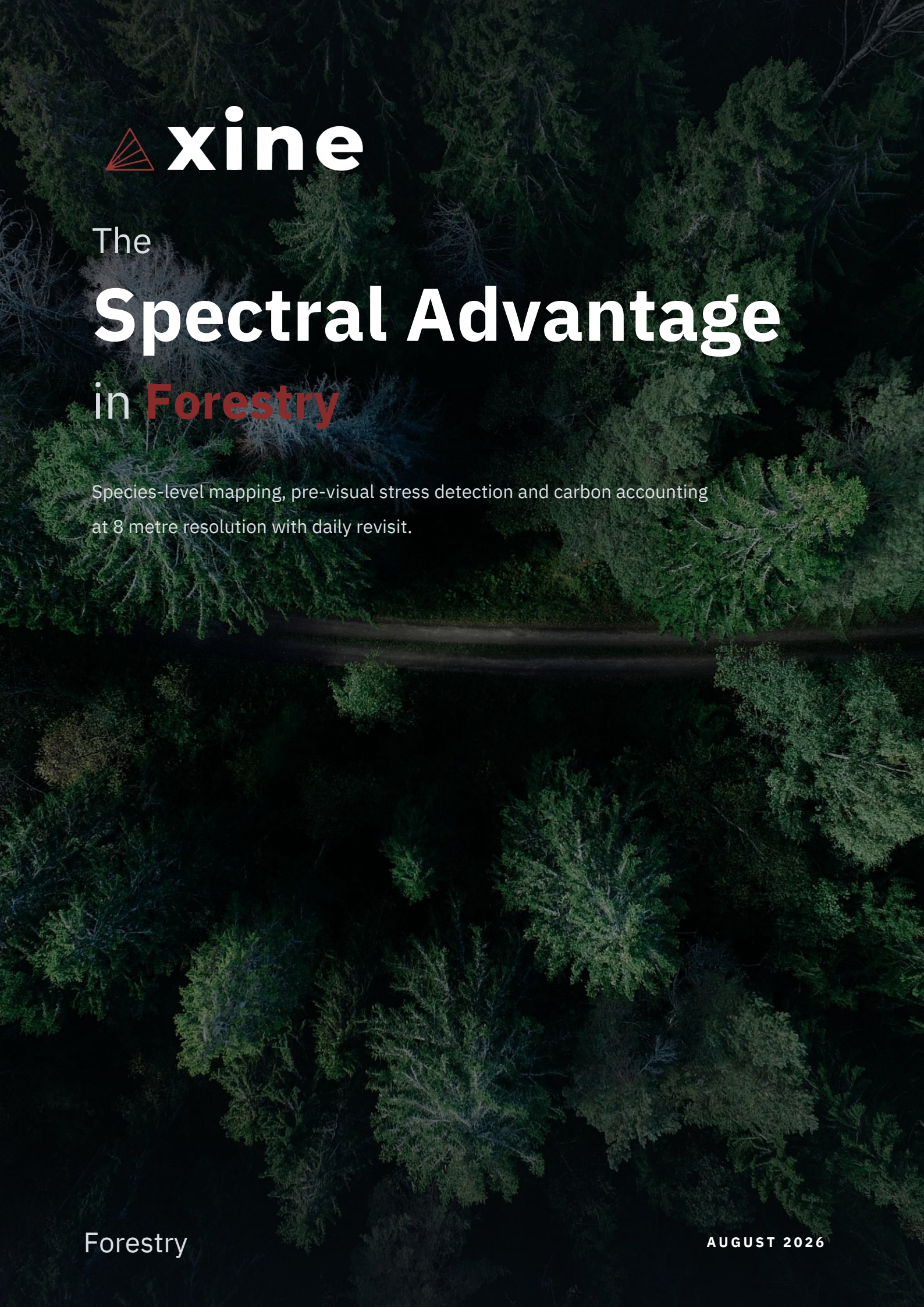

xine

The Spectral Advantage in Forestry

Species-level mapping, pre-visual stress detection and carbon accounting at 8 metre resolution with daily revisit.

Forestry

AUGUST 2026

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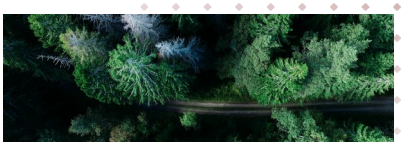
Introduction



This paper sets out how hyperspectral imaging supports forest management, and how Axine Laboratories applies satellite spectroscopy to species composition mapping, pre-visual stress and pest detection, fire risk assessment and carbon accounting. It is written for forest managers, inventory and planning teams, conservation agencies and organisations carrying deforestation-free supply chain or carbon reporting obligations.

Mist over mixed stands on a slope. Cloud and haze are screened rather than interpolated, which is why revisit frequency matters more to a forest programme than the quality of any single acquisition.

Motivation: forests under pressure, measured too rarely

The world holds 4.14 billion hectares of forest, about 32 per cent of the land surface. Deforestation has slowed, from 17.6 million hectares a year in the 1990s to 10.9 million hectares a year between 2015 and 2025, but 489 million hectares have been lost since 1990, nearly 88 per cent of it in the tropics, and forest fires affect an average of 261 million hectares annually[1]. The pressures are not diminishing; the measurement of them has simply improved faster than the outcomes.

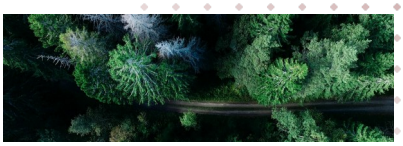
Biotic disturbance has moved from a background factor to a first-order commercial risk. The 2018 drought in Central Europe triggered bark beetle outbreaks that destroyed roughly 40 million cubic metres of timber in that year alone[2], and the outbreak that followed in Sweden killed some 17 million cubic metres of spruce over the two subsequent years[3]. Czechia extracted more than 5.6 million cubic metres of infested spruce in 2022 alone[4]. These are events where the interval between the onset of infestation and the loss of merchantable value is measured in weeks.

The reporting obligations have tightened in parallel. The EU Deforestation Regulation entered into force in June 2023 and applies from 30 December 2026 for large and medium operators, and from

30 June 2027 for smaller enterprises. It requires plot-level geolocation, with a boundary polygon for any production area above four hectares, and evidence that the commodity was not produced on land deforested or degraded after 31 December 2020[5]. Compliance rests on being able to demonstrate, plot by plot, what the land cover was and what it has become.

Conventional forest assessment cannot meet that demand at that cadence. Inventory plots, aerial survey and ground cruising deliver excellent information about a small sample and nothing about the rest of the estate, and the interval between assessments is usually measured in years. Satellite hyperspectral imaging measures the biochemical state of the canopy directly, across whole estates and concessions, on a schedule set by orbital revisit.

What is hyperspectral imaging?



A leaf is a chemical assembly, and its reflectance spectrum records that chemistry. Chlorophyll absorbs strongly in the blue and red and weakly in the green. Carotenoids and anthocyanins, which accumulate as a plant responds to stress, absorb in narrow regions of the visible spectrum. Water in leaf tissue absorbs in the short-wave infrared. Lignin and cellulose absorb in the same region with different feature positions. Between the red and the near infrared sits the red edge, the steep rise in reflectance whose exact position shifts with chlorophyll concentration and canopy structure.

A riparian corridor from above. Species composition, canopy condition and the width of the retained buffer are all read from the same acquisition, in bands narrow enough to tell them apart.

Those features are the basis of everything in this paper. A tree under stress alters its pigment balance and its water status before it changes colour to the human eye, and those alterations are measurable as shifts of a few nanometres in feature position and a few per cent in feature depth. Resolving them requires bands narrower than the shifts themselves.

A comparison of RGB, multispectral and hyperspectral imagery.

Type	Number of bands	Bandwidth (FWHM)	Wavelength range
RGB	3	~50-70 nm	450-700 nm
Multispectral	4-20	~15-35 nm	400-2350 nm, discontinuous
Hyperspectral	100-500+	Under 10 nm	400-2500 nm, contiguous

The operational consequence is the difference between condition and cause. A broadband vegetation index reports that a stand is less vigorous than it was. It cannot separate drought stress from nutrient deficiency from early infestation, because all three depress the same index. Narrowband pigment indices respond differently to each, and the combination of several such indices is what allows a stress signal to be attributed rather than merely observed.

The tasked acquisition tier

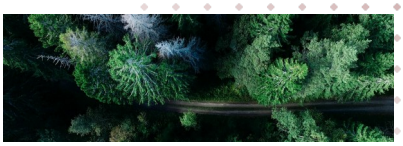
For operational monitoring, Axine acquires imagery from a commercial hyperspectral constellation of six identical microsatellites offering:

+ 472 contiguous spectral bands across the full visible to short-wave infrared range, 400 to 2500 nm, covering the pigment, water, lignin and cellulose features together.
+ 8 metre ground sample distance in the hyperspectral channels, the finest commercially available hyperspectral resolution currently in orbit.
+ 3 metre panchromatic imagery co-acquired for spatial context and stand boundary definition.
+ Revisit of up to daily for most locations worldwide, with directed tasking over a specified estate or concession.

Resolution determines the unit of management the imagery can address. At 30 metres a pixel spans a substantial part of a stand and averages healthy and infested crowns together, which is precisely the averaging that hides an outbreak in its early phase. At 8 metres a pixel approaches the scale of a mature crown group, so an infestation focus of a few dozen trees registers as a coherent anomaly rather than as a marginal shift in a stand average.

Revisit determines whether detection arrives in time to act. Green-attack infestation progresses over weeks. A sixteen day repeat cycle with cloud losses can miss the window entirely; daily tasking availability does not.

Challenges in forest management



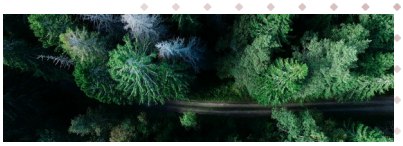
Forest managers are being asked to characterise larger estates, in more detail, against more reporting frameworks, on inventory cycles designed for a slower-moving world. The constraints below are the ones satellite spectroscopy is well positioned to relieve.

Steep, dissected ground. Terrain like this bounds what a ground crew can survey in a season, and it is exactly where wall-to-wall coverage earns its place in the programme.

+ **Assessment cadence:** Ground cruising and aerial survey are expensive, slow and dependent on specialist personnel, which in practice limits comprehensive assessment to intervals of several years. Much of what a manager needs to know changes faster than that.
+ **Detection after the fact:** By the time an infestation is visible from the air, the affected timber has usually lost most of its value and the beetle generation responsible has already dispersed. The operational window sits earlier than conventional detection reaches.
+ **Species composition and risk concentration:** Monoculture plantations concentrate risk. A single-species estate is a single-pathogen estate, and the case for diversification is difficult to make without a species map to argue from.
+ **Invasive species establishment:** Invasive plants and pests establish at small scale and expand quickly, and the early phase, when control is still affordable, is also the phase that is hardest to survey for.
+ **Fire risk assessment:** Fire risk is a function of fuel load, fuel moisture and continuity, none of which appear in a stand register and all of which change through a season.
+ **Verifiable reporting:** Carbon crediting, deforestation-free supply chain rules and sustainability reporting all require plot-level, time-stamped, independently verifiable evidence rather than sampled estimates carried forward.

+ **Enforcement coverage:** Illegal harvesting and unauthorised clearing occur where enforcement presence is thinnest, which is also where conventional monitoring coverage is weakest.

Hyperspectral imagery in action



Across forested landscapes, hyperspectral imagery supports three fundamental capabilities.

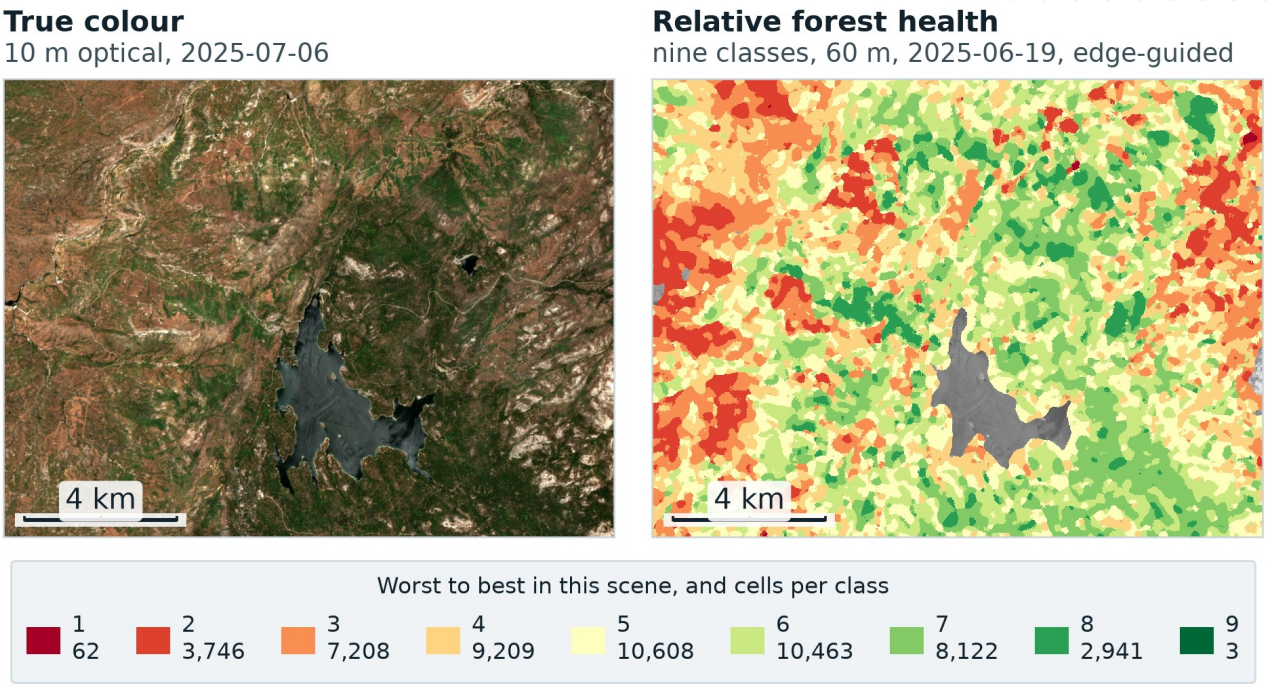
+ **Detection:** Identifying stress, disturbance, disease, invasive establishment and clearing across the full extent of an estate, including stands that have never been walked.
+ **Classification:** Distinguishing tree species and species groups, separating stress causes from one another, and categorising disturbance by type.
+ **Quantification:** Measuring pigment concentration, canopy water content, biomass and burn severity, and tracking how each changes between acquisitions.

Axine computes a narrowband index pack developed specifically for forest condition. These are established indices with published formulations, computed here at full spectral resolution rather than approximated from broad bands.

Narrowband forestry index pack, wavelengths and purpose.

Index	Wavelengths (nm)	Purpose
MCARI	550, 670, 700	Chlorophyll absorption ratio; canopy productivity
MCARI2	550, 670, 800	Stress detection with reduced soil background influence
TCARI	550, 670, 700	Leaf chlorophyll content
NDVI705	705, 750	Red edge vegetation health, sensitive at high biomass
Vogelmann 1	720, 740	Stress and chlorophyll status
Vogelmann 2	715, 726, 734, 747	Vegetation type and health differentiation
ARI1 and ARI2	550, 700, 800	Anthocyanin content; stress response indicator
CRI1 and CRI2	510, 550, 700	Carotenoid content; pigment status under stress
PSRI	500, 678, 750	Senescence and canopy stress
RGRI	Red and green means	Water stress and light use efficiency
NDMI and MSI	820, 1600	Canopy water content and fuel moisture
NBR and dNBR	820, 880, 2080, 2350	Burn severity and pre- to post-fire change

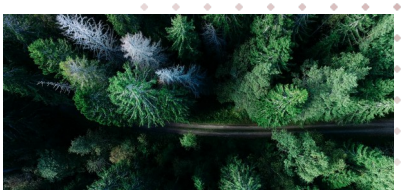
Axine layers are released progressively and each carries an explicit validation posture, described in section 8.



The score is RELATIVE to this scene: 9 is the healthiest ground in this image, not healthy in absolute terms, and it cannot be compared between scenes or dates. The weights are editorial. Because the score is a weighted mean of uniform ranks it concentrates near the middle, so the end classes are rare by construction, not by finding: 224 pixels in class 1 and 4 in class 9 of 107,915 vegetated. Masked to NDVI above 0.3, or granite and water would take the bottom bins and compress the forest into a narrow part of the scale. The 10 m detail is a categorical edge guide: each class is upsampled as its own indicator and the winner taken, so no pixel is given a class the 60 m measurement did not contain.

Figure 1 — *A forest estate in true colour, beside a nine-class relative health composite over the same ground. The score ranks this scene against itself — class 9 is the healthiest ground in this image, not healthy in absolute terms — and it does not carry between scenes or between dates.*

Hyperspectral versus multispectral imaging in forestry

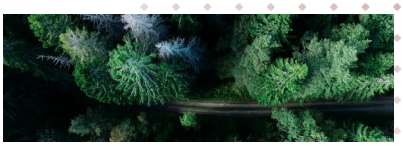


Multispectral imagery underpins most operational forest monitoring and does so effectively for extent, gross change and broad vigour. Hyperspectral imagery extends that basis into species and condition discrimination, because separating pigments and species requires bands narrower than the features that distinguish them.

Parameter	Multispectral imaging	Hyperspectral imaging
Forest extent and cover	Reliable land cover classification	Equivalent, with species composition attached
Species classification	Broad forest type	Species-level discrimination, including within closed canopy
Stress detection	General vigour decline once established	Pre-visual stress through narrowband pigment response
Stress attribution	Not resolvable	Drought, nutrient and biotic stress differentiated by index combination
Disease and pest	Visible mortality	Early-stage infestation detectable before crown discolouration
Invasive species	Large infestations	Species-specific detection at smaller extent
Biomass and carbon	Structural proxies and indices	Canopy biochemistry contributing to plant functional type and density
Fire risk	Land cover fuel classes	Fuel moisture and dry matter mapped directly
Spatial detail	10-30 m typical	8 m, approaching crown group scale
Revisit	Fixed orbital schedule	Directed tasking, up to daily for most locations

The distinction is a matter of physics rather than vendor preference: pigment and species discrimination require narrow contiguous bands, and narrow contiguous bands are what defines a hyperspectral sensor.

The Axine analytical method



Reflectance and screening

Imagery is ingested from any supported sensor and reduced to surface reflectance. Cloud, cloud shadow, terrain shadow and non-forest cover are screened, and screened ground is reported explicitly as not evaluated rather than as unchanged. On steep terrain, illumination correction is applied before any index is computed, because an uncorrected slope produces a vigour gradient that has nothing to do with the trees.

Narrowband index computation

The index pack is computed at native spectral resolution, resolving bands by wavelength rather than by band number, so the same definitions apply across every supported sensor. Every ratio-based layer carries a validity floor, so that unwritten or near-zero cells cannot divide out into apparent maximum readings.

Forest health composite

Individual indices are combined into a single interpretable health score on a one to nine scale, weighted across pigment, red edge and canopy water inputs. The weighting is an editorial judgement rather than a physical constant, and the platform states as much on the layer, with the contributing indices always available underneath so that a forester can see what drove a score.

Pre-visual stress detection

Early infestation is detected as a departure in narrowband chlorophyll and pigment response across roughly 450 to 890 nm, combined with canopy water indicators, measured against the expected response for that species at that point in the season. Anomaly against an expected spectral state is what separates early infestation from ordinary phenological variation, and it is why a phenology-indexed reference matters as much as the detection algorithm.

Species classification

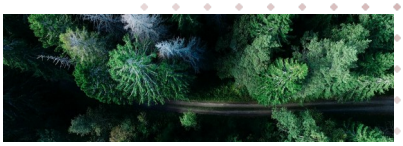
Species and species-group classification operates on full spectra rather than on a handful of bands, which is what permits discrimination between spectrally similar species from a single acquisition rather than from a multi-date phenological time series. Classification is calibrated per region against forest inventory data, and reports per-pixel confidence alongside the class.

Change detection and time series

Repeat acquisitions are differenced against a baseline within an estate or compartment boundary, producing trajectories per stand. Burn severity is computed as pre- to post-fire index change,

clearing is detected as abrupt cover transition, and regrowth is tracked as recovery against the pre-disturbance state.

Use cases in forest management



An air tanker over a running fire. Fuel condition and moisture stress are measurable across a whole estate before the season starts, which is a different problem from watching a fire once it is alight.

Forest health and pest management

+ **Early bark beetle detection:** Detection of infestation during the green-attack phase, before crowns discolour, when sanitation felling still removes the beetle generation and recovers merchantable timber. This is the application where the value of spectral detection over visual detection is largest and most directly measurable in revenue.
+ **Disease detection:** Anomalies in canopy reflectance consistent with pathogen infection, supporting proactive management before symptoms spread through a stand.
+ **Invasive species:** Species-specific detection of invasive plants, particularly relevant where commercial plantations adjoin natural forest and where machinery and planting stock provide introduction pathways.
+ **Estate-wide health composite:** A single interpretable score across an entire estate, giving managers a triage layer that directs inspection effort to the stands that warrant it.

Inventory and composition

+ **Species classification:** Species and species-group mapping across an estate from a single acquisition, including within closed and mixed canopy where crown-level discrimination is otherwise difficult.
+ **Diversity assessment:** Composition mapped against concrete diversity rules, including the Santamour 10-20-30 guideline of no more than 10 per cent of any one species, 20 per cent of any one genus and 30 per cent of any one family, turning a planting principle into a measurable compliance check.

+ **Stand characterisation:** Canopy density, stand condition and structural variation characterised across compartments, supporting thinning, harvest scheduling and yield planning.

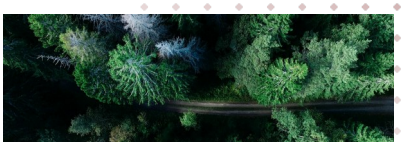
Fire management

+ **Fuel moisture and fire risk:** Canopy and surface water content mapped through short-wave infrared indices, identifying the dry fuel accumulations that determine where a fire will run.
+ **Burn severity mapping:** Pre- and post-fire index differencing across the burn perimeter, producing a severity surface rather than a burned or unburned boundary.
+ **Salvage assessment:** Assessment of surviving timber and its condition following a fire, supporting salvage decisions while the timber retains value.
+ **Regeneration monitoring:** Recovery tracked against the pre-fire baseline, providing evidence of natural regeneration and of the effectiveness of replanting.

Carbon, compliance and enforcement

+ **Above-ground biomass:** Canopy biochemistry contributing to biomass and carbon stock estimation, supporting carbon project reporting and national inventory contributions.
+ **Deforestation-free verification:** Plot-level land cover state and change against a fixed reference date, addressing the geolocation and deforestation-free evidence requirements that supply chain regulation now imposes.
+ **Illegal logging and clearing:** Detection of clearing, road building and canopy opening across concessions and protected areas, including in ground where enforcement presence is limited.
+ **Restoration monitoring:** Survival, growth and species composition of planted areas tracked against establishment targets, providing objective evidence of restoration outcomes rather than planting inputs.

Validation and confidence



Axine treats validation as a product feature. Every analytical layer carries a stated validation posture, and every performance figure we publish is traceable to a documented test against an independent reference.

Validation posture on every layer

Each layer renders with an explicit posture: calibrated region, validated region, or screening. Deterministic index mathematics quotes no accuracy figure because none is claimed for it. Classified and learned products quote accuracy where they have been tested against ground truth for that region and forest type, and ship as screening elsewhere with the reason stated. A client always knows which of the three they are looking at.

Reference data

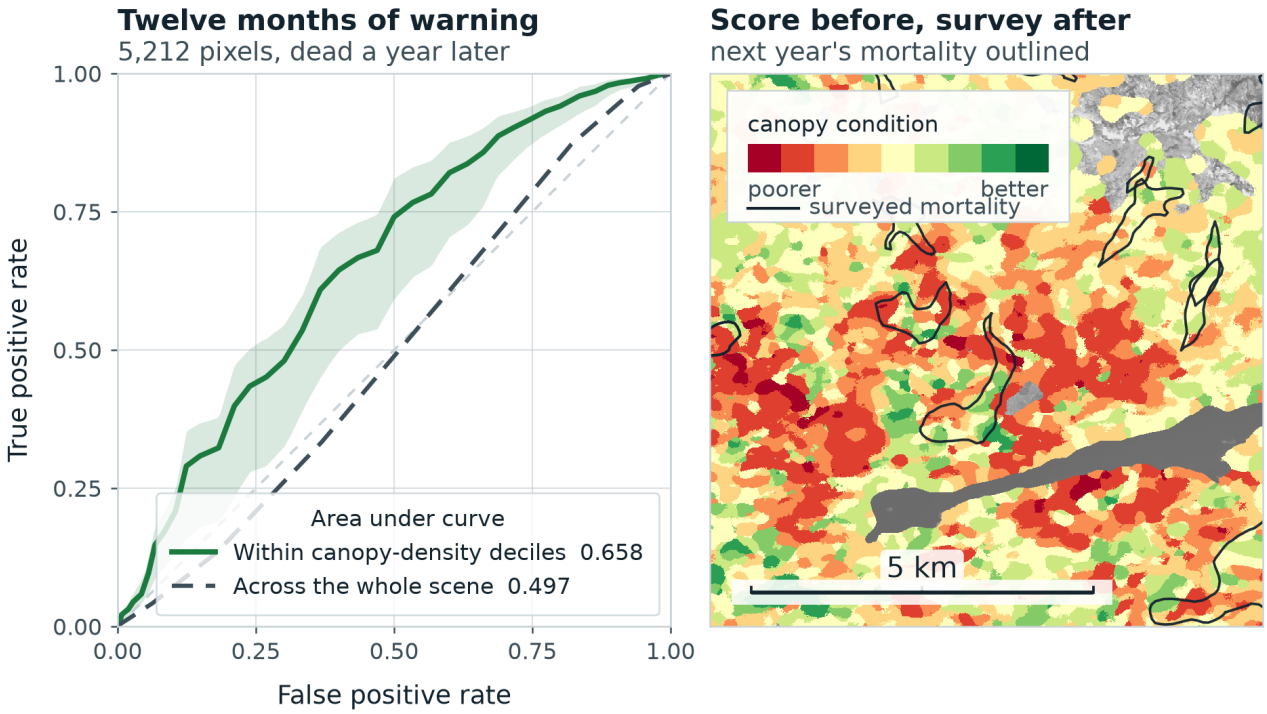
For forestry products the reference is field data: inventory plots for species classification and biomass, field-verified infestation polygons for pest detection, and scouting records for disease. Axine secures reference data alongside development rather than after it, and characterises performance per forest type rather than quoting a single global figure, because a closed tropical canopy and an even-aged boreal plantation are not the same classification problem.

Protocol

+ **Pre-registration:** Test design, thresholds and success criteria are fixed and recorded before evaluation data is examined.
+ **Frozen parameters:** Model and index parameters are fixed prior to evaluation and are not adjusted after results are seen.
+ **Hash-sealed inputs:** Input imagery and reference data are hashed, so any published result can be reproduced against the exact data that produced it.
+ **Stability testing:** Leave-one-region-out and single-site-removal runs confirm that reported performance is not carried by any single estate.
+ **Leakage controls:** Label permutation runs confirm that measured performance collapses when labels are destroyed, the standard test for information leakage.
+ **Append-only logging:** Every comparison run is written to an append-only log, providing a complete audit trail behind any figure we quote.

Reporting practice

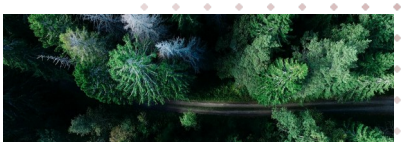
Classification performance is reported as full confusion matrices with Cohen's kappa and per-class accuracy rather than as a single headline figure, because an overall accuracy on an imbalanced species map is dominated by the commonest class. On the mineral products where this discipline is longest established, Axine publishes comparisons against independent United States Geological Survey reference products and quotes ranking performance as an area under the ROC curve of 0.7465 with a 95 per cent credible interval of 0.663 to 0.819 under spatially blocked validation. The same reporting standard governs every vertical.



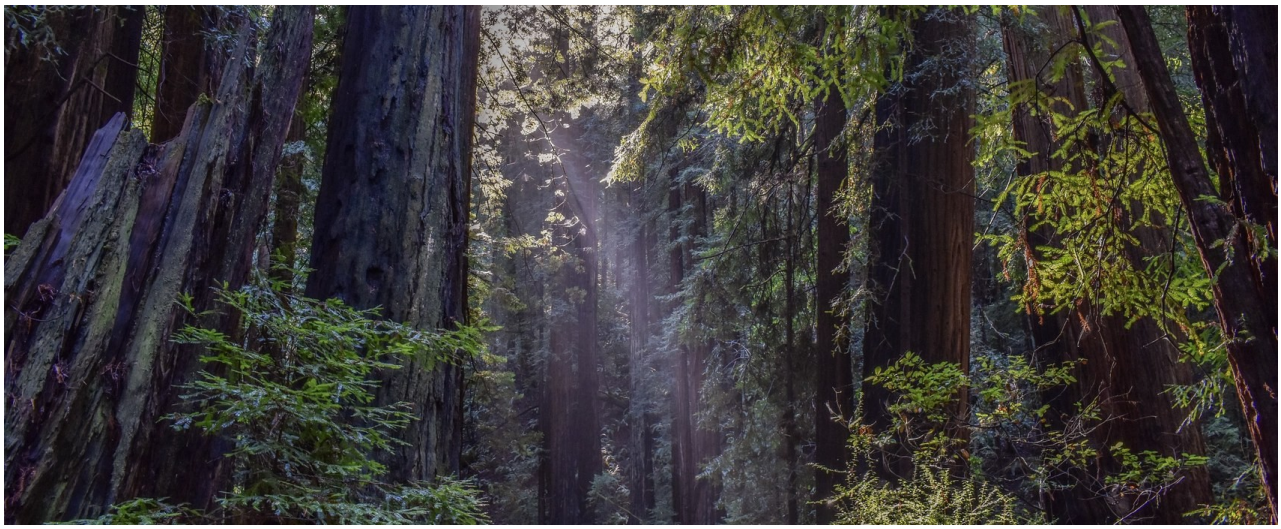
Ground truth is an aerial mortality survey flown the following year, independent of the imagery. Comparing the stands that died against the whole scene answers the wrong question: crews outline mortality where there were live host trees to kill, so the doomed stands are the dense green ones while the rest of the window is granite, chaparral and meadow. Measured that way the layer sits at chance. Comparing within a canopy-density bin holds host availability roughly fixed, and the signal appears: AUC 0.66, interval 0.57 to 0.70. That interval resamples whole survey polygons, not pixels, because 5,212 pixels came from 50 polygons and a pixel bootstrap would claim a precision the survey never had. Polygons outline affected areas rather than crowns, so the positives contain healthy trees. One site, one season, and an association with a survey record, not a diagnosis.

Figure 2 — *Canopy condition scored before an aerial mortality survey flown the following year, with the surveyed polygons outlined on the right. Across the whole scene the layer sits at chance; compared within canopy-density bins, which holds host availability roughly fixed, it reaches an area under the curve of 0.66 on an interval of 0.57 to 0.70.*

Operational benefits

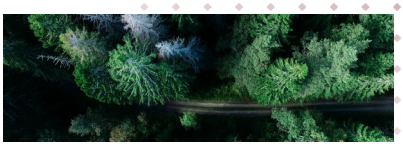


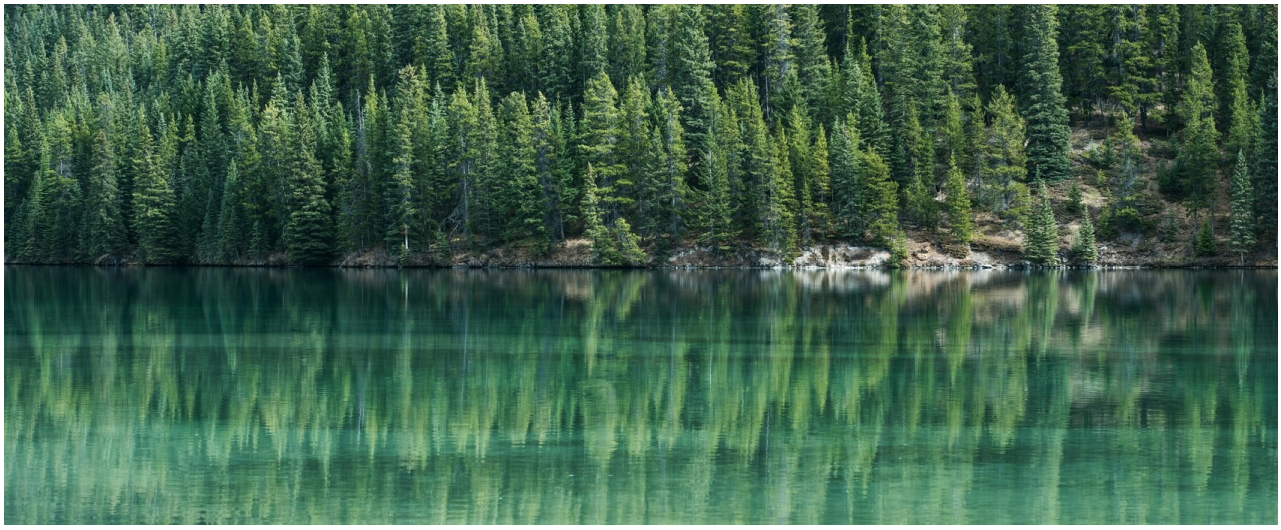
- **Estate-wide coverage:** A single acquisition characterises an entire estate rather than a plot network, converting a sampling exercise into a census and revealing the spatial structure that plot averages conceal.
- **Lead time on infestation:** Stress detected before crowns discolour turns a salvage problem into a management problem, which is where the difference between a sanitation felling and a stand loss is decided.
- **One acquisition, several answers:** Species, condition, fuel moisture and disturbance derived from the same acquisition, replacing several separately commissioned survey programmes with one coherent record.
- **Evidence-grade reporting:** Plot-level, time-stamped, reproducible evidence of land cover and condition, which is the form that carbon crediting and supply chain regulation now require.
- **Reach without deployment:** Concessions, protected areas and remote holdings are monitored without deploying crews into terrain that is difficult, expensive or unsafe to survey on the ground.
- **Predictable economics:** Everything derived from public satellite data is free, permanently. Tasked acquisition is priced per square kilometre against a defined area of interest, so programme cost is known before commitment.
- **Complements field programmes:** Satellite monitoring directs field effort rather than replacing it, concentrating inventory and inspection resources where the imagery indicates they will be informative.



Inside a mature stand. What a satellite measures is the top of the canopy; everything reported about the stand below is inferred from that surface, and the products say so rather than implying otherwise.

Inherent product properties





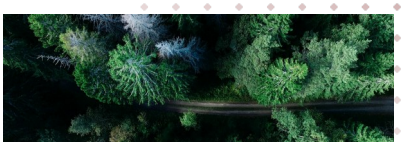
Even-aged conifer along a lake shore. Uniform stands make a health composite legible: because the ranking is relative to the scene, what it shows is departure from the stand around it.

+ **Pre-visual sensitivity:** Contiguous narrow-band coverage resolves pigment features and red edge position shifts of a few nanometres, which is what makes pre-visual stress detection possible at all.
+ **Species-level discrimination:** Full spectra rather than a handful of bands, permitting species-level discrimination from a single acquisition rather than from a multi-date phenological series.
+ **Resolution matched to stand management:** 8 metre hyperspectral ground sampling with 3 metre panchromatic context, approaching crown group scale so that infestation foci register as coherent anomalies.
+ **Monitoring cadence:** Revisit of up to daily for most locations, which is what allows detection to arrive inside the operational window rather than after it.
+ **Standard indices, full resolution:** Established published index formulations computed at native resolution, so results are comparable with the wider forestry remote sensing literature rather than proprietary and unverifiable.
+ **Analysis-ready delivery:** Cloud-optimised GeoTIFF outputs, API access and generated reports designed to enter an existing forest management information system.
+ **Explicit data integrity:** Screened ground reported as not evaluated and validity floors applied on every ratio layer, so unmeasurable canopy is never rendered as a measurement.

Optimal operating conditions

Optical spectroscopy measures the illuminated canopy surface, so the method performs best in daylight, cloud-free conditions, with terrain illumination correction applied on steep ground. Optical biomass estimation is strongest in open to moderately dense canopy and is designed to be combined with lidar or radar where those data exist, which is standard practice in carbon accounting and is how our biomass layers are intended to be used. Screened areas are reported as not evaluated rather than inferred.

Platform, access and data handling



The platform

Work is ordered and delivered through a web application. Users define an estate or upload compartment boundaries, search available imagery or request a tasked acquisition, and follow the order through a staged job queue. Results are served as cloud-optimised GeoTIFFs with map tiling, and any pixel can be opened to inspect its full spectrum and the indices computed from it. Monitoring subscriptions run the same analysis on a schedule and raise alerts against a baseline. Results are catalogued, reports are generated as PDF, and workspaces support teams, roles and notifications. An API is available for clients working in their own GIS or forest management system.

Lisa

Lisa is a client-facing assistant that runs entirely on Axine infrastructure rather than on a third-party model service. She searches imagery, estimates pricing, retrieves results, saves and lists areas of interest, geocodes, and reports the current model version with its validation metrics. Order submission is confirmation-gated by design, and any request requiring judgement is escalated to a human analyst.

Self-hosting is a procurement decision rather than an engineering preference. Estate boundaries, concession geometries and results remain within Axine infrastructure and are never transmitted to an external model provider.

Access tiers

Tier	Coverage
Free	Everything derived from public satellite data, including the narrowband index pack, health composite, visualisation, Lisa and API access. Axine does not charge for information obtained freely.
Tasked	Directed 8 metre hyperspectral acquisition over a specified estate or concession, with full analysis, priced per square kilometre against a stated minimum area.
Monitoring	Scheduled repeat acquisition with change detection, alerting and reporting between epochs, on volume terms.

About Axine Laboratories

Axine Laboratories builds commercial hyperspectral analytics for forestry, water monitoring, energy, mining and agriculture. The company is registered in the United States and run by a technical team of geologists and engineers.

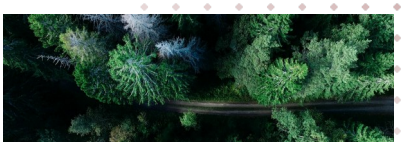
Our approach rests on three commitments. Detection is physics-based and reproducible, derived from measured spectra and published formulations rather than inferred by an untraceable model. Every published figure is backed by a pre-registered test against an independent reference, with the validation regime stated alongside it. And analysis derived from public satellite data is free and will remain so, because we do not charge for information obtained freely.

Revenue comes from tasked high-resolution acquisition and the analysis performed on it, which aligns our interest with delivering observations a client could not otherwise obtain rather than with metering access to imagery that is already public.

Axine Laboratories

axinelabs.com | contact@axinelabs.com

References



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