CODEX PLANETARIUS

Land Remote Sensing in Support of *Codex Planetarius*

M. Hansen
University of Maryland

About *Codex Planetarius*

Codex Planetarius is a proposed system of minimum environmental performance standards for producing globally traded food. It is modeled on the *Codex Alimentarius*, a set of minimum mandatory health and safety standards for globally traded food. The goal of *Codex Planetarius* is to measure and manage the key environmental impacts of food production, acknowledging that while some resources may be renewable, they may be consumed at a faster rate than the planet can renew them.

The global production of food has had the largest impact of any human activity on the planet. Continuing increases in population and per capita income, accompanied by dietary shifts, are putting even more pressure on the planet and its ability to regenerate renewable resources. We need to reduce food production's key impacts.

The impacts of food production are not spread evenly among producers. Data across commodities suggest that the bottom 10-20% of producers account for 60-80% of the impacts associated globally with producing any commodity, even though they produce only 5-10% of the product. We need to focus on the bottom.

Once approved, *Codex Planetarius* will provide governments and trade authorities with a baseline for environmental performance in the global trade of food and soft commodities. It won't replace what governments already do. Rather, it will help build consensus about key impacts, how to measure them, and what minimum acceptable performance should be for global trade. We need a common escalator of continuous improvement.

These papers are part of a multiyear proof of concept to answer questions and explore issues, launch an informed discussion, and help create a pathway to assess the overall viability of *Codex Planetarius*. We believe *Codex Planetarius* would improve food production and reduce its environmental impact on the planet.

This proof-of-concept research and analysis is funded by the Gordon and Betty Moore Foundation and led by World Wildlife Fund in collaboration with a number of global organizations and experts.

For more information, visit www.codexplanetarius.org

Abstract

Global-scale monitoring of land cover and land use is rapidly maturing, with established methods ready to support natural lands extent mapping, and loss to encroaching commodity land uses. Such a capability is core to the *Codex Planetarius* goal of reducing the environmental impacts of food production. Spatially explicit map products can also facilitate the work of other *Codex* indicators through map-based targeting of in situ data collections. Monitoring land use expansion within natural lands is deemed straightforward and will provide definitive information from parcel to ecoregion and biome scales. Other dynamics of interest occur outside of intact natural lands, including commodity expansion replacing other land uses, intensification of agricultural lands via double cropping or other means, and restoration of natural land covers within marginal lands. These dynamics are directly related to expansions in intact natural lands as no land use change dynamic exists in isolation. Thus, a comprehensive per commodity monitoring scheme is necessary to understand the interplay of markets, land tenure, policy, and other factors governing agricultural land use change. A net land use change monitoring system that quantifies all such dynamics is feasible, but considerably more challenging than tracking encroachment in extent natural land covers.

Use of Land Remote Sensing in Context of *Codex Planetarius*

Agricultural production can increase via intensification of existing lands under crop or pasture land uses, or by expanding these land uses into other, often natural habitats by converting land cover. While both options have externalities that deleteriously affect natural systems, expansion has greater long-term impacts and poses a greater, often seemingly impossible, mitigation challenge. The expansion of agriculture into nature results in the loss of biodiversity and other key ecosystem services with severe consequences for earth system functioning. For example, 13-21% of global human-induced greenhouse gas emissions result from land use change with the largest contributor being the loss of dense humid tropical forest to agricultural expansion (Nabuurs et al., 2022). Tropical deforestation also has the greatest impact on terrestrial biodiversity loss. Despite numerous global initiatives aimed at slowing the loss of rainforests – a finite natural resource – deforestation continues to increase over time. Clearly, global policy interventions are not working.

Codex Planetarius highlights outcomes of global food production on key environmental variables, including biodiversity loss, habitat conversion/loss, soil health, water take quantity, water effluent quality, GHG emissions, and agrochemical toxicity. Remote sensing can directly address habitat loss, which is closely linked to biodiversity loss. Mapping conversions also enables emissions calculations from natural land covers, given appropriate emissions parameters. Comprehensive land cover and land use change monitoring can also be used to facilitate data collection of other variables, such as soil health. A planetary-scale monitoring capability exists for assessing the magnitude and trends of expanding food production over time, with the possibility of quantifying concomitant impacts on ecosystem services. Restoration of natural lands is also observable via time-series satellite imagery and can track efforts to optimize land use and improve ecosystem service provisioning by retiring marginal agricultural lands.

A land cover/land use change pathway must be monitored to quantify continued conversion of natural lands to agricultural land uses. The pathway starts with establishing the extent of natural lands, for which the available satellite record provides sufficient information to support characterization at medium or finer spatial resolutions. Pathfinding attempts have set the stage (Sanderson et al., 2002; Venter et al., 2016) for operational monitoring using consistent satellite inputs. One example is that of primary humid tropical forest extent (Turubanova et al., 2018), within which forest loss is mapped annually and trends reported through the Global Forest Watch program (globalforestwatch.org). A broader global natural lands extent map would similarly become the target for monitoring a combination of the following land dynamics, per the model of the land use transition (Foley et al., 2005) - date of degradation activities, date of clearing, date of land use establishment, date of land use intensification or higher order land use replacement, and future possible abandonment and natural vegetation recovery. As an example, we can consider a common case of conversion of Mato Grosso Tropical Dry Forest in Brazil: it is first logged, then completely deforested (degradation and clearing), followed by conversion to pasture within two to three years (land use establishment), and eventually converted to soybean cultivation after 20 years (land use intensification/higher order land use replacement). Not all of these dynamics need be present in all scenarios, for example the Chiquitano Forest in Bolivia or Brazilian Cerrado can be cleared and planted with soybean in a single year. On the other hand, a lowland Borneo rainforest can be logged and cleared in one to two years, then left idle for a decade before the planting of oil palm. Geographies exhibit different land use dynamics, the timelines of which are critical to applying policy and intervention strategies in the expansion of agricultural land uses. Key to any monitoring scheme is establishing a baseline, without which no policy implementation can be assessed.

The first impacts on natural land covers are often not wholescale conversion, but dynamics that modify and degrade natural vegetation and associated ecosystem functions. Given an area identified as being natural land cover, forward monitoring would focus initially on a disturbance alert that may capture initial modifications, including fire, logging, thinning, or fragmentation. A monitoring system must include such degradation dynamics as a precursor alert for future conversion, because most land disturbances are correlated temporally and spatially. Complete clearing of native vegetation is itself a target for monitoring, as land wasting or land banking constitute significant dynamics in their own right. Over 55Mha of South American land cover has been disturbed since 1985 without the establishment of a recognizable land use (Zalles et al., 2021). Over 8Mha of cleared Indonesian rainforest similarly has no identifiable land use (Parker et al., 2024). Such areas must be monitored and are clearly targets for restoration, or possible land use expansion if used to redirect future conversion pressures. Land use expansion histories and regular updating with low latency are the data needed for reporting rates of natural land cover conversion to agricultural land uses.

Example intact natural land cover loss transitions:

intact natural land cover → degradation due to extractive activities, fire, or fragmentation intact

intact natural land cover → degradation → conversion with no land use

intact natural land cover → degradation → conversion to land use other than agriculture

intact natural land cover → degradation → conversion to agriculture land use

intact natural land cover → degradation → conversion from one agriculture land use to another

Intensification of land use is another dynamic relevant to agriculture and its areal footprint. Intensification can mean a change to a more profitable, and more resource intensive, land use, for example, pasture conversion to row crops. Intensification can also mean improved management of an existing land use. For example, oil palm yields in Indonesia lag those of Malaysia, largely due to inferior management of palm estates (Varkkey et al., 2018). Intensification is a goal of many development efforts in Africa, but expansion remains the dominant mode for increasing production (Potapov et al., 2022; Jayne and Sanchez, 2021). Croplands can also be intensified via double and triple cropping, for example, the dramatic expansion of maize in Brazil as a winter crop to support ethanol production following summer season soybean (Gurgel et al., 2024). Monitoring of these practices is critical. Despite the additional externalities, they represent a land use efficiency that increases overall production without land conversion.

Approach to Monitoring

From a remote sensing perspective, our most appropriate record for global monitoring starts in 1999 with the launch of Landsat-7, the first medium spatial resolution sensor to have a global acquisition strategy. From 1999 to present, we have global data at an appropriate spatial resolution for monitoring land change. Prior to 1999, there was no systematic global acquisition strategy, precluding a consistent land change record at the global scale. For some countries that operated receiving stations (United States, Brazil, South Africa, as examples), a record from 1985 was possible. However, the data gaps for other regions of the world limit longer term characterization of global land dynamics. Using the global data, a baseline of land change can be created, resulting in a natural land extent map, a layer viable for policy initiatives such as the European Union's Deforestation Regulation (EUDR) (EU 2023). While there are a few caveats, for example, that not all land change is human induced, such a map would be a key layer supporting a consensus on limiting the appropriation of natural lands for agricultural land uses, the dominant driver of land use change globally (Curtis et al., 2018; Pendrill et al., 2022). To date, the EUDR has produced a forest map as reference, with caveats around the use of the FAO forest definition and no natural lands outside of the forest category included in the regulatory framework (European Commission, 2024).

A monitoring approach to establish a natural land cover map would be based on a stable inter-annual spectral response for the 20+ year global Landsat data record, where time-series without discontinuities indicate stable land cover. Challenges to accurately depict intact land covers include: 1) Ephemeral dynamics that do not result in land cover change, such as savanna fires (note that fires that result in vegetation cover conversion, such as stand-replacement forest fires, can be directly mapped with attribution of human causation assigned separately); 2) Ephemeral dynamics that represent land modification, but are not readily observable, such as some types of selective logging; 3) Natural land change, such as landslides or natural stand-replacing fires; 4) Pre-existing stable land uses, such as pasture on forests converted before the satellite record; 5) Land uses on natural land cover, such as pastures on natural grasslands and; 6) Naturally spectrally varying land covers, such as vegetation in wetlands.

Overcoming all these issues is not feasible, but a few mitigation strategies can be employed. First, annual spectral measures can be derived to avoid ephemeral dynamics, such as savanna fires, but may also exclude ephemeral human-induced dynamics such as logging. Logging, however, is typically close to roads or other logging infrastructure and can be accounted for through location proximity measures. Pre-existing stable land uses resulting from historic deforestation may not be uniquely identifiable by satellite, for example, pastures, but may be accounted for by ecoregion maps and proximity to remnant natural land cover. Land use where the cover remains unchanged, such as grasslands converted to pastures, are more problematic, but can be identified due to roads, fence lines, cattle trails, and watering holes, though this kind of mapping is more challenging. Wetlands, which are spectrally/temporally dynamic and often confound land use change characterization, should be mapped separately and updated when unambiguous land use-related forest disturbance, cropland, or built-up land uses are identified. In summary, our ability to monitor global land use dynamics is not generic, and a portion remains in the research-to-operations domain. All such limitations should be assessed for impacts on land change monitoring accuracy, with appropriate guidance on the use of results/trends for decision support.

Land disturbance and conversion would ideally be monitored in near-real time. Alert systems which identify anomalous spectral data trends indicative of vegetation loss are in operation (https://glad.earthengine.app/view/dist-alert) and are the first signal of incursions into natural land covers. Annual updates of cropland, crop type, built-up area, and other land uses would verify agricultural land use establishment within previously baselined natural land cover. A final monitoring system would verify natural land cover extent spatially explicitly, assessing fragmentation and distance of natural land cover to land use as shown in Figure 1 (Figure 2 is same map with focus on the Southeast United States, highlighting the prevalence of government lands as home to natural land cover) (Hansen et al., 2022). Updates of the map would be made in near-real time as algorithm runs on new inputs are generated. Applying such an approach to land use generally, and agriculture specifically, is readily achievable in support of *Codex Planetarius.*

The monitoring system would serve different purposes at different spatial scales. For example, property level dynamics could be tracked to support policies around supply chain initiatives such as the EUDR. Figure 3 shows a dynamic scenario of Brazilian Cerrado clearing for soybean expansion over a three-year period. The observational scale is sufficient to link the dynamic to specific properties. On the other hand, large intact habitats can also be identified and monitored, in support of programs like 30x30 (UNCBD, 2022; Eckert et al., 2023). Figure 4 illustrates large, contiguous blocks of land cover as in Figure 1, with the goal of identifying areas best suited for conservation. Monitoring natural land extent by fragment size would be a useful input to biodiversity and other measures of ecological integrity (Gonçalves-Souza et al., 2024).

Figure 1. Global land use extent (percent area in land use) and dispersion (distance to land use) at a 500m spatial resolution (Hansen et al., 2022).

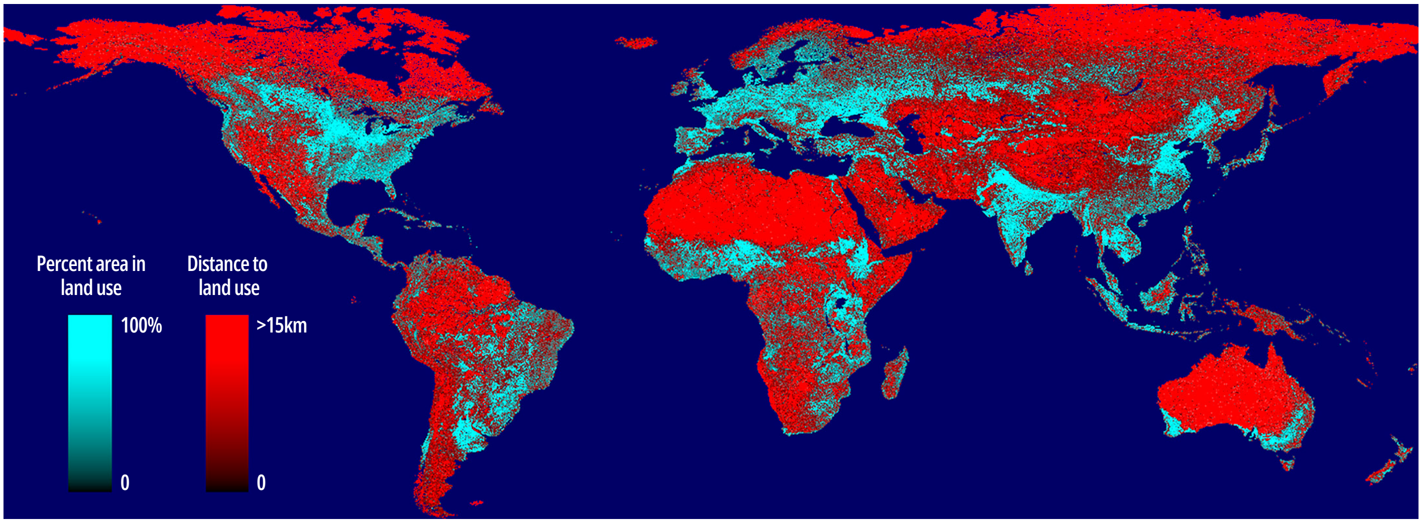
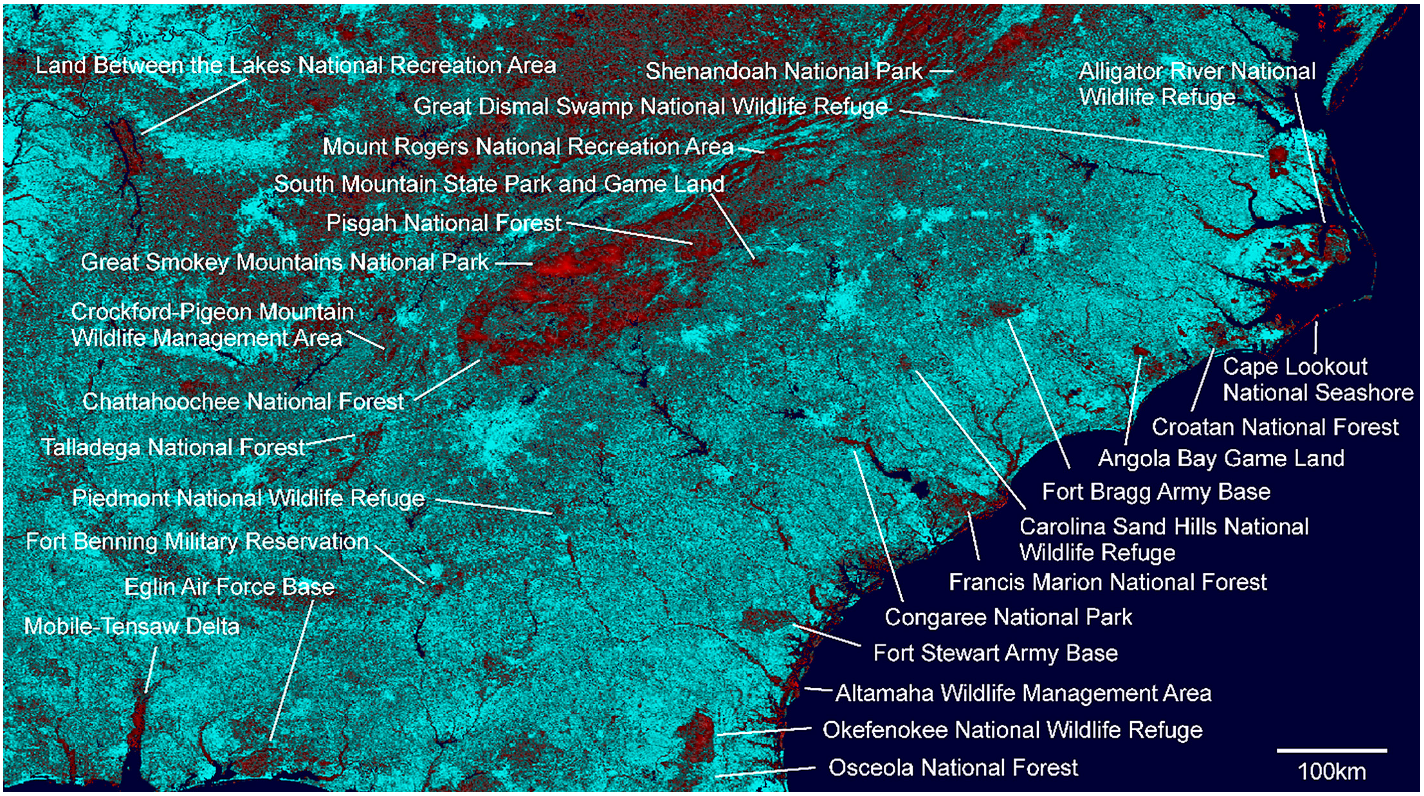


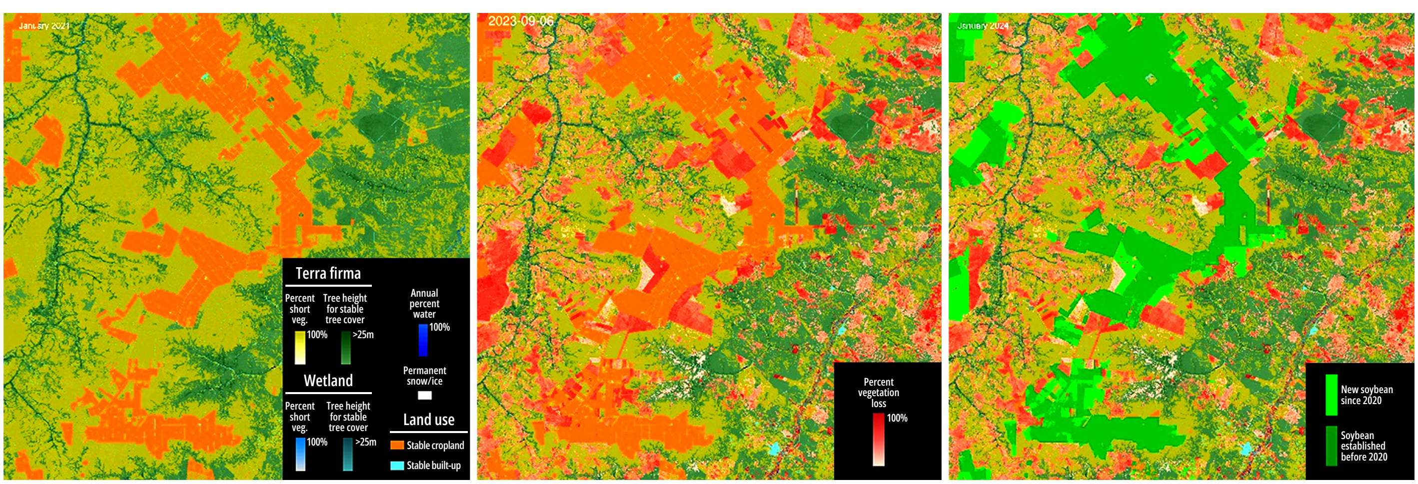
Figure 2. Land use extent (percent area in land use) and dispersion (distance to land use) measures for the Southeast USA, part of the sub-tropical and temperate climate domains (Hansen et al., 2022).



Targeted Land Uses

Commodity drivers of natural land cover conversion would be the targets for monitoring. For example, the EUDR policy lists cattle, cocoa, coffee, oil palm, rubber, soy, and wood for deforestation-free sourcing. Each commodity would be monitored separately. A key advantage of policies related to deforestation is that they limit the monitoring target to areas where we see forest disturbance after the policy's baseline date, a more tractable target than monitoring all agricultural land. Disturbed lands within natural forest cover for EUDR then become targets for land use identification, in this case, specific commodities. For example, soybean is a crop type that may be directly mapped at continental scales, with an example shown in Figure 3 below (Song et al., 2021).

Figure 3. Example land conversion in Piaui, Brazil, of natural Cerrado savanna to soybean from 2021 through 2023.



Tree crops are also readily tracked with a multi-year delay prior to identification as rubber, oil palm, or wood-producing stands. Cocoa and coffee are often shade-grown, challenging accurate characterization. However, the disturbance associated with their establishment can be recorded and field verification made possible. Cattle would similarly be verified, either through high spatial resolution imagery or field visits. Lands with long delays before land use establishment would be continually monitored for signs of development.

Broader tracking of commodity land uses would illuminate their interplay in response to policy. For example, countries such as Bolivia have a pro-conversion land policy, which includes the use of fire for land clearing. The result is one of the most dramatic losses of natural lands in recent years to fire, soybean, and cattle ranching. Another example is the role of Brazil's soybean moratorium's dual role in reducing soy-driven deforestation in the Amazon while potentially increasing deforestation driven by other commodities and in other biomes. Soybean production in Brazil has steadily backfilled pastures, thereby reducing its apparent impact on deforestation as cattle ranching opens up frontier humid tropical forests. On the other hand, non-forest Cerrado savannas have been converted directly to soybean given their non-inclusion in the moratorium.

Tracking of commodity land uses can also inform policy decisions. For example, expansion of commodity land uses outside of natural lands is critically important as it may represent a policy to reclaim degraded lands. Indonesia's current administration has the goal of 20Mha of new food and bioenergy estates (phys.org, 2025). Given the 8Mha of idle cleared rainforest and relatively poor oil palm productivity, there is the possibility of dramatically increasing production without the clearing of vast areas of humid tropical forest, particularly peatlands.

A conceptual, but certainly not exhaustive, list of mapped themes to support *Codex Planetarius:*

Natural lands

- Mapped per pixel and by contiguous extent (fragmentation), disaggregated by ecoregion and dominant land use change – baseline for 2015 derived using 2000-forward land cover/land use, updated continuously

Human-induced disturbances

- Vegetation disturbances within natural land and no establishment of land use – derived using alert systems

Land uses - Intensive

- Impervious surface – vertical/horizontal structures and transportation infrastructure
- Cropland – row crops, including soybean, maize, wheat, rice, sugar cane, other, single or double-cropped, till/no-till, off season cover crops, irrigated
- Pastures – enclosed land grazed by domesticated livestock under intensive management, planted/fertilized/irrigated
- Tree plantations/estates – perennial tree cover – wood (eucalyptus, pine, acacia), rubber, oil palm, other large-scale managed commercial tree cover
- Mining – large scale industrial open pit mining

Land uses - Non-intensive

- Cropland – smallholder food production, small scale and non-intensive
- Pastures – enclosed grassland grazed by domesticated livestock under minimal management
- Tree cover – selective logging
- Tree crops – smallholder agroforestry or monoculture tree cover
- Mining – artisanal mining

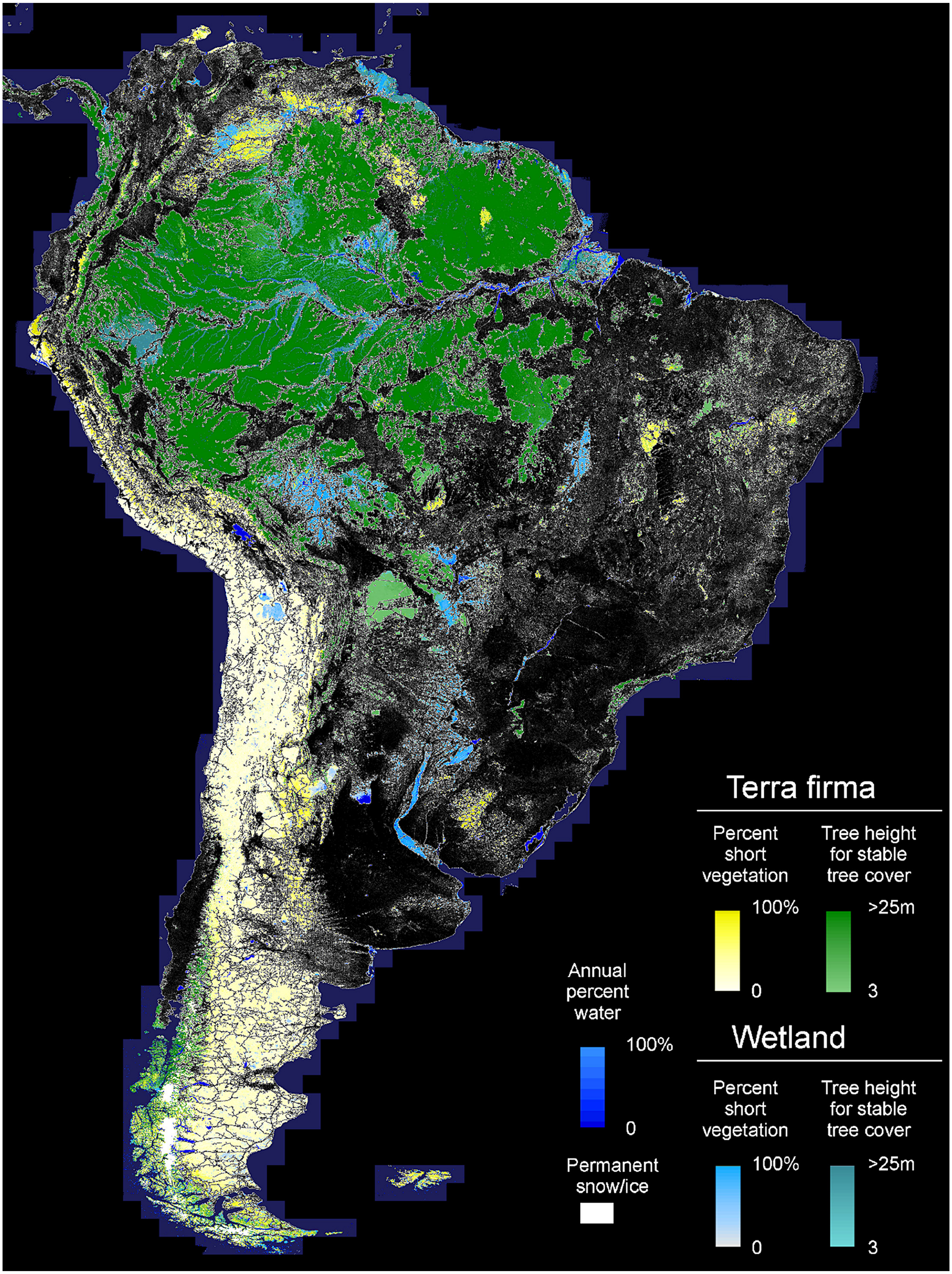
Abandonment/restoration

- Natural vegetation recovery

Surface water

- Monthly surface water dynamics, floods, droughts, and permanent change due to natural dynamics and human-induced diversions/impoundments
- Water quality – long term baseline measures of total suspended sediments and algal indicators

Figure 4. Lands of a minimum extent of 100km2 without observable land use.



Implementation

Remote-sensing based mapping and monitoring from national to global scales has several requirements to ensure low-latency, accurate information to support policy, including the following:

1) Publicly available/accessible, high quality remote sensing imagery - Public earth observation infrastructure, such as that operated by the United States through NASA and USGS, and the European Space Agency Copernicus program, consists of medium spatial resolution, sub-weekly cadence, high quality multi-spectral imagery appropriate for operational land monitoring. Global public good remote sensing data provisioning ensures participation and promotes consistency across all countries.
2) Computing sufficient to process national-scale data. All nations should have the ability to produce systematic updates of land change and in-house or cloud computing must be affordable and accessible in order to operationalize mapping. By definition, computing costs increase with country size, and, if possible, in-house computing is recommended as low latency data visualization is most easily realized with local data, and the derivation of several intermediate products over decadal time-scales can be costly cloud propositions, particularly for egress.
3) Geographers/environmental scientists with domain knowledge about image interpretation, processing, and characterization using coding/scripting, statistical analyses, and algorithm implementation. While the skills are varied, they are required in order to make accurate maps. A small team of such talent is sufficient for data preparation, characterization, and validation. The team must be housed in the office responsible for land change data production and have exclusive purview over all tasks and deliverables.
4) Experts paid as civil servant staff with core (full-time) responsibilities tied to national-scale land cover and land use monitoring.
5) Consistency of data and methods is key to operational environmental data records. If the input data change, or the algorithm changes, or the staff feature high turnover, the consistency of the land change characterization will be compromised. A key aspect is the discipline to perform the same work over the long term. The best example of this is the PRODES data from the Brazilian Space Agency. Despite improvements in data richness, algorithms, and other methodological considerations, PRODES has not changed its approach and remains a stable, consistent, and reliable record of Brazilian deforestation in the Amazon.
6) State of the practice validation and area estimation methods. A key component of land cover and land use change monitoring concerns the application of statistical methods to measure product accuracy, specifically bias and uncertainty. Best practice methods endorsed by the UNFCCC and demonstrated through peer-reviewed science must be mastered and performed in tandem with map-making. Importantly, a field component must exist in confirming product accuracy, with the satellite-derived maps providing a targeting mechanism for efficient sample allocation. For example, mapped disturbance within natural lands would be a target theme. In this way, in situ sample-based assessments provide key evidence of monitoring performance at the pixel (parcel/property) scale.
7) Transparency of data, methods, and results is required for assessing rigor and validity of monitoring systems. Geospatial data used as inputs and product outputs, including validation data, must be publicly accessible.

Limitations

While advances in tracking grasslands have been made (Parente et al., 2024), the most challenging land use to characterize remains pasture, due to the varying levels of intensity, i.e., stocking rates, planted pastures, and other management practices. Pasture is also a land use that often takes place on natural land cover, i.e., grasslands and parkland/savannas, making successful identification a challenge. However, conversion dynamics in establishing pastures, such as clearing of Amazon humid tropical forest, or Chaco dry tropical woodlands, are readily observable and can be treated as land use; as stated before, transportation networks can also be used at a landscape scale to infer land uses such as pasture. In research mode, higher spatial resolution inputs using deep learning algorithms may be a solution to identify pasturelands based on characteristic landscape markers that may be trained upon to classify pasture. Further, land uses other than agriculture are also relevant to monitoring the loss of nature. For example, mining is a major threat to opening up intact landscapes (Asner et al., 2013) and should be incorporated into global natural lands monitoring schemes. Adding themes as needed and as feasible should be a constant ambition. For the time being, spatially explicit maps of row crops, forestry/estates, and settlements/infrastructure are possible and allow for the tracking of the human footprint as it encroaches on natural land covers.

A final and fundamental limitation are mapping errors, either commission or omission errors of land use/natural lands. No map is perfect, but a highly accurate map can provide reliable estimates and a framework for sample-based remote or in situ assessments that can be used in decision support. For example, national/regional/global rates of the conversion of natural lands to land use can be easily derived using a targeted stratified sampling approach, where available reference imagery per sampling unit are used to estimate area and associated drivers. For parcel-level change, in situ samples are most appropriate and may be allocated using satellite-derived maps in confirming land use change outcomes and their relevancy to policy. In this mode, the satellite data reveals which parcels should be visited, and ground expertise takes over from there.

Codex Synergies from Land Use Mapping

Synergies with other *Codex* variables in support of minimum standards of food production, such as soil organic carbon, are not readily observable from space. This fact makes them hard to monitor at scale. In general, satellite data should be leveraged to efficiently target in situ data collection. A global land use monitoring system can be used to deploy in situ assets to track variables such as soil organic carbon, water quality, and possibly other variables. For example, Figure 5 shows a field from Maranhao, Brazil, affected by an escaped fire where cover crops had been used to build up soil organic carbon. Areas affected by the fire experienced a total loss of the multi-year management effort to enhance the soil. Combining soybean and burned area maps would target fields likely to have lost soil organic carbon due to fire.

Water quality can also be monitored using earth observation imagery with dynamics related to land use change within watersheds. Total suspended sediments and/or algal indicators can be modeled and estimated in the water column using remote sensing time-series imagery (Harrington et al., 1992; Johansen et al., 2022), enabling the relation of land use expansion or intensification to changes in water quality. Again, sample designs of in situ data collection should leverage remote-sensing indicators of changing water quality to increase efficiency of field efforts in assessing overall trends.

Figure 5. Soil organic carbon pre- and post-fire for a soybean field in Piaui, Brazil.

Summary

Bringing transparency to the ongoing and increasing environmental impacts of agricultural land use dynamics is possible given a robust and broad-based coalition of data providers and decision support services. Global land cover and land use monitoring of agricultural lands and their encroachment on natural land covers, intensification, and abandonment/restoration, is feasible with current data and methods. An operational system regularly updated and integrated with applications tracking supply chains, land use policy implementation, and conservation/restoration initiatives is a further ambition. *Codex Planetarius* can facilitate the realization of such an integrated monitoring system in mitigating the worst impacts of agriculture on natural systems.

References

Asner G.P., Llactayo W., Tupayachi R., Luna E.R. Elevated rates of gold mining in the Amazon revealed through high-resolution monitoring. *Proc Natl Acad Sci U S A*. 2013 Nov 12;110(46):18454-9. doi: 10.1073/pnas.1318271110.

Curtis, P.B., Slay, C.M., Harris, N.L., Tyukavina, A., Hansen, M.C. (2018). Classifying drivers of global forest loss. *Science* 361 (6407), 1108-1111.

Eckert, I., Brown, A., Caron, D. et al. (2023). 30×30 biodiversity gains rely on national coordination. *Nat Commun* 14, 7113. https://doi.org/10.1038/s41467-023-42737-x

European Commission, Joint Research Centre, Bourgoin, C., Ameztoy, I., Verhegghen, A., Desclée, B., Carboni, S., Bastin, J., Beuchle, R., Brink, A., Defourny, P., Delhez, B., Fritz, S., Gond, V., Herold, M., Lamarche, C., Mansuy, N., Mollicone, D., Oom, D., Peedell, S., San-Miguel, J., Colditz, R. and Achard, F., Mapping Global Forest Cover of the Year 2020 to Support the EU Regulation on Deforestation-free Supply Chains, Publications Office of the European Union, Luxembourg, 2024, https://data.europa.eu/doi/10.2760/262532, JRC136960.

European Union (2023). Regulation (EU) 2023/1115 of the European Parliament and of the Council of 31 May 2023 on the making available on the Union market and the export from the Union of certain commodities and products associated with deforestation and forest degradation and repealing Regulation (EU) No 995/2010.

Foley, J.A., et al. (2005). Global Consequences of Land Use. *Science*, 309, 570-574.

Gonçalves-Souza, T., Chase, J.M., Haddad, N.M. et al. (2025). Species turnover does not rescue biodiversity in fragmented landscapes. *Nature*. https://doi.org/10.1038/s41586-025-08688-7

Gurgel, A.C., Seabra, J.E.A., Arantes, S.M. et al. (2024). Contribution of double-cropped maize ethanol in Brazil to sustainable development. *Nat Sustain* 7, 1429–1440. https://doi.org/10.1038/s41893-024-01424-5

Hansen, M.C., Potapov, P.V., Pickens, A., Tyukavina, A., Hernandez Serna, A., Zalles, V., Turubanova, S., Kommareddy, I., Stehman, S.V., Song, X-P (2022). Global land use extent and dispersion within natural land cover using Landsat data. *Environ. Res. Lett.* 17 034050

Harrington, Jr., J.A., Schiebe, F.R., and Nix, J.F. (1992). Remote sensing of Lake Chicot, Arkansas: Monitoring suspended sediments, turbidity, and Secchi depth with Landsat MSS data, *Remote Sensing of Environment*, 39, 15-27.

Jayne, T.S., and Sanchez, P.A. (2021). Agricultural productivity must improve in sub-Saharan Africa, *Science*, 372, 1045-1047.

Johansen, R.A., Reif, M.K., Saltus, C. L., and Pokrzywinski, K.L. (2022). A review of empirical algorithms for the detection and quantification of harmful algal blooms using satellite-borne remote sensing, US Army Corp of Engineers, Engineer Research and Development Center, ERDC/EL SR-22-2.

Nabuurs, G-J., R. Mrabet, A. Abu Hatab, M. Bustamante, H. Clark, P. Havlík, J. House, C. Mbow, K.N. Ninan, A. Popp, S. Roe, B. Sohngen, S. Towprayoon (2022). *Agriculture, Forestry and Other Land Uses (AFOLU). In IPCC, 2022: Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [P.R. Shukla, J. Skea, R. Slade, A. Al Khourdajie, R. van Diemen, D. McCollum, M. Pathak, S. Some, P. Vyas, R. Fradera, M. Belkacemi, A. Hasija, G. Lisboa, S. Luz, J. Malley, (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA. doi: 10.1017/9781009157926.009

Parente, L., Sloat, L., Mesquita, V. et al. (2024). Annual 30-m maps of global grassland class and extent (2000–2022) based on spatiotemporal Machine Learning. *Sci Data* 11, 1303. https://doi.org/10.1038/s41597-024-04139-6

Parker, D., Tosiani, A., Yazid, M., Sari, I. L., Kartika, T., Kustiyo, Firmansyah, R., Said, Z., Wijaya, A., Potapov, Tyukavina, A., Stehman, S.V., Zalles, V., Pickens, A., Pickering, J., Turubanova, S., Hansen, M. C. (2024). Land in limbo: Nearly one third of Indonesia's cleared old-growth forests left idle. *Proc Natl Acad Sci USA*, 121(28), e2318029121.

Pendrill, F., Gardner, T. A., Meyfroidt, P., Persson, U. M., Adams, J., Azevedo, T., Bastos Lima, M. G., Baumann, M., Curtis, P. G., De Sy, V., Garrett, R., Godar, J., Goldman, E. D., Hansen, M. C., Heilmayr, R., Herold, M., Kuemmerle, T., Lathuillière, M. J., Ribeiro, V., ... West, C. (2022). Disentangling the numbers behind agriculture-driven tropical deforestation. *Science*, 377(6611), Article eabm9267. https://doi.org/10.1126/science.abm9267

Phys.org, (2025). https://phys.org/news/2025-01-activists-slam-destructive-indonesia-forest.html

Potapov, P., Turubanova, S., Hansen, M.C., Tyukavina, A., Zalles, V., Khan, A., Song, X-P, Pickens, A., Shen, Q., Cortez, J. (2022). Global maps of cropland extent and change show accelerated cropland expansion in the twenty-first century. Nat Food, 3, 19-28

Turubanova, S., Potapov, P., Tyukavina, A., and Hansen, M. (2018). Ongoing primary forest loss in Brazil, Democratic Republic of the Congo, and Indonesia. *Environ. Res. Lett.* 13 074028

Eric W. Sanderson, Malanding Jaiteh, Marc A. Levy, Kent H. Redford, Antoinette V. Wannebo, Gillian Woolmer. The Human Footprint and the Last of the Wild: The human footprint is a global map of human influence on the land surface, which suggests that human beings are stewards of nature, whether we like it or not, *Biosci*, Volume 52, Issue 10, October 2002, Pages 891–904

Song, X.-P., Hansen, M.C., Potapov, P., Adusei, B., Pickering, J., Adami, M., Lima, A., Zalles, V., Stehman, S.V., Di Bella, C.M., Cecilia, C.M., Copati, E.J., Fernandes, L.B., Hernandez-Serna, A., Jantz, S.M., Pickens, A.H., Turubanova, S., Tyukavina A. (2021). Massive soybean expansion in South America since 2000 and implications for conservation. *Nat Sustain*, 4, 784–792

United Nations Convention on Biological Diversity. (2022). In *Proc. Kunming-Montreal Global Biodiversity Framework*.

Varkkey, H., Tyson, A., Choiruzzad, S.A.B. (2018). Palm oil intensification and expansion in Indonesia and Malaysia: Environmental and socio-political factors influencing policy. *For Policy and Econ*, 93, 148-159.

Venter, O., Sanderson, E., Magrach, A. et al. (2016). Global terrestrial Human Footprint maps for 1993 and 2009. Sci Data 3, 160067. https://doi.org/10.1038/sdata.2016.67

Zalles, V., Hansen, M.C., Potapov, P.V., Parker, D., Stehman, S.V., Pickens A.H., Leal Parente, L., Ferreira, L.G., Song, X.-P., Hernandez-Serna, A., Kommareddy, I. (2021). Rapid expansion of human impact on natural land in South America since 1985. *Sci Adv,* 7(14)