CSQ-2 Summary

Question	Knowledge Advancement Objectives	Observables	Measurement Specifications	Tools & Models	Policies / Benefits
How has the land biosphere responded to human activity and climate change?	A) Quantify enhancements in the extra-tropical carbon sink over North America and Eurasia and identify human activities and climate variations driving these changes	• LULUC from NDVi, NIRv and SIF • Atmospheric CO_2 concentration gradients • Soil & air temperature and water content	• High-spatial resolution (< 30m) multi-spectral and hyperspectral imaging • High-spectral-resolution imaging spectroscopy	• DGVMS • Atmospheric GHG retrieval algorithms • Atmospheric assimilation systems • Geostatistical models	CC mitigation and adaptation policy Climate finance Monitor the efficacy of natural decarbonization policies and CO_2 removal strategies.
	B) Distinguish the relative roles of climate change and disturbances (wildfire and land use change) on the tropical carbon sink across equatorial Africa, the Amazon basin and Oceania	• LULUC from NDVI, NIRv and SIF • Atmospheric CO_2 concentration gradients • Soil & air temperature and water content • Fire Radiative Power	• High-spatial resolution (< 30m) multi-spectral and hyperspectral imaging • High-spectral-resolution imaging spectroscopy	• DGVMS • Atmospheric GHG retrieval algorithms • Atmospheric assimilation systems • Geostatistical inverse models	
	C) Quantify above ground biomass (AGB) in tropical and extratropical forests to the accuracy needed to resolve changes in stocks on sub-decadal time scales	• microwave vegetation optical depth (VOD) • Canopy structure from Synthetic aperture Radar (SAR) and Biomass LiDAR	• Measure forest biomass at 1 km resolution with errors < 20% or ±10 tons/hectare between 70N and 56S	In situ reference systems Enhanced techniques for integrating data sources	
	D) Catalogue the impacts of climate change on crop health and forest mortality across the North American Great Plains, Central Europe and South and East Asia	• Forest/Cropland Cover • GPP via NDVI/NIRv/SIF • Impacts of disturbance (wildfire, drought, pests and disease)	• High-spatial resolution (< 30m) multi-spectral and hyperspectral imaging • Soil and air temperature and water content • Fire Radiative Power	• DGVMS • Empirical light Use Efficiency and Machine learning models	

CSQ-2 Narrative

As atmospheric CO_2 concentrations have increased, the land biosphere has become a more efficient sink, and is now absorbing almost 30% of all anthropogenic emissions (Friedlingstein et al., 2022). However, land use change continues to be the second largest source of CO_2 emissions, after fossil fuel use. Over the industrial age, CO_2 uptake by intact forests and other natural parts of the land biosphere has roughly balanced anthropogenic emissions from land use change. While the efficiency of the land biospheric sink has been roughly constant over the past 60 years, its uptake varies substantially from year to year in response to climate fluctuations (e.g., ENSO), volcanic eruptions, disturbances (wildfire, floods, droughts) and other processes less well understood. In addition, observations of carbon stocks and fluxes acquired since the 1990s indicate that the tropical land sink is now weakening while the northern hemisphere extratropical sink is intensifying in response to continued human activities and climate change.

Atmospheric CO_2 and CH_4 observations reinforce these conclusions about the land carbon sink by providing an integrated constraint on net fluxes by all processes. However, these data provide much less insight into the physical and biological processes driving these changes. A much greater understanding of these processes is needed to diagnose the current state of the land biosphere and to predict it's response to continuing human activities and climate change. To achieve these goals, we need high-resolution (30 m to 1 km), global, space-based measurements of above-ground carbon stocks, land use and land use change, as well as climate variations and disturbances that impact forest mortality and crop health to enhance the scientific basis for carbon management. Even higher spatial resolution (1-10 m) is needed to assess forest degradation, tree mortality, or to map individual species and monitor changes in biodiversity.

Observations needed to understand processes driving change in the land biosphere

Space-based multi-spectral imaging of the land biosphere has long been the primary tool for characterizing land use and land use change (LULUC) and to track disturbances such as deforestation and wildfires. These data yield vegetation indices (e.g., enhanced vegetation index, EVI, normalized difference vegetation index, NDVI, leaf area index, LAI, near-infrared reflectance of vegetation, NIRv) that quantify "greenness". Vegetation indices are used to estimate the absorbed photosynthetically active radiation (fAPAR) and to parameterize other processes in semi-empirical gross primary production (GPP) models. They are also incorporated with other measurements in dynamic global vegetation models (DGVMs) to estimate the net ecosystem exchange (NEE) of carbon.

These measurement capabilities have recently been augmented with high-spatial resolution hyperspectral imagers, which better exploit spectroscopic information throughout the reflected solar spectrum. In addition, moderate-spatial-resolution observations of solar induced chlorophyll fluorescence (SIF) are providing more reliable constraints on light use efficiency, and thus the relative efficiency of the land carbon sink. These new tools are being used to provide more insight into plant species types (biodiversity), GPP and to track forest mortality and crop health on regional scales.

Existing space-based multi-spectral imaging sensors, such as Landsat, MODIS, VIIRS, and Sentinel 2 are expected to continue providing data and extending their time series. Public sector hyperspectral imaging sensors such as PRISMA, EnMAP, HISUI and EMIT will soon be joined by private sector sensors such as Carbon Mapper and Orbital Sidekick GHOSt constellations and lager public sector systems such as NASA Surface Biology and Geology (SBG) mission. These hyperspectral sensors can detect intense plumes of CO_2 and CH_4 as well as well as land surface properties, providing additional insight into carbon cycle processes. Moderate-spatial-resolution (2-10 km) observations of SIF from GOME-2, GOSAT/GOSAT-2, OCO-2/OCO-3 and TROPOMI will be augmented with higher-spatial resolution (300 m x 300 m) observations from FLEX in 2025.

These multi-spectral and hyperspectral observations are expected to continue playing major roles in tracking land use and land use change and disturbances that govern the exchange of CO_2 and CH_4 between the land biosphere and the oceanic and atmospheric carbon reservoirs. Insights into the land biospheric processes from these measurements are also expected to drive the development of more sophisticated DGVMs and Earth System Models (ESMs) for diagnosing the and predicting the impacts of human activities and climate change on the land carbon cycle.

Recent advances in space-based remote sensing measurements of above-ground biomass (AGB) are providing more direct ways to track long-term changes in carbon stocks at increasingly high resolution across the globe. Remote sensing cannot directly measure above ground woody biomass, but this quantity can be estimated from optical, passive and active microwave and Light Detection and Ranging (LiDAR) observations. Optical data from sensors such as Landsat and MODIS have been combined with empirical and statistical models to estimate above-ground biomass (e.g., Powell et al. 2010). These data provide the longest records of biomass change, but have large uncertainties.

Passive microwave observations of vegetation optical depth (VOD) have been collected since the early 1990s and provide the second longest space-based record of land carbon stock changes (e.g., Liu et al., 2015). Their main disadvantage is their relatively low spatial resolution (> 10 km). This limitation is mitigated in some investigations, which combine biomass estimates derived from VOD with high-spatial-resolution maps of forest cover and disturbances derived from optical measurements to model carbon losses (e.g., Fawcett et al., 2022). Existing passive VOD sensors such as AMSR-E, AMSR-2, SMOS and SMAP will soon be joined by AMSR-3 on GOSAT-GW, the Copernicus Imaging Microwave Radiometer, CIMR, extending the VOD record.

These passive VOD measurements are now being augmented by higher spatial resolution (0.1 to 1 km) above ground biomass measurements from synthetic aperture radars (SARs) and lidars. Data from existing SARs, such as the ALOS and ALOS-2 PALSARs, Sentinel-1 C-band and TanDEM-X PollInSAR have been used to create above ground biomass maps with spatial resolutions as find a 100 m (e.g., Berninger et al., 2018). In addition to their high resolution, SAR penetrates both clouds and vegetation better than optical remote sensing. The principal limitation of SAR data is signal saturation in regions of high biomass, such as tropical forests and strong dependence to environmental conditions (e.g., rainfall, humidity, freeze/thaw). SAR measurements also require costly, high-power satellites with large antennas. In spite of these challenges, existing SAR missions will soon be joined by the ESA BIOMASS, NASA NISAR and DLR Tandem-L missions, which will extend the data record with increased spatial resolution and sensitivity.

LiDAR missions, such as ICESat-2 and GEDI provide a third method for characterizing canopy height and above-ground biomass. LiDAR, like SAR, penetrates vegetation, providing some insight into its 3-d structure, but is less affected by signal saturation in regions with high biomass (Duncanson et al., 2022). LiDAR measurements may therefore provide both high accuracy and high spatial resolution (~25 m). The primary limitation of this method is its spatial coverage, since LiDARs only sample a narrow (~100 m) track along the satellite ground track. The coverage from GEDI is further restricted by the orbit of the International Space Station (ISS), which is constrained between ±51° latitude.

Because high-resolution, global measurements of above ground biomass are critical parameter for monitoring carbon stocks and because all existing space-based remote sensing methods face challenges, there have been numerous effort to combine the data types to extend coverage and reduce uncertainties (e.g., Saatchi et al., 2011; Urbazaev et al., 2018). There have also been broad community-wide efforts to establish a forest biomass reference system for validating remote sensing estimates of biomass (Labrière et al., 2022).

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