Chapter 10
Continuous Monitoring of Tree Responses to Climate Change for Smart Forestry: A Cybernetic Web of Trees

Roberto Tognetti, Riccardo Valentini, Luca Belelli Marchesini, Damiano Gianelle, Pietro Panzacchi, and John D. Marshall

Abstract Trees are long-lived organisms that contribute to forest development over centuries and beyond. However, trees are vulnerable to increasing natural and anthropic disturbances. Spatially distributed, continuous data are required to predict mortality risk and impact on the fate of forest ecosystems. In order to enable monitoring over sensitive and often remote forest areas that cannot be patrolled regularly, early warning tools/platforms of mortality risk need to be established across regions. Although remote sensing tools are good at detecting change once it has occurred, early warning tools require ecophysiological information that is more easily collected from single trees on the ground.

Here, we discuss the requirements for developing and implementing such a tree-based platform to collect and transmit ecophysiological forest observations and

R. Tognetti (✉)
Dipartimento di Agricoltura, Ambiente e Alimenti, Università degli Studi del Molise, Campobasso, Italy
e-mail: tognetti@unimol.it

R. Valentini
DIBAF – Department for Innovation in Biological, Agri-Food and Forest Systems, University of Tuscia, Viterbo, Italy

Smart Urban Nature Laboratory, RUDN University, Moscow, Russia
e-mail: rik@unitus.it

L. B. Marchesini · D. Gianelle
Department of Sustainable Agro-Ecosystems and Bioresources, Fondazione Edmund Mach, San Michele all'Adige, Italy
e-mail: luca.belellimarchesini@fmach.it; damiano.gianelle@fmach.it

P. Panzacchi
Department of Biosciences and Territory, Università degli Studi del Molise, Pesche, Italy

Faculty of Science and Technology, Free University of Bolzano-Bozen, Bolzano, Italy

J. D. Marshall
Department of Forest Ecology and Management, SLU, Umea, Sweden
e-mail: john.marshall@slu.se

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environmental measurements from representative forest sites, where the goals are to identify and to monitor ecological tipping points for rapid forest decline. Long-term monitoring of forest research plots will contribute to better understanding of disturbance and the conditions that precede it. International networks of these sites will provide a regional view of susceptibility and impacts and would play an important role in ground-truthing remotely sensed data.

10.1 Ground-Based Measures of Forest Ecophysiological Indicators for Climate Smartness

A set of criteria and indicators have been proposed, by which the "climate smartness" of a forest can be assessed (Bowditch et al. 2020; Santopuoli et al. 2020). Likewise, Bussotti and Pollastrini (2017) proposed a mix of traditional and novel indicators of forest health, at tree and stand levels, to support visual tree assessment, as well as to improve the prediction of stand dynamics and forest productivity under climate change in European forests.

The indicators are quantitative or qualitative variables that are evaluated periodically to reveal the direction of change with respect to these criteria (Bowditch et al. 2020; see also Chaps. 3 and 2 of this book: del Río et al. 2021; Weatherall et al. 2021, respectively). Within a particular management framework, one begins by choosing which forest processes are relevant for the criteria of "climate smartness." Forestry has traditionally privileged tree growth and wood production as main management goals, assuming that productivity is the ultimate indicator of tree responses to environmental conditions. However, climate change has challenged this view due to uncertainties in disturbance-growth relationships related to climatic variability and extreme weather events. In addition, management now addresses trade-offs between different forest functions and services (Thom and Seidl 2016; Albrich et al. 2018). The widened horizon of modern forest management is well recognized and interpreted by the Sustainable Development Goals 13 and 15 (United Nations 2015) as sustainably managed forests are instrumental to combat climate change and its impacts; to protect, restore, and promote sustainable use of terrestrial ecosystems; to strive against desertification; to halt and reverse land degradation; and to halt biodiversity loss.

Research in forest ecosystems has mostly focused on ring-width time series, forest stand yield measured on plots, or long-term successional dynamics (Harmon and Pabst 2015). These do not require frequent sampling. However, mechanistic analysis of climate-driven and disturbance-related events (e.g., droughts, fires, windthrows, outbreaks) requires direct and frequent repeated observations of processes related to forest demography and resilience (i.e., mortality and recruitment) to identify the causes. Therefore, parameters that reveal ecophysiological status become more valued than in traditional forest monitoring. Within a certain range of climatic conditions (short- to midterm), ecophysiological traits and growth patterns follow climate variability, with species plasticity allowing trees to recover from climate perturbations. However, extreme events may trigger anomalous physiological responses beyond the safe operation mode, leading to irreversible changes and eventually causing the death of trees (Fig. 10.1). The exit of tree responses from the safe operation mode is often difficult to detect without a long-term and high-frequency record of tree functions. Autonomous sensor networks may produce information valuable to monitor tree status, allowing foresters to make informed management decisions.

Numerous experiments and observational studies have been established to address global change-related questions across multiple temporal and spatial scales (Halbritter et al. 2020). In particular, studies on forest decline aim to establish the causal relations, to unravel the climate drivers, and to understand the ecological processes related to trees' mortality. Nevertheless, some ecological processes are more sensitive to changes in extremes than in mean values (Allen et al. 2010; Hansen et al. 2012), including important effects of microclimate. For example, extreme temperatures combined with prolonged drought have been implicated as drivers of forest die-off (Adams et al. 2017).

There is growing scientific interest in forest reactions to drought across different biomes to discern which growth features or functional traits best characterize different species-specific responses to these climate extremes (Lindner et al. 2010;

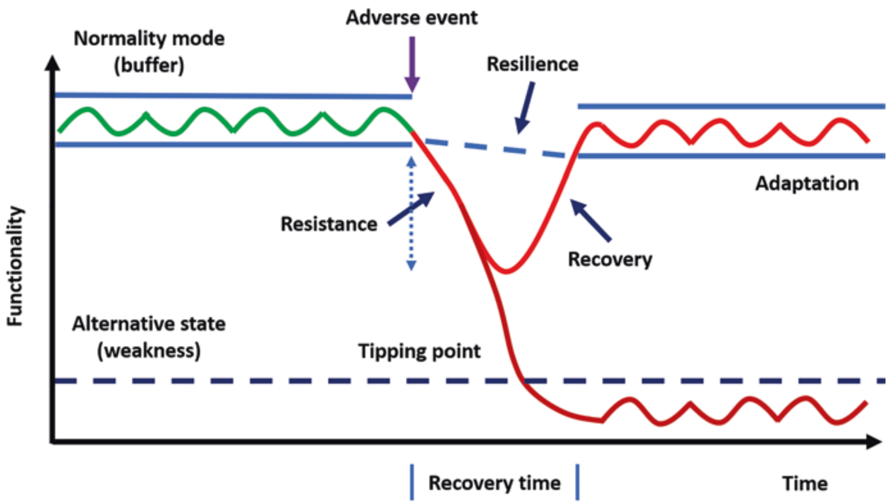

Fig. 10.1 The normal or safe operation mode (normality mode) of the single tree can be perturbed by climatic events or environmental disturbances, leading to anomalous physiological responses beyond the buffer space. Eventually, extreme events (single or series) may provoke persistent changes in the short- to midterm; recovery to an alternative stable state may occur within the resistance limits of the species. Indeed, as climate changes over longer time frames and tree populations display some degree of adaptation, the normality mode may adjust accordingly. The "tipping point," which prevents the tree from recovering physiological functions and triggers tree decline, varies with species and environment, and is not easy to predict

Anderegg et al. 2015). For example, in Mediterranean forests, water availability is the major tree growth constraint, and drought conditions are predicted to increase (Giorgi and Lionello 2008). Nevertheless, the responses of these forests to such extreme climatic events are poorly understood, because controlled field experiments able to mimic drought conditions are costly and difficult to operate on a large scale without introducing environmental modifications. Adaptive forest management strategies to combat climate change need a clear framework of indicators useful for predicting the different components of tree resilience and the ability of trees to recover after disturbance (or their mortality). Therefore, we may pose the following question: how can the observational approach be linked with datasets gathered from in situ experiments, products of hypothesis testing, to detect critical changes in ecological conditions and to determine the ways in which those changes impact ecosystem functions?

Adaptive management practices aimed at combating forest decline need to implement real-time control of the environment and a quick response to changing growth conditions. In this context, a range of sensors is needed to provide a picture of interactions occurring between data and to enable key forest indicators to be identified. A selection of indicators, enabling the assessment of climate smartness of forests at stand level, is provided in Table 10.1; measurable parameters, data solutions, and monitoring tools are also reported. Data from monitoring networks and model forecasts are essential instruments, both to understand forest ecosystem responses to rapid environmental variation and to support forest decision-makers under a climate change scenario (Lindner et al. 2014).

The "smartness" of climate-smart forestry (CSF) comes in part from its ability to predict and respond to changes in stand dynamics using early warning signals, which precede the occurrence of unwanted events, such as forest decline. Large-scale and long-term forest monitoring networks have been collecting information for characterizing forest responses to global change (structure, function, damage, diversity), e.g., CTFS-ForestGEO (Anderson-Teixeira et al. 2015), ICP Forests (http://icp-forests.net/), and eLTER (https://www.lter-europe.net/). However, a mechanistic understanding of forest adjustment to global change is still missing. In this context, a new observational and experimental paradigm based on biogeographic scale, single-tree, high-frequency, and long-term monitoring is required (Steppe et al. 2016).

10.2 Tree Mortality, Tipping Points, and Resilience

Climate scenarios for the next decades predict warmer temperatures, greater vapor pressure deficits, and more frequent and severe drought spells and heat waves than experienced in the recent (Sillmann et al. 2013a, b). These changes are expected to result in increased frequency, intensity, and duration of drought (Polade et al. 2014). Intensifying impacts of drought events on tree functionality have been recently observed across biomes (e.g., Shestakova et al. 2019). Drought episodes interact

Table 10.1 Selected climate-smart forestry (CSF) indicators, stand-level measurable parameters, cybertechnologies for data collection and transmission, and related techniques and tools

Climate-smart forestry indicators	Description based on MCPFE and Forest Europe	Source (CLIMO or Forest Europe, FE)	Criteria classification	Parameters	Cybertechnology for data collection	Cybertechnology for data transmission	Measurement techniques	Tools
1.3 Age structure and/or diameter distribution	Age structure and/or diameter distribution of forest and other wooded land, classified by availability for wood supply	FE	Management	Tree diameter, TRI	Cable	LoRa, wireless Internet	Dendrochronology, forest mensuration	Diameter tape, tree ring analysis
1.4 Carbon stock	Carbon stock and carbon stock changes in forest biomass, forest soils, and harvested wood products	FE	Ecological	GPP=WUEi*gs, NPP, carbon stock partitioning	Cable	LoRa, wireless internet	Stable isotopes, sap flow = WUE/gs	Dendrometers, tree ring analysis, tree talker, stable isotope (13C) gas analyzer
2.1 Deposition of air pollutants	Deposition and concentration of air pollutants on forest and other wooded land	FE	Ecological	Photochemical reflectance index	Wireless	LoRa, wireless Internet	Spectral reflectance	Spectral reflectance sensor

(continued)

Table 10.1 (continued)

Climate-smart forestry indicators	Description based on MCPFE and Forest Europe	Source (CLIMO or Forest Europe, FE)	Criteria classification	Parameters	Cybertechnology for data collection	Cybertechnology for data transmission	Measurement techniques	Tools
2.2 Soil condition	Chemical soil properties (pH, CEC, C/N, organic C, base saturation) on forest and other wooded land related to soil acidity and eutrophication, classified by main soil types	FE	Ecological	Soil temperature, soil moisture	Radio, cell phone, Wi-Fi, satellite, Ethernet/cable, meteor burst, wireless Internet, telemetry	LoRa, wireless Internet	Electrical capacitance, gamma attenuation, soil heat flux, time-domain reflectometry (TDR), ground-penetrating radar (GPR), infrared thermal imaging (TIR)	Soil temperature-moisture probe, soil temperature-moisture profile probe
2.3 Defoliation	Defoliation of one or more main tree species on forest and other wooded land in each of the defoliation classes	FE	Ecological	Photochemical reflectance index, leaf temperature	Wireless	LoRa, wireless Internet	Spectral reflectance, thermal resistance, thermocouple, infrared, infrared thermal imaging (TIR)	Spectral reflectance sensor, infrared thermometer, UAV
2.4 Forest damage	Forest and other wooded land with damage, classified by primary damaging agent (abiotic, biotic, and human induced)	FE	Ecological	Photochemical reflectance index	Wireless	LoRa, wireless Internet	Spectral reflectance	Spectral reflectance sensor
4.1 Tree species composition	Area of forest and other wooded land, classified by number of tree species occurring	FE	Management	Number	Wireless	LoRa, wireless Internet	Laser	Fieldmap

Climate-smart forestry indicators	Description based on MCPFE and Forest Europe	Source (CLIMO or Forest Europe, FE)	Criteria classification	Parameters	Cybertechnology for data collection	Cybertechnology for data transmission	Measurement techniques	Tools
4.2 Regeneration	Total forest area by stand origin and area of annual forest regeneration and expansion	FE	Management	Area	Wireless	LoRa, wireless Internet	Laser	LiDAR-UAV
4.4 Introduced tree species	Area of forest and other wooded land dominated by introduced tree species	FE	Management	Area, crown	Wireless	LoRa, wireless Internet	Laser	LiDAR-UAV
4.5 Deadwood	Volume of standing deadwood and of lying deadwood on forest and other wooded land	FE	Ecological	Volume, 3D point cloud	Wireless	LoRa, wireless Internet	Laser	TLS
5.1 Protective forests – soil, water, and other ecosystem functions, and infrastructures	Area of forest and other wooded land designated to prevent soil erosion, preserve water resources, maintain other protective functions, protect infrastructure, and manage natural resources against natural hazards	FE	Ecological	Canopy cover	Wireless	LoRa, wireless Internet	Laser	LiDAR-UAV
7.2 Slenderness coefficient	The ratio of tree total height to diameter outside bark at 1.3 m above ground level	CLIMO	Management	DBH, height	Wireless	LoRa, wireless Internet	Laser, modeling	TLS, Fieldmap, DTM-CHM

(continued)

Table 10.1 (continued)

Climate-smart forestry indicators	Description based on MCPFE and Forest Europe	Source (CLIMO or Forest Europe, FE)	Criteria classification	Parameters	Cybertechnology for data collection	Cybertechnology for data transmission	Measurement techniques	Tools
7.3 Vertical distribution of tree crowns	Distribution of tree crown in the vertical space. It can be measured in terms of layers (one, two, multiple), or in terms of ratio between tree height and crown length	CLIMO	Management	Stand vertical structure, 3D point clod	Wireless	LoRa, wireless Internet	Laser	LiDAR, TLS
4.92 Horizontal distribution of tree crowns	Canopy space filling and can be expressed in measure of density of tree crowns, such as crown area, tree crown diameter. It can be also expressed in measure of density of trees, such as trees per hectare, basal area per hectare (in this case the horizontal distribution refers to the tree)	CLIMO	Management	Tree density, 3D point cloud	Wireless	LoRa, wireless Internet	Laser	LiDAR, TLS

with heat waves, possibly inducing die-off events (Allen et al. 2010; Anderegg et al. 2016). Direct effects on tree physiological functions (runaway embolism and/or carbon starvation and their interactions) may kill trees (McDowell et al. 2013) (Fig. 10.2). Globally, tree mortality is expected to increase because of biogeochemical and biophysical climatic feedback following shifts in land carbon and energy balance (Bonan 2008). Reorienting forestry systems to support sustainable forest management under the new realities of climate change needs an integrated understanding of tree adaptation to climate change under field conditions and explicit testing of plasticity-growth relationships for sustaining productivity under more extreme climatic conditions (Millar and Stephenson 2015).

Examples of climate-smart measures include, among others, managing forest disturbances and extreme events; selecting resilient trees and implementing forest reserves; combining carbon storage, sequestration, and substitution; using forest bioenergy and wood in the construction sector; and valuing ecosystems and their services that help halt land degradation. In order to withstand the changing climate, forest ecosystems need to be healthy and strong. Forest health, described by the functional envelope for disease-free trees at the individual level (Hartmann et al. 2018), can be monitored by determining mortality rates that deviate from normal background mortality rates (excess deaths). Recording the normal space of operation and the detection of functional anomalies requires long-term and high-frequency monitoring of trees in forest ecosystems (Trumbore et al. 2015). Abiotic and biotic factors make the tree mortality process complicated. The failure of hydraulic

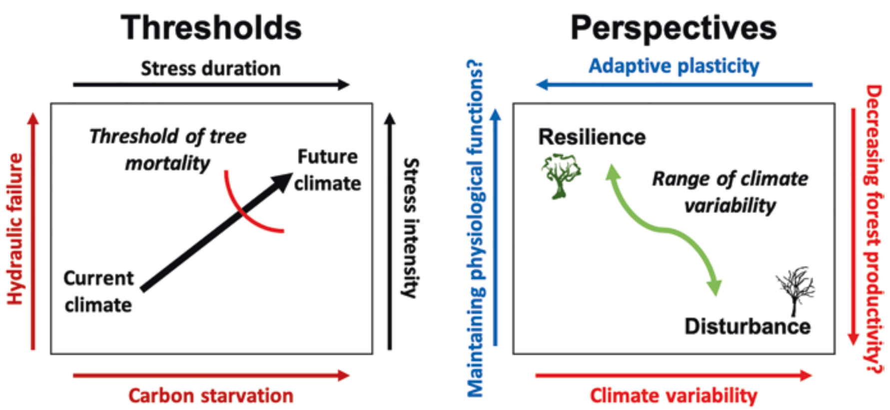

Fig. 10.2 Despite rapid directional environmental changes, forest managers struggle against environmental changes to maintain forests within historical ranges of conditions. However, forests are inherently unstable under climate change, and, beyond a certain threshold, substantial mortality occurs, with an abrupt loss of forest functions and services. Drought may cause tree mortality directly or indirectly through increased vulnerability to insects or pathogens. Although drought-induced mortality is expected to occur more frequently at the southern range limits of tree species, tree death may increase regardless of location. Should forest managers anticipate and assist forest transition by reducing the probability of sudden die-back (e.g., thinning to reduce competition for resources, establishing species adapted to future conditions), the transition will be gradual rather than abrupt, and ecosystem services will be maintained at a higher (although reduced) level

systems and the depletion of carbon reserves determine the physiological response of trees to drought and the pathway of drought-induced mortality (Choat et al. 2018). Vulnerability to pests and pathogens adds to abiotic stress, causing physiological decline and physical damage.

In order to implement CSF practices and assess forest ecosystem resilience, drivers of forest dynamics, indicators of environmental disturbances, and the occurrence of tree mortality need to be selected and monitored (Bowditch et al. 2020). To this end, trends and their directions in tree traits in response to disturbance events can be considered to assess changes in temporal (and spatial) synchrony associated with time series of ecophysiological and growth data and used as early warning signals of mortality risk (Cocozza et al. 2009, 2012; Fierravanti et al. 2015; Cailleret et al. 2016, 2017). Phase synchronization of time series relevant for signal analysis may help understand the relationships between fluctuations in functional traits and impacts of environmental drivers (Perone et al. 2016; Cocozza et al. 2018). Early warning signals of forest systems that are approaching a critical transition are caused by the gradual decrease in the recovery rate after a disturbance event (Wissel 1984; Drake and Griffen 2010; Veraart et al. 2012; Dai et al. 2012; Jarvis et al. 2016). Under increasing levels of stress (e.g., drought), damaged trees are no longer able to use natural resources. Interacting stressors, hence, may lead to system failure (Anderegg et al. 2012). The accumulated physiological damage may cross the tipping point and trigger tree mortality. This critical transition is caused by the combined changes in the intensity, frequency, and duration of stress factors (Dakos et al. 2015) and high sensitivity of the tree to these specific stresses (Brandt et al. 2017).

Models of physiological processes may provide an understanding of mechanisms underlying responses to climate in forest trees that experience drought-induced mortality (McDowell et al. 2013). When physiological models fail, however, empirical data are useful to determine mechanisms and thresholds that may trigger tree mortality. Estimates of the relationships among evaporative demand (dry season), water supply (wet season), and tree growth may help develop indices that capture mortality (Park Williams et al. 2013). Integration of mechanistic approaches with empirical observations can be achieved with specific studies of tree growth in permanent sample plots (prospective studies, e.g., (Cocozza et al. 2016); see also Chap. 5 of this book: Pretzsch et al. 2021) and tree ring analyses (retrospective studies, e.g., Tognetti et al. 2019).

Prior to tree mortality, an ecosystem may cross a critical transition (a tipping point) in forest functions. These might include, for example, runaway embolism caused by drought stress (Tyree and Sperry 1988) or crown damage caused by wind or snow loading (Peltola and Kellomäki 1993; Nadrowski et al. 2014). The exact location of the tipping point depends on species- and stress-specific sensitivity. Although dynamic phenomena are intrinsically difficult to observe, efficient monitoring of spatially and temporally dynamic phenomena is possible through multiscale sampling schemes based on a coarse-to-fine hierarchy system (Rundel et al. 2009). With this approach, the region of interest can be identified and surveyed through low-spatial/time resolution sensors (e.g., airborne surveys and sparse ground-based devices), and selected areas that need high-resolution and real-time observation can be monitored. Mobile nodes may supplement fixed sensors to adapt sampling protocols and instrument modalities (Jordan et al. 2007). Similarly, ecosystem flux studies, which started in the late 1980s (Baldocchi et al. 1987; Jarvis et al. 1989), utilized fixed experimental infrastructures to measure the net ecosystem gas exchange by eddy covariance methods across a global network of terrestrial ecosystems. Because of the difficulty of moving the complex flux infrastructures from site to site for short campaigns, low-cost eddy covariance setups were developed and deployed as roving towers for characterizing the spatial variability at the landscape level (Cavaleri et al. 2008; Markwitz and Siebicke 2019).

Tree mortality and forest dieback may themselves be considered tipping points (Cailleret et al. 2019), which, once passed, may induce further major changes in the system's dynamics. Tipping points are difficult to predict due to species interactions and driver stochasticity. Understanding these thresholds would help predict the circumstances under which trade-offs between different forest functions are minimal and, therefore, when their simultaneous provisioning, that is, ecosystem multifunctionality, is amplified (Gamfeldt et al. 2013; Baeten et al. 2019). Long-term and high-resolution data, in combination with modelling exercises and short-term experiments, may help explain the mechanisms behind tipping points and runaway perturbations. As an example, time-series data may integrate flux tower measurements, which cover only the last three decades, and forest inventories, which have multiannual gaps between successive samplings.

The tipping point can be reached after a series of extreme events, which may vary in duration among tree species and environmental conditions or can be induced by sequential exposure to extreme events (memory or legacy effect) (Fig. 10.3). The extent by which climate extremes impact functional processes and resistance/recovery in tree patterns is also dependent on forest structure (age, height, and diameter classes), genotypic and phenotypic profiles, soil characteristics, and degree and type of disturbances (windstorms, fires, droughts, outbreaks) (Kannenberg et al. 2019). The comprehension of these dynamics, as well as the identification of potential early warning signals in trees, preceding the occurrence of irreversible tree decline (tipping point), requires a new monitoring paradigm based on large-scale, single-tree, high-frequency, and long-term monitoring. This will allow us to follow tree dynamics under climate change in real time at a resolution and accuracy that cannot always be provided through forest inventories or remote sensing.

Measuring forest ecosystem performance in response to changing environmental conditions and detecting threshold responses may improve predictions of tree resilience to disturbance and provide early warning signs of forest transitions (Munson et al. 2018). Critical environmental conditions, such as warming-induced drought stress (e.g., Allen et al. 2010), may shift trees and forests into a different state. Since the returning of the environmental condition to the pre-stress level does not necessarily result in the previous tree or forest state, forcing management to maintain stands within their historic ranges of variability may result in substantial tree mortality and forest dieback once a threshold is exceeded, with a consequent loss of

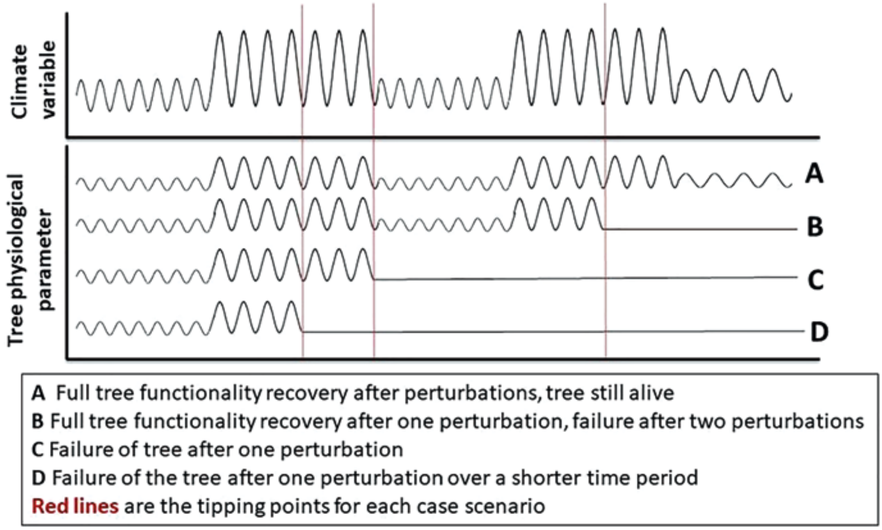

Fig. 10.3 Physiological responses to climatic perturbations could be defined as the normal or safe operation mode of the single tree (**a**). However, extreme events might lead to anomalous physiological responses beyond the safe operation mode, leading to persistent irreversible changes, tree decline, and tree death. The tipping point, which triggers the exit of tree responses from the safe operation mode, is often not easy to detect without a long-term and high-frequency record of tree functions. The tipping could be reached after a series of extreme days, which might vary among species and conditions (**c** and **d**) or be induced by sequential exposure to extreme events in time (memory effect) (**b**)

forest ecosystem services (Millar and Stephenson 2015). Climate-smart forestry anticipates tree and stand instability in the new environmental condition, facilitating forest adaptation by promoting species mixtures and silvicultural practices aimed at reducing the competition for water and nutrients, thereby ensuring the provision of ecosystem services.

Resource availability strongly influences biogeochemical cycles shaping ecosystem resilience to environmental changes and hence the avoidance of tipping points. Changes in climate and other large-scale environmental alterations (e.g., nitrogen deposition) affect forest ecosystems worldwide (Lindner et al. 2010). At the local scale, these changes magnify the effects of disturbance events and changes in land-use practices, inducing land cover changes and vegetation shifts (Millar and Stephenson 2015).

Although protecting intact forests, restoring degraded forests and managing sustainably productive forests are essential issues to ensure carbon storage, and many other ecosystem services (Pan et al. 2011), forests, and forestry also provide forcing and feedbacks to climate, affecting the exchange of energy and water between land surfaces and the atmosphere (Naudts et al. 2016). In fact, forests influence climate in different and contrasting ways by storing large amounts of carbon (assimilating CO_2), masking the high albedo of snow (warming climate), and sustaining the hydrologic cycle through evapotranspiration (cooling climate) (Bonan 2008). Indeed, the effect of competing processes (carbon emission vs. albedo increase from land-use changes) is large in temperate and boreal latitudes of Europe, where forests have been cleared for agriculture (with an increase in surface albedo), offsetting the warming due to deforestation (Luyssaert et al. 2018). However, in the tropics, forest loss leads to additional warming. Forest resilience to drought and the interaction of disturbances with climate (e.g., fires, pollutants), as well as the effect of deforestation on cloud formation, affect carbon sequestration potential and evaporative cooling of tropical forests.

Inferring the direction of causal dependence between drivers and processes within complex mosaics of forest stands is challenging. Across regions and species, trees that died during drought events were found to be less resilient to stress conditions occurring previously relative to co-occurring resilient trees of the same species (DeSoto et al. 2020). Therefore, widespread (in space) and continuous (in time) monitoring of individual functionality should be planned for describing the causal relationships between climatic patterns or environmental disturbances and tree resilience/vulnerability.

Droughts are linked to a wide range of climatic conditions, such as increased mean and maximum air temperatures, which increase evapotranspiration rate and vapor pressure deficit, with variable impacts on tree functioning across different forest types (Choat et al. 2012; Rita et al. 2020). When coping with drought stress, trees must finely tune the loss of water (transpiration) and the uptake of carbon (growth). Although trees may adjust to extreme conditions, it is not clear whether rapid physiological adjustments in stress tolerance occur in response to heat waves and/or drought spells or whether this is an effective protectant during the extreme events that are predicted to occur in the future (O'Sullivan et al. 2017). Yet, it is unknown whether acclimation to long-term warming modifies the physiological performance of trees during an extreme event (Teskey et al. 2015).

Tree water and carbon management strategies vary with species (e.g., regulation of water potential, vulnerability to xylem embolism, pattern of carbon allocation, etc.), but a clear framework of indicators useful for predicting the different components of tree resilience and the capacity of trees to recover after disturbance (or their mortality) is still missing. Similarly, the relative influence of specific climate parameters on forest decline is poorly understood (Park Williams et al. 2013). Specific functional traits for adapting to climate change and coping with environmental disturbances include tree height, wood density, seed size, specific leaf area, resprout ability, bark thickness, and rooting depth (Aubin et al. 2018). However, a combination of ecophysiological indicators, measured continuously and representing the coupling of tree productivity and water relations, would best explain the tipping point of tree resilience/mortality, predicting the probability of departure from the safe operational space.

10.3 From Tree Observation to Functional Understanding

Single-tree characteristics provide information about the response of stands to disturbance events and the growing stock of stands (see Chap. 4 of this book: Temperli et al. 2021). Similar information can be estimated from remote sensing, but the quality, sensitivity, and resolution of the information are not as high. In addition, ecophysiological traits of trees are increasingly recognized as a useful tool to predict vulnerability to disturbance (namely, drought and the drought-induced xylem dysfunction) and to forecast composition, structure, and function of future forests under climate change scenarios (O'Brien et al. 2017). The increased frequency of extreme events and climate anomalies (e.g., late frosts, heavy storms) may produce immediate damage to stands or alter local phenology of trees, leading to increased risks of pest exposure or carbon starvation. However, widespread climate-driven forest die-off from drought and heat stress is expected to have consequences distinct from those of other forest disturbances (Allen et al. 2010).

Luyssaert et al. (2018) argued that Europe should not rely on forest management to mitigate climate change, whereas adaptation to future climate should be favored. Whether this adaptation can be obtained by changes in species composition and/or revision of silvicultural systems over major biogeographic regions needs standardized data collection across field experiments. In particular, ecophysiological responses of fine-scale processes may help to understand regional-scale trajectories of adaptation patterns and long-term consequences. While acknowledging the importance of biophysical effects on climate, Grassi et al. (2019) claimed that the net annual biophysical climate impact of forest management in Europe remains more uncertain than the net atmospheric CO_2 uptake impact.

The primary reason for forest monitoring to move forward and integrate tree-level and landscape-level data is to operate tools in a manner that consistently generate information in a dynamic environment. A number of traits are good indicators of tree responses to resource availability, or biotic disturbance, and data processed by software platforms can be readily converted into descriptions of these traits. Integrating image processing (e.g., scientific digital webcams; Bothmann et al. 2017) with functional monitoring (e.g., sap flow gauges; Flo et al. 2019) provides an example of how different sensors can be linked to address rapid dynamics in plant response to environmental changes. The fast development of advanced equipment and the vast amount of generated data may allow innovative data-driven approaches to replace traditional hypothesis-driven analyses, providing new insights on forest ecophysiology by means of artificial intelligence, e.g., machine learning approaches (Torresan et al. 2021).

A network of sensors and imagers deployed in the forest can be also used to monitor the simultaneous response of interacting variables, partitioning aboveground and belowground dynamics in the soil-plant-atmosphere continuum. Ground-penetrating radar (GPR) (e.g., Lambot et al. 2006) and wireless soil moisture sensor networks (Rosenbaum et al. 2012) allow the assessment of spatial patterns of soil moisture and soil hydraulic properties, which may integrate measurements of hydraulic redistribution by deep roots, following reversal in sap flow (Oliveira et al. 2005). Cosmic ray sensors provide soil moisture measurements for a footprint with a radius of approximately 300 m and a vertical depth of up to 70 cm (Zreda et al. 2012; Baatz et al. 2014). In drought-stress physiology, in particular, questions about the proportion of water sources accessed by plants during the season can be answered by tracing stable isotopes of hydrogen and oxygen ($^{2}H/^{1}H$, $^{16}O/^{18}O$) in the water molecule (Dawson et al. 2002). Relatively cheap and transportable instruments, made available by recent technical development, allow measurement of the stable isotope composition of different waters, including transpired and leaf water, directly in the field (Cernusak et al. 2016; Marshall et al. 2020).

Stable isotopes can be used to trace the uptake and movement of water through the tree, interpreting temporal and spatial variation between neighboring plants. For example, walnut trees were reported to extract water from deeper soils compared to the Italian alder in a mixed plantation in central Italy (Lauteri et al. 2005). In contrast, black walnut was found to extract water from shallow soils compared to a hybrid poplar (*Populus deltoides* x *Populus nigra* clone) in an agroforestry system in Ontario, Canada (Link et al. 2015). Switches between different soil water sources may also occur as a function of seasonal patterns (dry vs. wet periods) or weather events (high vs. low soil moisture) (Sun et al. 2011). Given that transpiration is strongly controlled by water supply and demand, stable isotopes of hydrogen and oxygen in plant organic matter (e.g., leaf tissues, tree rings) reflect the environmental conditions (particularly the evaporative demand) in which the tree grew and the biophysical response to those conditions. Schwendenmann et al. (2010) observed that a higher proportion of deep-water uptake associated with more foliage cover in the dry season (phenological stage), as well as higher sap flux densities and water use rates (transpiration rate). Age and size of trees also have an impact on soil water-use depths and dynamics. The development of technologies for quantifying stable isotope ratios of transpired water and water extracted from plant tissues provides a means to understand the environmental and physiological controls over leaf hydraulics. Labelling experiments, in which labelled water (with D_2O) is added to the soil surface, may further illuminate patterns of water uptake (Koeniger et al. 2010).

Digital sensors open new opportunities for low-cost measurements of vertical soil moisture storage and temperature, including vertical and horizontal patterns of root water uptake (Blonquist et al. 2005; Nadezhdina et al. 2006). Full-range tensiometers (filled with a polymer solution) can be used to measure the soil water matric potential directly in forest, in the range of 0–2 MPa with enough accuracy and low maintenance (Bakker et al. 2007). Estimates of soil hydraulic properties are, however, critical for understanding drought-induced changes in soil hydrological processes, including water infiltration, surface runoff, water retention, moisture content, and solute transport (Robinson et al. 2019), as well as plant transpiration, the principal component of the hydrologic cycle.

The energy associated with water transpired by plants and evaporated directly from wet surfaces (the latent heat flux) is a fundamental component of the Earth's surface energy balance. Soil moisture and evaporative demand affect transpiration, which is the dominant component of the latent heat flux in areas covered by forest. Eddy covariance technique can be used to measure the latent heat flux above the forest canopy, but it does not distinguish between transpiration and evaporation. In this sense, sap flow (sap flux when referred to an area, e.g., conducting sapwood or transpiring foliage) measurements may help disentangle transpiration and evaporation, as well as determine species-specific contributions (for a comparison of sap flow methods, see Steppe et al. 2010; Cermák et al. 2015; Poyatos et al. 2016; Halbritter et al. 2020). Soil properties (e.g., water holding capacity, water content) and plant traits (e.g., sap flow rate, water potential) can be used to derive relative extractable water and water stress indices.

Tree growth dynamics and biomass increment are of high importance as indicators of forest condition in long-term forest monitoring (Dobbertin et al. 2013; see also Chaps. 6 and 7: Pretzsch et al. 2021; Bosela et al. 2021) and of potential uptake of CO_2 by forest ecosystems (Law et al. 2018). Stem radial growth and seasonal cambial rhythm are strongly dependent on environmental factors and, as such, good indicators of tree vitality and of tree responses to stress factors, such as drought (Zweifel 2016; Prislan et al. 2019). Furthermore, strong relationships between annual tree biomass increment and yearly net ecosystem productivity measurement have been observed (Teets et al. 2018). Living trees have similar utility as living laboratories in enabling forest researchers and operators to document and assess the response of trees to climate change in real-life contexts (Farrell et al. 2015). Diel patterns in stem diameter variations (radial growth, water content) and plant water dynamics (sap flow, gas exchange) can be related to mechanisms controlling water and carbon balance and their seasonal variation (Fig. 10.4). In connecting different devices, computer-assisted continuous monitoring of individual trees is essential for the major facets of detection, prediction, and adaptation associated with climate change.

Environmental changes regulate ecosystem processes. Periodic, stochastic, and catastrophic variations in environmental conditions produce, respectively, stress, noise, and disturbance (Sabo and Post 2008). In response to environmental fluctuations, trees generate periodic signals that delineate the boundaries of normal operation. Outside the envelope of normal operation, functional processes in trees (e.g., water and sugar transport between plant organs) may collapse, leading to tree mortality. Sap flow gauges and dendrometers are tools that can be used to monitor the synchronicity of tree signals and environmental fluctuations (Cocozza et al. 2009), providing continuous information on hydraulic safety and carbon status.

Sap flow dynamics can be related to stem diameter variations, considering radial flow of water between xylem and phloem (Steppe et al. 2016). Radial water flow causes changes in stem water capacitance, highlighting functional links between phloem and xylem (Pfautsch et al. 2015), facilitated by wood anatomical traits (parenchyma cells). Complementary measurements of stem tissue moisture can be used to derive the relative water content (i.e., the difference between fresh weight and dry mass, divided by the difference between turgid weight and dry mass of the tissues), an indicator of water stress, which trees try to maintain as constant as possible or above species-specific irreversible thresholds of

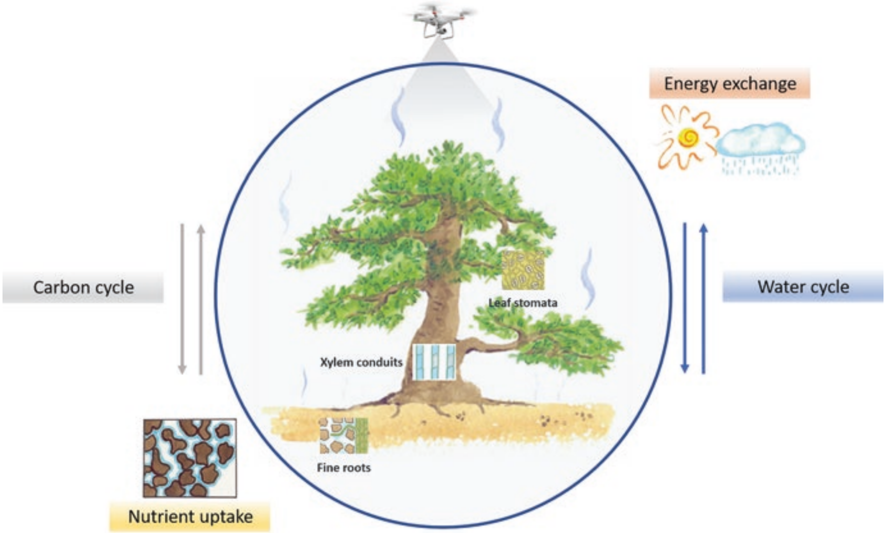

Fig. 10.4 The tree biogeophysical-chemical unit. Ecophysiological processes influence, over time and from tissue to tree level, biogeophysical processes (surface energy fluxes, the hydrologic cycle) and biogeochemical processes (the carbon cycle, the nutrient cycle), as well as biogeographical processes (land use, vegetation dynamics). Single-tree observation provides data for process integration at fine scales, while remote-sensing monitoring is important for scaling indicators to landscape levels. Unmanned aerial vehicles (UAVs, e.g., drones) equipped with miniaturized sensors may map landscape features at high spatial and temporal resolution. Imagery from UAVs may help derive tree growth and monitor forest health (e.g., healthy, dead, or stressed/infested trees)

dehydration (Martinez-Vilalta et al. 2019). Further, transportable computed tomography may represent a powerful tool for measuring density distributions and water contents in the xylem with high spatial resolution in the field (Raschi et al. 1995; Tognetti et al. 1996).

Spectral properties of leaves, based on reflectance-absorbance of light by pigments, may add information on the health status of the forest canopy (Rautiainen et al. 2018). Field spectroscopy provides a cost-effective and practical means to monitor forest functioning with a capacity to upscale to airborne and satellite imagery. Comparing measurements taken with below-canopy sensors, used to measure inside the forest, with reference sensors, located above the forest canopy, may help disentangle the seasonal contribution of understory vegetation to forest reflectance. While multispectral cameras can be used to derive plot-level spectral vegetation indices (SVIs) from discrete spectral wavelengths, hyperspectral analysis of leaf-level photosynthetic parameters has technical challenges (e.g., data storage, sensor availability).

Extensive within-canopy light gradients importantly affect the photosynthetic productivity of leaves in different canopy positions and lead to light-dependent increases in foliage photosynthetic capacity per area (Niinemets et al. 2015).

Within-canopy changes in leaf dry mass per unit area, leaf nitrogen content, and nitrogen partitioning among proteins of the photosynthetic machinery determine the within-canopy photosynthetic modifications. The sun-exposed upper-canopy leaves differ from the shaded lower-canopy leaves in their chlorophyll and nitrogen contents, relative water content, and specific leaf area, and these variations influence the foliar spectral reflectance. Since leaf traits and leaf reflectance co-vary across the canopy layers (Gara et al. 2018), leaf spectral reflectance can be valuable for monitoring the canopy level variation due to environmental stress and reflectance indices, such as the enhanced vegetation index (EVI), normalized difference vegetation index (NDVI), and, more recently, solar-induced fluorescence (SIF). These indices can be used for assessing the plant physiological status by proximal or remote sensing.

Proximal sensing (portable spectrometers and cameras mounted on mobile platforms, towers, or drones) provides validation for the large-scale air-/spaceborne remote sensing, taking advantage of variation in canopy reflectance (Gamon et al. 2019), though the spatial resolution can be too coarse for measuring photosynthetic capacity at the scale of individual leaves in small plots. Fractal analysis can be used to assess architectural complexity based on laser scanning data, providing a link between single-tree canopy attributes and plot-level structural complexity. Combination of structural data (e.g., proximal spectrometry) and ecophysiological measurements (e.g., sap flow) is a valid tool for scaling purposes. The positive relationships between the structural heterogeneity and complexity of forest stands and their functions and services provide a link between proximal spectrometry and forest management (Seidel et al. 2019).

10.4 Experimental Field Trials

It remains difficult to use discrete sampling strategies to address long-term response to multiple stress conditions, relationship between stress response and tree growth, and early detection of plant stress conditions. Understanding rapid changes in functional signals requires quantitative continuous monitoring of both plant physiology and environment conditions. Remote sensing techniques are low in spatial or temporal resolutions, or do not provide timely response to events that influence plant physiology. Therefore, sensors continuously monitoring physiological and environmental parameters (e.g., plant water status, soil moisture content, stem diameter variation, spectral reflectance properties), which are either fixed on plant organs with fixtures or placed in their close proximity, may allow communication with trees.

At heavily instrumented sites, field-portable instruments for analyzing stable isotope compositions may become useful for determining spatial patterns of root water extraction at varying soil depths with succeeding phenological stages (Liu et al. 2019), thus complementing plant transpiration measurements (Nadezhdina et al. 2010; Rothfuss and Javaux 2017). Canopy transpiration flux can be combined with water-use efficiency, as inferred from carbon isotope analysis, to infer gross primary productivity (GPP) of forest canopies (Klein et al. 2016; Vernay et al. 2020).

Continuous measurement of soil respiration can be coupled with chamber CO_2 measurement systems (Tang and Baldocchi 2005), as well as tree- and canopy-scale rates of CO_2 uptake derived by sap flow time series in combination with ^{13}C data, to determine temporal (and spatial) dynamics in autotrophic vs. heterotrophic respiration. Multispectral and/or hyperspectral imaging systems may provide for automated detection of living root dynamics (Bodner et al. 2018), though establishing a sensor network belowground requires considering trade-offs between expensive vs. low-cost multimodal minirhizotrons (Rahman et al. 2020). In this sense, preliminary work with GPR would gather initial imaging analysis of coarse root turnover (Stover et al. 2007), in order to integrate soil texture and soil microclimate (temperature, moisture) and contribute to determine the positions of soil sensor nodes in patchy forest stands (Rundel et al. 2009).

Although stands are the logical operational units for forestry, within-stand variability often hinders identification of the causal relation between mortality episodes and stochastic events (i.e., disturbances). Indeed, a comprehensive assessment of how natural disturbances determine the decline and death of individual trees across sites is still missing. We argue that high frequency and real-time sensor-based measurements of ecophysiological parameters in combination with long-term ecological and silvicultural field-scale studies would enhance our capacity to identify early warning signals in trees, preceding the occurrence of irreversible tree decline, and, thus, monitor forest dieback at sites that are distributed strategically across biogeographic regions. These networks should be able to characterize the spatial and temporal scales of disturbance events.

Observational studies and in situ experiments identify cause-effect relationships, which can be conveniently implemented in ecological syntheses and model exercises to understand interactions between global drivers and change processes. Yet, understanding how functional traits vary among genotypes (tree species or populations) and to what extent this variation has adaptive value is central to CSF. Long-term provenance field trials established in the twentieth century have been conducted to assess genetic diversity in forest tree species. Their coordination may become important in providing data to address climate- and disturbance-related questions for forest productivity and determine species or provenance adaptation to changing environmental conditions.

10.5 Networked Sensors and Wireless Communication at a Site

Low-power communication networks may support data transfer over large distances (kilometers) (Talla et al. 2017). Electro-biochemical devices may run on starch in plants, the most widely used energy storage compound in nature (Zhu et al. 2014).

Potentially, they contain an energy storage density of one order of magnitude higher than that of lithium-ion batteries. Microclimatic sensors can, therefore, be deployed in remote areas and receive continuous electricity supply from trees within dense canopies to run electronics for long-term sampling and monitoring, where solar power is not sufficient and other communication methods are not feasible (Allan et al. 2018). With Internet of things (IoT) technology, many of these networked devices can be connected wirelessly (e.g., temperature sensors, camera traps, and acoustic monitors) and, therefore, able to communicate with each other and transmit data to central nodes.

To reach the ambitious goal of introducing massive data observation and analysis, it is necessary to deploy a great number of specifically designed sensors, connect them in clouds in real time, and analyze the collected data by using big data analytics and machine learning algorithms. Deploying a standardized cybernetic web of specifically designed low-cost sensors will provide real-time access to environmental data from established forest research sites and help identify tree nonlinear responses beyond the safe operation mode (Fig. 10.1), as well as triggering thresholds. A critical feature of a network of sites that are digitally connected is the visualization of records and data storytelling to engage researchers, stakeholders, educators, and the public with climate-smart forests. However, wired systems are costly and energy-demanding, and their use in remote sites is limited (Torresan et al. 2021). Advancements in wireless communication and sensor technologies provide researchers with flexible and scalable tools to monitor smart forestry systems. Agrometeorological data by wireless technology has been implemented in climate-smart agriculture and integrated pest management (Asseng et al. 2016; Marchi et al. 2016), allowing for the control of farming operations based on spatial data (Kaivosoja et al. 2014).

Modern forestry needs to address questions on continuous monitoring and assessing of climate smartness in forests and the impact of disturbance, using the most recent tree-based tools and proximal sensing techniques, combined with field surveys. The complex terrain of mountain regions complicates the study of climate-related disturbances that challenge tree physiology and forest productivity. These forests show large variation in tree density, species composition, and carbon stocks that can hardly be derived from coarse-scale forest inventory and remote sensing (Pan et al. 2011). Rather, fine-scale measurements of ecophysiological traits on individual trees add to leaf- and landscape-level studies, integrating the texture for a comprehensive understanding of forest dynamics (Beer et al. 2010; Brown et al. 2016).

Effects of slope, aspect, and topographic complexity on shaping species-specific physiological responses of mountain forests to seasonal variation in air temperature and soil moisture can be better characterized through instrumented experimental plots. Indeed, mountain forests are subject to landscape-scale differences in soil structure, moisture availability, and energy input that do not apply to plant communities in flat terrain (Zapata-Rios et al. 2015; Wei et al. 2018). Recent development in flexible electronics, sensor designs, and wireless communications is leading to the development of a new generation of sensing devices (e.g., Zhao et al. 2019), which may further advance low-cost and low-power monitoring of microclimate and ecophysiological changes across diverse environmental conditions.

10.6 Measurement Harmonization, Data Integration, and Interoperability Across Sites

The tree-scale measurements emphasized here would be most valuable as part of a larger integrated network. Ground data can be conveniently coupled with standardized observations from highly instrumented research infrastructures. Research infrastructures of multisite networks may provide data on biogeochemical monitoring and allow us to envisage future trajectories of forest-climate relations (Vicca et al. 2018). For example, research infrastructures and networks, such as NEON (https://www.neonscience.org/), collect empirical data of carbon and water fluxes from forest stands and their response to environmental changes in different biogeographic regions (Hinckley et al. 2016; Richter et al. 2018).

Representative forest ecosystem sites can be part of a global Earth observatory, consisting of many well-equipped and similarly equipped ground stations around the world that track key ecosystems fully and continuously (Kulmala 2018). Observational data from these stations can be linked to remote sensing imagery, knowledge from laboratory experiments, and computer modelling simulations to create a coherent dataset, which can be explored in different directions and for specific purposes. Data or product users may include researchers, benefiting from a comprehensive dataset to explore new avenues in the analysis of forest ecosystem functionality and its feedback loops with climate. Other users might include the public and private sector interested in providing diagnostic products, such as early warning alerts for forest managers (e.g., forest fire risk, pest outbreak risk, tree mortality risk, etc.) or ecosystem service assessment for decision-making (payments for ecosystem services).

Such an observational system cannot operate effectively and efficiently without considering data quality standards along the whole pipeline, starting from instrumental measurements up to the processed outputs or products available for different user needs. First, instruments need to be calibrated and harmonized and measurement protocols standardized. Professional staff is needed to install and maintain the instrumentation at the sites, with less assistance required the higher the level of power autonomy, signal stability, and automation of the data collection and transmission. Data processing workflows need to be harmonized across the site network and require the implementation of a raw data quality control (QC) that arises from data quality assessment (QA) procedures agreed and adopted by research scientists operating in the same community. Quality control steps include, for instance, data timestamp verification, elimination of duplicated records, and signal despiking. Obtained raw data time series should, when necessary, be converted to standard physical variables, or further post-processed to produce standard variables, parameters, and indicators of interest. This last set of operations is fundamental to guarantee consistency in the scientific data output across the monitoring network; they underpin data interoperability, defined as the possibility of readily connecting different databases on separate hardware/software systems, and perform data retrieval, analysis, and other applications without regard to the boundaries between the systems (National Research Council 1995).

In an extended forest ecosystem monitoring framework, reducing semantic differences between data from disparate sources (naming conventions, fundamental differences in temporal and spatial scale) means approaching the full interoperability among ground-based monitoring datasets and between these and gridded products (remote and proximal sensing, model simulations). However, differences in technical details at software or hardware level, such as communication protocols and ways of structuring and indexing databases, may hamper the way forward. If, on the one hand, spatial and temporal aggregation of tree-level data into larger scales would allow the comparison with variables typical of forest plot- or catchment-scale observations, information at the original and finest level of detail should be archived and available.

Accessing site information at the single tree scale, including accurate georeferencing of observations, can be fundamental to support climate-smart precision forestry. Yet, the importance of archiving data, as retrieved from the source, lies in the possibility of reprocessing datasets whenever methodological updates are required or a different output standard is chosen to improve data interoperability. Accessing primary data would also give the possibility to scientists to analyze data and develop new products that flow along the virtual line connecting the monitored ecosystem sites to the archives and data users, thus generating more trust about the reliability and utility of the data. It is worth noting that these issues have previously been dealt with by the remote sensing and eddy flux communities.

Comparing functional traits among sites remains challenging due to the large variability in environmental conditions (soil, microclimate, topography, etc.) that modify resource availability (e.g., soil pH, species mixture, terrain slope) and due to species-specific strategies of resource acquisition (e.g., root depths, leaf traits). Integrating field measurements and model representations is not a straightforward exercise (Vicca et al. 2018), though important for understanding processes that occur at various spatial and temporal scales. Nonetheless, the simultaneous measurement of key physiological traits with resource availability indicators may help reduce the caveats associated with any single measurement. Improved capability to record slow and subtle physiological changes and plant-environment interactions is particularly important when comparing stress resilience within and among sites toward an integrated impact assessment of stress events.

A cybernetic web of trees monitors the response of forests to environmental change in near real time. This requires that the data collected by environmental sensors from core sites should be transmitted through wireless technologies (Wi-Fi, LoRa) to a single data concentration point from which collected records are, in turn, transmitted to a data archive (server) through the Internet. These sites should be distributed strategically across major biogeographic regions and forest types. Such a technological platform may combine high-frequency (seconds to days) sensor-based monitoring (e.g., physiological processes) with middle-frequency (weeks to seasons) stand-scale observations and more traditional low-frequency (annual to decadal) forest-level mensuration, in order to respond rapidly to environmental changes and monitor long-term ecological processes.

Studying ecophysiological responses of forest trees enables the prediction of thresholds and, therefore, when changes can be expected in the functioning of individual trees and forest stands. For example, scaling up to stand-level transpiration from measurements on individual trees can be difficult due to errors related to intrinsic wood properties and method characteristics (Vandegehuchte and Steppe 2013; Poyatos et al. 2016; Flo et al. 2019). Scale-up steps from tree to plot level include selecting representative trees for stem diameter classes (depending on the general research objective and species mixture), measuring sapwood area and sap flow radial profiles, quantifying transpiration for all trees in the plot expressed per unit leaf area, and gap-filling data (Ford et al. 2007). Transpiration of the whole stand can then be derived by estimating sapwood area from the diameter distribution of the stand.

Advances in information technology and electronic engineering have prompted the development of smart sensor networks to address complex ecological questions. The proliferation of digital devices allows the creation of cybernetic infrastructures of highly instrumented sites, with advanced storage capacity, data handling, and processing tools, even in mountain environments. Computerized monitoring units can capture and remotely transmit continuous data from a forest site to a remote server over long periods (Sethi et al. 2018). In CSF, a wireless monitoring system is envisaged to obtain field ecological parameters and provide disturbance-related early warning signals in real time. However, autonomous systems for acquiring data should not have high unit costs (Aide et al. 2013) or require complex communication systems (Saito et al. 2015). A new generation of sensors is now accessible for collecting and transmitting physiological data to control units in real time, from an integrated research and monitoring climate-smart forest network, in order to assess tree and forest functionality. A cybernetic web of instrumented trees may provide data on environmental change and alerts at a critical value. In this context, each monitoring unit uploads data from a mobile network of capturing sensors and conveys information for processing and displaying (Fig. 10.5).

Modular multifunctional devices can be developed for the real-time monitoring of tree physiology. An example is represented by the TreeTalker device (Valentini et al. 2019), which measures plant water transport, stem radial fluctuations, leaf spectral characteristics, stem moisture content, tree stem tilting, and environmental microclimatic parameters. It is intended to be deployed on tree clusters and transmit data using IoT technologies, providing cost-effective data. The low-power requirements of the devices are met by high-efficiency batteries and embedded solar panels, which confer power autonomy to the system and allow its deployment in remote and off-grid areas, reducing the need for frequent system maintenance and maintaining the operativity of all the sensors. A large-scale, single-tree, high-frequency, and long-term monitoring network of ecophysiological parameters is represented

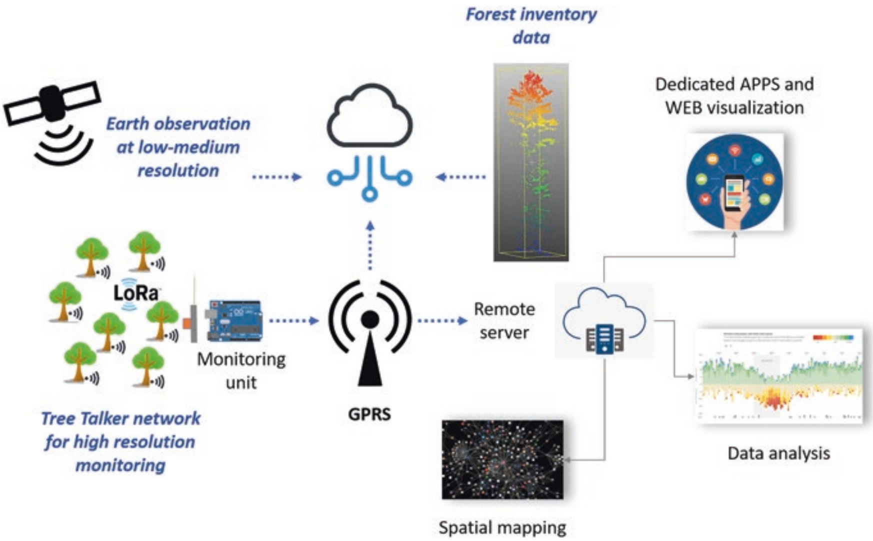

Fig. 10.5 The cybernetic web of modular multifunctional devices (the biogeochemical unit) includes nodes: (**a**) a common suite of low-cost sensors for biological, physical, and chemical measurements, (**b**) real-time data delivery to a single web access point, and (**c**) interactive data visualization and content for scientists, educators, and the public. This networked device allows for data acquisition, processing, and management. Data collected by the device platform and transferred to the cloud can be combined with earth observation datasets and/or forest inventory data. With cyberinfrastructures, near real-time access to all data streams from sensor networks is possible. Therefore, instrument failures, power interruptions, and calibration errors can be quickly identified and corrected, minimizing major data gaps

by forest monitoring research projects in several countries, including China, Italy, Russia, and Spain (Valentini et al. 2019). Based on this example of integrated device technology, a set of variables for identifying drivers of physiological disturbance and a list of measurements and tools for collecting data from experimental forest stands can be outlined (Table 10.2) (other variables can be included to merge diverse approaches). This integrated framework of structural and functional components at monitoring sites is intended to describe the health status of a forest and may feed into climate-smart forest indicators.

Major limitations to continuous monitoring of tree physiological functions are generated by the elevated costs of multi-sensor devices, which are usually energy- and labor-demanding. Current tree monitoring refers to limited sets of devices and trees and/or campaigns in space and time. The TreeTalker network represents a large-scale monitoring system of individual trees in forest plots distributed across a latitudinal gradient. This approach takes advantage of the IoT cyber ecosystem of interconnected sensors and the radio LoRa protocols for data transmission and access to cloud services. The duration of the measurement periods of variables, the acquisition intervals of data, and the frequency of data transmission are customizable, allowing flexible instrument configuration, depending on specific monitoring

Table 10.2 Measurement variables, sensors, and methods for in situ monitoring of climate-smart forest status, considering the stand-level structures and processes and their components

Climate-smart forest	Static and dynamic components	Measurement variables	In situ sensors and methods
Forest structures	Stand heterogeneity	*Canopy height*	Forest inventory, TLS
		Crown depth	Forest inventory, TLS
		Tree height	Forest inventory, TLS
		DBH and basal area	Forest inventory, TLS
		Species composition	LiDAR and spectral data
		Tree density	Survey, TLS
		Canopy gaps, crown transparency	Survey, TLS, spectral reflectance
	Biotic diversity	*Microhabitats*	Survey, TLS
		Land cover	ULS
		Species diversity	TLS, survey
		Saproxylic insects	Traps and analysis
		Saproxylic fungi	Survey and analysis
		Lichens	Survey and analysis
		Vertebrates	Counts, camera traps, GPS telemetry
Forest processes	Energy budget	*Solar radiation*	Pyranometer, light meters
		Albedo	Pyranometer, light meters
		Soil heat flux	Heat flux plate, distributed temperature sensors
		CO_2 *and* H_2O *atmospheric concentrations*	Portable GHG gas analyzer
		Latent and sensible heat fluxes	Modeling and land surface temperatures
		LAI	Plant canopy analyzer
		Leaf temperature	Thermal resistance, thermocouple, infrared thermal imaging (TIR)
	Water budget	*Precipitation, wind, evaporation, temperature, humidity, snow depth*	Pluviometer, anemometer, thermometer, hygrometer, optical sensor
		Transpiration	Sap flow meter
		Throughfall and stemflow	Collectors and samplers
		VPD	Multiparameter probes
		Soil moisture	TDR, electrical capacitance, gamma attenuation
		Soil texture and depth	Shortwave infrared reflectance, ground-penetrating radar (GPR)
		Leaf spectral properties	Spectroradiometer

(continued)

Table 10.2 (continued)

Climate-smart forest	Static and dynamic components	Measurement variables	In situ sensors and methods
	Carbon cycle	*GPP*	Sap flow and stable isotopes (GPP=WUEi*gs)
		Respiration	CO2 flux system
		NPP, aboveground and belowground	Dendrometers, dendrochronology, minirhizotrons, GPR
		SOC	Spectroscopy
		Soil CO_2 flux	CO_2 flux system
		Photosynthesis	CO_2 and H2O flux system, stable isotopes
		Deadwood	Survey, TLS
	Nutrient cycling	*Atmospheric deposition*	Deposition samplers and analysis
		Nutrient uptake	Hyperspectral vegetation indexes, stable isotope labeling
		Soil organic matter	Spectroscopy
		Decomposition and mineralization	Litter bags
		Nitrates and phosphorus	Nitrate and phosphorus sensors
		Litter production	Litter traps
		Soil solution chemistry	Soil solution samplers and analysis

requirements and expected power autonomy. Each single device includes a set of low-cost sensors capable of monitoring tree functions continuously: (1) tree radial growth, as indicator of photosynthetic carbon allocation in biomass; (2) sap flow, as indicator of tree transpiration and functionality of xylem transport; (3) stem wood temperature and xylem water content, as indicators of heat storage and water status of the plant; (4) light penetration through the canopy, as indicator of absorbed radiation fraction; (5) light spectral components, as related to foliage dieback, phenology, and physiology; (6) plant stability (angular deviation of the trunk from the normal along three coordinate axes), related to tree stem tilting, as a result of the momentum exerted by wind on tree canopies and estimated using an automatic accelerometer (gyroscopic sensor); and (7) air temperature and relative humidity in the proximity of the tree trunk, at device installation height (typically 1.3 m), as indicator of tree surrounding microclimate. Each tree can transmit high-frequency data on the web cloud with a unique IoT identifier. This networked device deploys a range of digital sensors, featuring continuous operability and automatic transmission of real-time monitoring data, which provides the basis for translating functional variables into decision support indicators and new research questions (Bayne et al. 2017; Subashini et al. 2018; Valentini et al. 2019).

10.7 Strengths and Limitations

Deploying a standardized cybernetic web of specifically designed low-cost sensors may provide real-time access to environmental data from established forest research sites and help detect nonlinear responses beyond the safe operation mode. Multifunctional devices, based on IoT systems, for the real-time observation of physical and biological parameters of trees can be considered a solution to provide efficient monitoring of forest health. In addition, with the increasing amount of data captured during forest surveys, monitoring systems are becoming important factors in decision-making for management. Modular multifunctional devices allow for long-term (months to years) data collection and observation of a single stand or multiple stands. The distributed nature of a wireless sensor network combined with the spatial resolution of remote sensing data will let a large forest area of study to be monitored in sufficient detail to offer new insights into functional traits and ecosystem services. Spatial links between the data at different scales, stand to landscape, will support researchers in increasing the spatial extent of datasets and performing spatially explicit analyses and predictions. New opportunities emerge to scale up ecological information about the tree-environment interactions at a fine scale, promoting knowledge of forest responses to climate change over coarse scale. Obviously, new technologies come with trade-offs, and integration with traditional inventory data collection is advised when planning forest surveys and monitoring campaigns. Proliferation of digital tools and technologized forest also have political and social impacts that need to be considered (Gabrys 2020). Indeed, forests provide key products and services and are crucial to mitigate global change, contributing to biogeochemical cycles and species diversity. However, though halting deforestation and contributing to reforestation are key to meet international goals (Griscom et al. 2017), climate benefits from carbon sequestration can be offset by environmental disturbances, which are also increasing.

Recent technological advances in instrumentation for measuring physiological ecology variables at experimental sites allow merging information into monitoring data collected in other research infrastructures (Haase et al. 2018). Though sites may differ in the temporal and spatial resolution of instrumentation and in the research questions addressed, modular research platforms may form a multilevel system of distributed monitoring sites, integrating site-specific data source and environmental stratification. Examples of initiatives that have been developed to watch trees grow and function in real time include TreeWatch.net (https://treewatch.net/) and TreeNet (https://treenet.info/) monitoring and modeling networks (Steppe et al. 2016; Zweifel et al. 2016). A global compilation of whole-plant transpiration data from sap flow measurements has been presented by Poyatos et al. (2020), with the aim of harmonizing individual datasets supplied by contributors worldwide (SAPFLUXNET), including subdaily time series of sap flow and ancillary data (https://sapfluxnet.creaf.cat/). Distributed research infrastructures, such as ICOS (https://www.icos-ri.eu/) and FLUXNET (https://fluxnet.fluxdata.org/), generate data and integrate knowledge on biogeochemical cycles and of their perturbations with high operating costs and complex instrumentations (Franz et al. 2018; Rebmann et al. 2018). The TRY database of plant traits (https://www.try-db.org) aims to improve the availability and accessibility of plant trait data for ecology and earth system sciences (Kattge et al. 2020). In this context, selection of key variables documenting early warning signals for critical forest status in highly instrumented sites (tree mortality, biodiversity change) would provide useful directions. Research integration will allow us to better understand the factors driving changes in species diversity, the effects of extreme events on tree productivity, the impacts of disturbances on forest function, and the interactions between short- and long-term trends. Data integration will also facilitate upscaling measurements from local conditions to addressing challenges from global objectives (Fig. 10.6).

The close link between physical properties of the forest canopy (e.g., leaf surface temperature, leaf pigment absorption, chlorophyll fluorescence emission, latent heat flux, etc.) with plant functioning opens a wide range of applications and methods to monitor forest health remotely. However, remote sensing methods may lack adequate resolution for application at the range edge of species distribution. Similarly, the eddy covariance method measures the net effects of a forest upwind of the sensor, ignoring individual trees or species within the stand. These methods are, therefore, unsuited to detect early signs of ecophysiological stress when the functional response of trees differs among ages or species, leading to a compensatory effect at the stand level. Since CSF has the ambition to tailor adaptive silviculture to ensure the resilience of individual trees and species, a more highly resolved

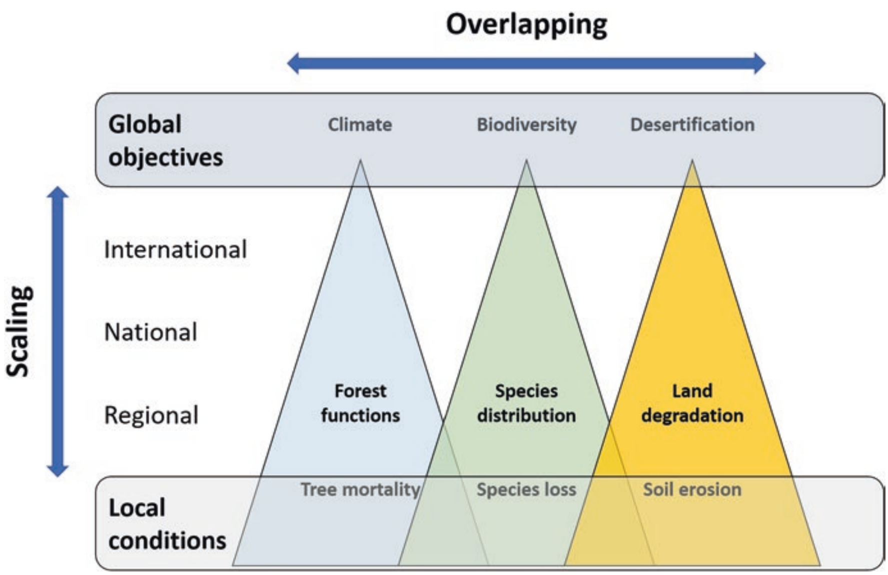

Fig. 10.6 Translation from local conditions (stand-based measurements) to global objectives (global convention requirements) should account for trade-offs and synergies between forest capacity to store carbon, adapt to climate change, and provide products and services

diagnosis of tree decline/mortality is needed. Indeed, risk assessments (diagnosis) and optimal treatments (therapy) require individualized analysis for individual trees exposed to multiple stresses. Effective monitoring of tree responses to environmental disturbance in marginal regions (e.g., mountain areas, range edges) is of critical importance in order to predict and manage threats to tree populations. Therefore, combining remote sensing observations with ground-based methods can be the most effective means of monitoring resilience and vulnerability of forest trees and ecosystems. Stand-based networks committed to long-term monitoring may provide representative datasets (e.g., tree biomass, tree mortality), which become useful for validation of forest modeling exercises and remote sensing missions (Chave et al. 2019). In this context, forest inventories and terrestrial laser scanning (TLS) surveys may contribute with accurate measurements of individual tree traits (e.g., volume, height, allometry, etc.) and forest stand structure, for modelling purposes (Calders et al. 2018). Detailed datasets of 3D vegetation structure from below (Kunz et al. 2019), provided by TLS, can be used for assessing canopy space filling, detecting leaf flush, monitoring tree growth, and deriving microclimate at plot scale. Therefore, information provided by TLS at the stand level may link ground-based measurements and integrate forest structural changes mapped by airborne laser scanning (ALS) from above (Marvin et al. 2016).

Wireless sensor network approach has only recently become cost-effective because of the availability of simple, inexpensive devices. But it also depends on a common, convenient platform for data processing and visualization. Such a platform would ease the use of data for storytelling aimed to engage researchers, stakeholders, educators, and the public with climate-smart forests. We propose using tree-based tools, proximal sensing techniques, and networking tools and coupling them to traditional field surveys and remote sensing in order to address the data needs of continuous monitoring and assessment of climate smartness and the impact of disturbance.

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