaled benchmarks, identifying, measuring, and verifying nature-based solutions, and identifying critical regions for climate responses.

Participants identified many opportunities within broader policy and management applications. Upscaling was considered essential for assessing and reconciling global carbon budgets, enhancing government policies on climate change, and validating high-resolution flux estimates to address greenwashing concerns in carbon markets. Upscaling products can help validate and refine existing global carbon cycle models and national emissions inventories by enabling the diagnosis of any major regional differences between data-driven (upscaled) and process-based models. As global climate policy and management increasingly involve financial incentives, it was emphasized that scientific merit, rigor, and ethics in global upscaling must be prioritized and held to the highest possible standards. Further opportunities at the global scale included promoting open data and methodologies, standardizing practices across different communities (e.g., AmeriFlux, FLUXNET), and improving the connection between flux, remote sensing, and modeling communities.

To improve global upscaling methods participants identified the need for new remote sensing indices for flux processes, real-time data assimilation, reviewing and selecting new causal or process models, and an overall emphasis on footprint conditions. Respiration, a key component of net ecosystem exchange (NEE) of carbon dioxide, was highlighted as a process lacking a remote sensing index, our ability to predict and attribute variations in NEE. Advanced AI that can automate data integration efficiently, with the goal of achieving near-real-time data integration in the future, was also highlighted. Additionally, matching remote sensing data to the scales and internal variability of the flux tower footprint was deemed very important. Lastly, to rigorously evaluate the strengths and limitations of existing models, a literature review of available models was recommended..

The workshop participants also highlighted the need for improved data collection methods, funding and collaboration opportunities, addressing technological limitations, and reducing biases through expanded and more representative measurement networks. The importance of international collaboration via networks and funding, particularly in under-represented areas like the tropics, was identified as a key factor in enhancing ecosystem representativeness. Establishing community best practices and accessible measurement and processing pipelines (e.g., FLUXNET, AmeriFlux) was also identified as keys to facilitating inclusive growth of global upscaling science, data, and community.

Connecting Across Scales

A significant portion of the workshop was dedicated to discussing how to link data and insights across local, regional, and global scales. This integration is critical for achieving accurate and actionable environmental monitoring and analysis.

Participants acknowledged that explicit spatio-temporal scale-matching, or colloquially “right scaling”, is crucial, especially in heterogeneous regions. This process involves handling temporal scale conflicts (e.g., tidal vs. diel cycles) and ensuring continuity of mass and energy from smaller to larger scales. While there is no universal method for scale-matching, the workshop identified two main conceptual approaches: "straight shot" scaling and "explicit nesting."

Nexus of Science and Industry

The workshop underscored the importance of connecting scientific research with real-world applications, particularly in carbon, heat, and water management. This nexus is vital for ensuring that scientific advancements translate into tangible societal benefits. Some of the real-world applications discussed include:

Carbon Management: Accurate flux measurements are essential for carbon credit verification and nature-based climate solutions. The workshop explored how integrating remote sensing data with flux measurements can improve carbon monitoring and help develop credible carbon market measurement, reporting, and verification protocols with quantified uncertainty.

Heat Management: Managing heat fluxes at various scales is crucial for understanding and mitigating the impacts of climate change. Discussions focused on how remote sensing and flux data integration can aid in developing heat management strategies for different ecosystems and urban environments.

Water Management: Water flux measurements play a significant role in sustainable water management practices, such as irrigation and groundwater management. The workshop highlighted the need for high-resolution data and advanced modeling techniques to enhance water flux monitoring and inform policy and management decisions. The need for partitioned water fluxes was emphasized to better understand the physiological and environmental processes driving water fluxes.

Main Outcomes

The workshop addressed the challenges and benefits of matching space-time scales among observations. While the geolocation of optical measurements and simulations is straightforward, flux measurements are more complex due to the variability in wind direction and the constantly changing flux footprint throughout the day. This complexity is especially pronounced in areas with high spatial heterogeneity, where biophysical responses and land cover properties can become confounded.

Upscaling Workflow

To tackle these challenges, a conceptual bottom-up scaling framework was proposed, information consistently from local to regional and global scales. The main outcome of the workshop was the development of a workflow for scaling flux data across different spatial and temporal domains. This workflow includes two primary conceptual approaches: "straight shot" scaling and "explicit nesting", which can differ in the variability explained by a factor of two at the pixel level.

Straight Shot Scaling

The "straight shot" approach involves directly applying environmental processes derived at their native resolution across different space-time resolutions. This method is likened to extrapolating measurements using simple or complex relationships; however, there is a potential limitation that scale-emergent behavior or scale-dependent feedback may not be fully captured.

Steps for Straight Shot Scaling:

1. Establish environmental relationships at their native resolution (step **A**, Figure 1).
2. Apply these relationships at different spatiotemporal resolutions (step **B** or **C**, Figure 1).
3. Parametric corrections: Address non-linearity and neglected scale-emergent behaviors and feedback via case studies using explicit nesting, or reconciliation with complementary top-down approaches, such as atmospheric inversions.

Explicit Nesting

The "explicit nesting" approach accommodates non-linear and scale-emergent behaviors and feedback by deriving environmental processes at each space-time domain interface.

Steps for Explicit Nesting:

1. Derive environmental relationships from sparsely measured states and flows, acknowledging their validity only at the native resolution (step **A**, Figure 1).
2. Apply these relationships at their native resolution to yield states and flows that resolve across the next larger space-time domain (step **B**, Figure 1).
3. Aggregate states and flows across the next larger space-time domain (step **B**, Figure 1), and use them to develop scale-aware environmental relationships at that resolution (step **B**, Figure 1).
4. Repeat for each space-time domain interface (Steps **A** → **B**, **B** → **C**, etc., Figure 1)

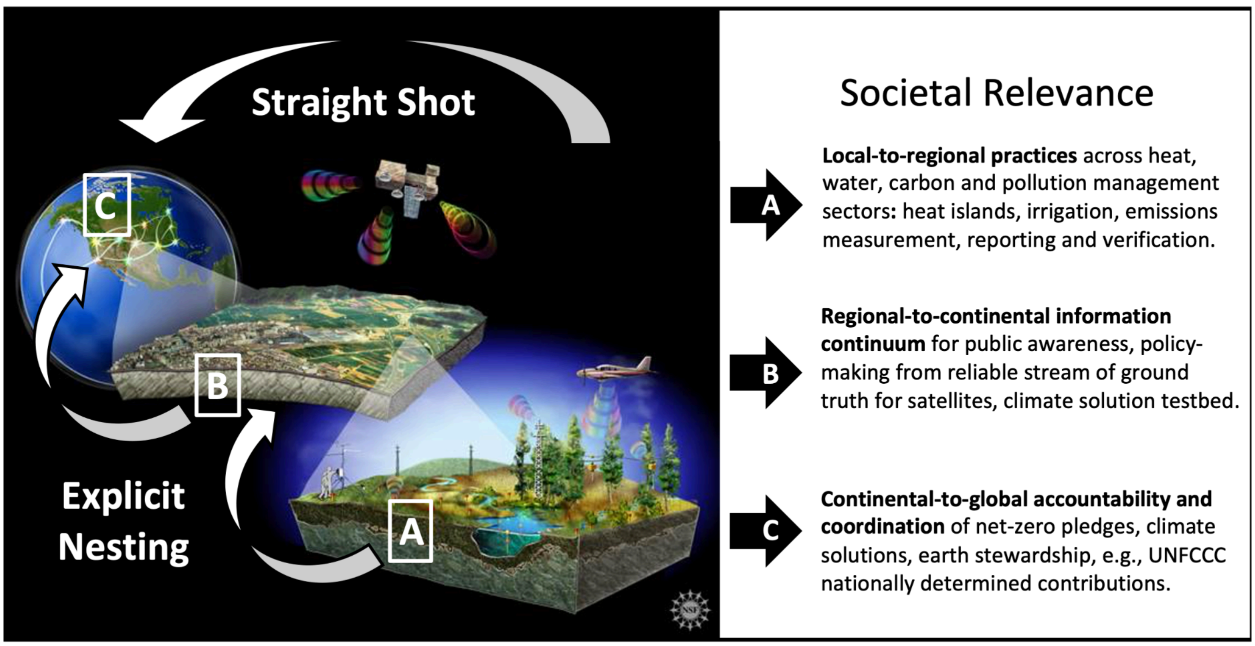

Figure 1. A workflow for upscaling fluxes via two approaches: straight shot and explicit nesting.

Quality and Uncertainty of Data Integration

The quality and uncertainty of data joins play a critical role in integrating optical remote sensing and aerodynamic flux perspectives.

Practical steps for achieving this integration:

1. Downscale state variables from satellite data.
2. Use the downscaled state variables to perform space-time explicit flux data integration, such as spatialized eddy covariance.
3. Aggregate space-time explicit fluxes over the target domain ("nesting").

4. Compare the nesting approach to the status-quo data integration approach (“straight shot”). Simplifying to the Straight Shot approach is warranted if the relationships remain consistent across the space-time domain interfaces (**A** → **B**, **B** → **C**, etc). Otherwise, the explicit nesting approach is preferable to accommodate the effects of scale-emergent behaviors.
5. Use first-principles benchmarks (e.g., energy and mass balances from atmospheric inversion) to evaluate potential improvements.

Societal Relevance

The nested fluxes across the levels (**A** → **B** → **C)** provide insights into unique ecological processes and real-world applications specific to each nesting level. Cohesive integration across the scales with flexibility in addressing unique processes across the levels is invaluable for ensuring transparency, consistency and interoperability of policy and management decisions with intended outcomes. This workshop brought the communities from multiple disciplines together to advance our capabilities to address societal needs.

Educational Tools

The workshop included hands-on sessions focused on using collaborative programming platforms such as Google Colab and Google Earth Engine. This tutorial aimed to equip participants with the tools and resources necessary for gathering remote sensing data efficiently. Through practical examples, attendees learned how to extract time series data from both remote sensing sources and flux towers. They derived simple relationships at site and regional scales, and explored potential pitfalls, challenges and opportunities through the use of spatialized eddy covariance. Additionally, the session showcased new products developed using geostationary satellites at continental scales, emphasizing the importance of multidisciplinary science that integrates flux measurements and remote sensing. We made the package of demonstrated educational tools public and is now available to the community on the AmeriFlux GitHub (https://github.com/AmeriFlux).

Conclusion

The "Remote Sensing and Fluxes Upscaling for Real-world Impact" workshop successfully brought together experts from various fields to discuss and address the challenges of integrating remote sensing and flux data across different spatiotemporal scales. The development of the scaling workflow and the emphasis on connecting scientific research with practical applications mark significant steps forward in the field of environmental monitoring and analysis.

By fostering collaborations between research communities and industry sectors, the workshop paved the way for future advancements and tangible societal benefits. The insights and outcomes from this event will guide future workshops, technology transfer, and research initiatives, ensuring continued progress in understanding and maximizing the potential of environmental fluxes to address real-world applications.

For more detailed information on the workshop agenda and sessions, please refer to the linked agenda document here https://go.lbl.gov/vy35rp..

Appendix 1

Feedback from Breakouts

Session 1 - Site-Level Breakout Summary

- **Key Strengths**:
    - Site-level, in-situ data are crucial for validating remote sensing products, parameterizing models, and providing nature-based climate solutions.
    - Site-level measurements must be representative of the ecosystem and scalable.
    - Other ground-level in-situ measurements, including proximal remote sensing techniques, are necessary to understand flux drivers.
- **Challenges and Limitations**:
    - High cost of instruments limits the number of flux/sample sites.
    - There is a need for novel, cost-effective approaches to replace expensive observations.
    - Intercomparison between flux sites is essential to address uncertainties.
    - Standardizing methods and protocols for many in-situ observations is needed.
    - Unmanned Airborne Systems (UAS) can help bridge the gap between site and regional scale observations.
- **Integration with Landscape/Regional Models**:
    - Large models need better integration with increasing remote sensing products for improved accuracy.
    - Temporal linking and spatial scaling must move beyond daily averages to align with satellite overpasses.
    - Site-level data is essential for validating, parameterizing, and course-correcting models and remote sensing datasets.
- **Applications**:
    - Site-level flux measurements are crucial for climate solutions, carbon credit verification, and agricultural management.
    - Accurate site-level data supports carbon market credibility and compensation verification.
    - Technological and cost barriers need to be addressed to fully utilize the potential of flux measurements.
- **Uncertainty**:
    - Acceptable uncertainty levels vary by scale and application, with tighter tolerance required for voluntary carbon markets.
    - Collective efforts are needed to reduce uncertainty in flux measurements.

Session 2 - Regional-Level Breakout Summary

- **Key Strengths**:
    - Regional scale assessments can smooth out noise from site-level data.
    - High-resolution remote sensing imagery enhances data accuracy and frequency.

- **Challenges and Limitations**:
    - Spatial heterogeneity challenges the representativeness of flux measurements.
    - Quality measurements are challenging under certain conditions (e.g., cloud cover, high albedo).
- **Advancements**:
    - Adding drone and aircraft remote sensing improves site and regional scale measurements.
    - Standardized large-scale programs and high-resolution imagery are beneficial.
    - New indices, model and machine learning methods, and computational tools enhance remote sensing capabilities.
- **Policy and Management**:
    - Regional measurements can evaluate the effectiveness of policy interventions.
    - High-resolution data is needed for specific locations and management units.
    - Different sectors have varying data resolution needs, from commercial sectors to government agencies.
- **Uncertainty**:
    - There is a trade-off between the cost of high-precision instruments and wider deployment of cheaper sensors.
    - Standardization and legal implications need to be considered in reducing uncertainty.

Session 3 - Global Upscaling Breakout Summary

- **Challenges**:
    - Gap filling and data consistency are major challenges.
    - Identifying emission sources accurately is difficult.
    - Long-term funding and international collaboration are needed.
- **Opportunities**:
    - Improving the coverage of under-represented areas enhances ecosystem representativeness.
    - Promoting open data and methodologies helps compare and account for uncertainties.
    - Closer connections between different research communities are necessary.
- **Integration**:
    - Developing remote sensing indices and improving remote sensing methods for respiration fluxes.
    - Enhancing AI and physical model integration for data fusion and global scale modeling.
    - Addressing bias issues in data and improving international training.

Session 4 - Linking Scales Breakout Summary

- **Challenges**:
    - Explicit scale-matching is crucial, especially for initial steps and heterogeneous regions.

    - Temporal scale conflicts and process scale challenges are significant, e.g. tidal cycle vs. diurnal cycle.
    - No universal method for scale-matching; varies with context and data types.
- **Opportunities**:
    - Sharpening spatial and temporal resolution in critical spectral ranges.
    - Ensuring accurate scaling to bring the best available science to bear on sustainability and integrity in managing heat, water, and GHGs.
    - Using multiple complementary data sources to capture extreme events and provide constraints.

Appendix 2

Feedback Future Workshop Topics Discussion

Key Suggestions and Feedback

Workshop Content and Structure

- **Pre-Workshop Preparation**:
  - Provide scripts, background reading material, and data source links beforehand.
  - Include references and tutorial videos to help participants prepare.
- **Learning Focus**:
  - Emphasize a learning-focused approach with step-by-step tutorials and more teaching workshops.
  - Reverse the order of sessions to start with practical, hands-on activities and follow with applications and talks.
- **Discussion and Interaction**:
  - Organize smaller discussion groups with more guidance, e.g. upvote, downvote.
  - Provide breakout session questions in advance to promote deeper discussions.

Technical and Thematic Focus

- **Remote Sensing**:
  - Focus on hyperspectral remote sensing and its applications.
  - Discuss the application of NEON AOP data and linking it with flux data at fine scales.
- **Machine Learning and Modeling**:
  - Include more topics related to machine learning and modeling techniques.
  - Provide step-by-step guidance on developing machine learning models for beginners.
- **Data Visualization and Integration**:
  - Develop better data visualization tools and standardize post-processing pipelines.
  - Offer spatialized eddy covariance datasets as a native data type alongside tabular data.
- **Carbon, Water, and Heat Management**:
  - Balance carbon and water flux applications, particularly in sustainable groundwater management.
  - Engage speakers from the public sector and science-policy space to discuss practical applications.

Collaboration and Community Building

- **Cross-Disciplinary Collaboration**:

    - Promote brainstorming sessions to make scientific research impactful for societal benefit.
    - Discuss missing instrumentation and software needs for funding opportunities.
- **Engagement with Stakeholders**:
    - Increase engagement with land and water managers, irrigation districts, and sustainability agencies.
    - Highlight the societal and scientific questions driving the need for flux measurements.
- **Community Platforms**:
    - Create a Slack workspace or Zulip for the workshop community.
    - Collaborate on developing a podcast series for conversations between flux scientists and stakeholders.
- **Future Workshop Topics**:
    - Explore upscaling and downscaling across different flux types and addressing non-linearities and emergent behaviors.
    - Focus on lateral flux data, isotopes in eddy covariance, and evaluation of data quality assessment approaches.

Appendix 3:

Participants

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