Washington Precision Forestry Cooperative

Scoping Paper

NEAR-SURFACE & SUBSURFACE SENSING AND MAPPING FOR SITE-SPECIFIC OPERATIONAL DECISONS

Operational practice of precision forestry enables improved forest industry competitiveness and heightened environmental performance. The present study explores precision forestry concepts and technologies in the context of forestry, forest management and silviculture. This paper looks primarily at the case of plantation forestry. Many of the concepts and details of precision forestry apply to short-rotation fiber farms, non-industrial forests and mixed-use public forests; however, sufficient differences exist to warrant separate consideration of how precision forestry applies to non-industrial plantation forestry. Skilled foresters with years of tenure on a property make observations and store in their minds a vast quantity of site-specific data that is not otherwise captured for use in centralized decision support. Through a process of interviews and experience, we have cataloged the kinds of observational data collected by professional foresters. Additionally, we have identified additional data that foresters would like to collect, but heretofore have not had the technical capability to measure.

We have translated forester observation and human senses information into technical terms and then surveyed the state of the art in sensor technology to match advanced sensors with the data needed. A literature review was conducted to determine the extent of research and commercial use that may be applicable to precision forestry in the State of Washington.

Our conclusions are that sensors exist or can be developed as extensions of the current art to enable the practice of precision forestry, forest management and silviculture. In all cases a significant investment in basic research, development and application support will be required. Development of research work plans, timelines and budget estimates is beyond the scope of the current project.

Concepts of Precision Forestry

There are a number of concepts that are fundamental to the practice of precision forestry.

1. Make decisions at successively smaller scales – eventually at the single plant level
2. Make decisions progressively closer to real-time – operational decisions should not be dependent on off-site chemical analysis and/or data analysis
3. Make decisions based on increasingly more directly-measured properties and attributes – apply sensors and real-time analysis to lessen the use of extrapolation and inference data
4. Include all relevant data and information in decision logic – discover and develop methods to measure data that presently depends on human observation and judgment
5. Accumulate longitudinal crop, soil and environmental legacy data and information to enable increasingly wise decisions over time
6. Pass crop/plant history forward to those doing subsequent forest operations and down-stream processing of forest products.

Limitations of Present Methods

From the time of Fernow and Pinchot forest management decisions have been made at the level of stands, watersheds or other landscape scales. The progress of decision-support technology primarily enables consideration of incrementally more factors in an analytical model, but not necessarily at finer spatial resolution. Modern computing and information science (informatics) provides the capacity and capability to include environmental, ecological, market and biological factors. The state of the art in landscape-scale forest management includes such programs as LMS – the landscape management system developed by the Silviculture Laboratory at the University of Washington (McCarter et al. 1998).

Early forest management presumed that each "management unit" was independent of all others. Change in forest practices and regulation has led to the need to consider adjacent units, public resources and other externalities that influence or constrain management. However, management decisions are still typically made on a scale of 20-200 acres (10-100 ha). As we consider precision forestry, we must move to a scale that is familiar to forest workers who are doing operations such as planting, thinning, pruning or harvesting. At the operational level workers are making decisions at an individual tree-site scale. In contrast to the forest planning scale of tens or hundreds of acres, tree planting occurs in an area of approximately 0.25 ft^2 (0.0000023 acres). The soil area occupied by the roots of a young rapidly growing conifer extends to approximately 100 ft^2 (0.0023 acres). At final rotation a crop tree will still only occupy approximately 500 ft^2 (0.01 acres). At the scale of single trees, extremely local conditions dominate growth, vigor, stability and operational aspects of forest productivity.

Operations workers are guided by landscape-scale policy such as planting density (seedlings per acre), number of trees per acre to prune, thinning density (leave-trees per acre) and other general guidelines (e.g., avoid snag trees with cavity nests). Workers add an immense amount of real-time local observation and information to make decisions as to exactly where to plant each seedling, which trees to prune, which trees to cut in thinning and which to leave. There is much truth in the oft-said observation that it is the person wielding a hoedag (planting tool) and chainsaw who really makes a stand of trees profitable or a losing proposition. To the extent that the technologies of precision forestry enable better, more consistent operational decisions by forest workers, the benefits of precision forestry will accrue to forest landowners and the communities that depend on a vibrant forest industry.

On June 12, 2000 we held a semi-structured focus group meeting with four senior level and retired foresters who were recruited from the members of SAF, the Society of American Foresters. The objective of the meeting was to learn the kinds of real-time data and observations that they believe would be critical to the practice of precision forestry. We further sought to gain their insights into the limitations of present-day forest management decision support.

We have combined our own experience with the insights of experienced foresters and the available literature to draw some conclusions about the limitations of present methods for forest management decision support.

1. Forest management decision support models "break-down" at very small scales, particularly at the scale of single tree decisions. Their limitation arises from the inherent presumption that at large scales the forest is sufficiently homogeneous to enable efficient model construction and inexpensive computing of results.

2. Skilled, experienced foresters and forest workers sense and use information that is not presently collected by sampling, cruising or other formal "measurement" activities.

3. Forest operations workers are instructed and trained to collect and use real-time information that is not available to them in contracts, prescriptions or existing in-field decision support tools.

RELEVANT SITE-SPECIFIC REAL-TIME AND LONGITUDINAL DATA

Forest Operations

Production forestry is a continuous process of silviculture coupled to a periodic process of commodity harvest and extraction. Silviculture in a broad sense includes the growing of crop trees plus the stewardship or intentional production of ecosystem and forest amenity values. Increasingly, forest products include berries, mushrooms, floral products, seasonal greens and other "special forest products." Ecosystem integrity, including fish, wildlife and plant communities, is expected to be maintained. Forest amenities, including fishing, hunting, hiking and vista are important to publics who increasingly seek recreation in and around production forests. Foresters must consider each of these factors as either objectives or constraints as they plan and execute forest operations.

The forest cycle traditionally begins at the time of planting and ends with a clearcut harvest. In the context of precision forestry there is a continuum over very long time periods (centuries at least) within which forested lands progress through a succession of natural and human-caused periods of growth and disturbance. For the purposes of this discussion we will assume that precision forestry is adopted at some point during the latter stages of growth of an existing forested area. This allows us to capture data and information during the harvesting operations that will be useful in subsequent silvicultural operations.

The principal on-the-ground operations include (bullets indicate functional titles of persons doing on-site work):

1. Forest cruising, measurements and mapping – collect data so that forest harvest plans, contracts and transportation infrastructure can be developed. Trees are marked for harvest, diameters, height, quality and abundance of crop and other species are documented. Wetlands, areas of special treatment, stream corridors and other sensitive areas are mapped. Chonic disease problems such as Armaleria are noted. (Note: shelterwood and partial cut harvest areas may already have the next stand present in the understory)
    - Technical forester,
    - Wildlife biologist, geomorphologist, fisheries biologist
2. Forest road and landing surveying, marking and construction.
    - Forest engineer, surveyor
    - Roads contractor, logging contractor
3. Felling, limbing and bucking of crop trees; leaving of wildlife trees and habitat management units; and, felling of undesirable "weed" trees.
    - Logging contractor, feller, mechanized logging equipment operator, harvest supervisor
4. Yarding and loading of merchantable logs.
    - Choker setter, logging contractor, forwarder operator, harvest supervisor
5. Redistribution of landing debris, trail scarification and site clean-up
    - Equipment operator, harvest supervisor, contracts manager

6. Site assessment prior to planting – assess need for site preparation and competition control; finalize planting contract specifications, species mix, stock types and planting method.
    - Technical forester, district forester
7. Site preparation – pile and burn, rip, spot spray, treat sprouting hardwood stumps, etc. if needed
    - Forest labor contractor, equipment operator, firefighter
8. Planting – selection of planting sites, dig planting hole, plant seedling
    - Forest labor contractor, forest operations workers
9. Planting Audit – Assess actual planting density and quality of planting job
    - Technical forester
10. Year-One Observation – Assess planting survival and vigor. Assess need for competition weed control, hardwood control and fertilization.
    - Technical forester
11. Year-Three Observation – Assess need for brush control, insect control and fertilization. Identify opportunities for special forest products extraction (berries, boughs, mushrooms, etc.)
    - Technical forester
12. Pruning and/or Precommercial Thinning
    - Forest labor contractor, forest operations workers, forester
13. Year-ten Observation – Assess vigor, need for fertilization, developing disease and insect problems. Identify opportunities for special forest products extraction (berries, boughs, mushrooms, etc.)
    - Technical forester
14. Pruning Second Lift
    - Forest labor contractor, forest operations workers, forester
15. Pruning Third Lift
    - Forest labor contractor, forest operations workers, forester
16. Year 20 Observation - Assess vigor, need for fertilization, developing disease and insect problems. Identify opportunities for special forest products extraction (berries, boughs, mushrooms, etc.)
    - Technical forester
17. Year 30 Observation - Assess vigor, need for fertilization, developing disease and insect problems. Identify opportunities for special forest products extraction (berries, boughs, mushrooms, etc.)
    - Technical forester

18. First Commercial Thinning Cruise and Planning – Same activities as planning for clearcut harvest, except that goal includes silvicultural thinning
19. Felling, limbing and bucking of crop trees; leaving of wildlife trees and habitat management units; and, felling of undesirable "weed" trees.
    - Logging contractor, feller, mechanized logging equipment operator, harvest supervisor
20. Yarding and loading of merchantable logs.
    - Choker setter, Logging contractor, forwarder operator, harvest supervisor
21. Year 40 Observation - Assess vigor, need for fertilization, developing disease and insect problems. Identify opportunities for special forest products extraction (berries, boughs, mushrooms, etc.)
    - Technical forester
22. Second Commercial Thinning Cruise and Planning – Same activities as planning for clearcut harvest, except that goal includes silvicultural thinning
23. Felling, limbing and bucking of crop trees; leaving of wildlife trees and habitat management units; and, felling of undesirable "weed" trees.
    - Logging contractor, feller, mechanized logging equipment operator, harvest supervisor
24. Yarding and loading of merchantable logs.
    - Choker setter, Logging contractor, forwarder operator, harvest supervisor
25. Final Observation and release for clearcut harvest –
    - Technical forester, district forester, forest manager, harvest manager

In addition to regularly scheduled entries into a forest stand, there are many unscheduled entries to extract special forest products, check for wildlife or newly-listed endangered and threatened species, assess insect and/or disease outbreaks, suppress fires, salvage windthrown areas, etc.

It is readily evident from the preceding list that forested lands are crisscrossed by technicians, forest operations workers, foresters and others a great many times during each round of the forest cycle. In most areas of western Washington, production forests are now in their third managed cycle. Various amounts of data already exist as a result of soil surveys, special surveys, boundary surveys, road construction records, crop histories and harvest records. In some locations, there are even long-term plots with photo points and photographic histories. To the extent that historic records can be mined for legacy data and information, precision forestry efforts will benefit.

As we consider implementation of precision forestry, all of those persons and machines that participate in forest operations are necessary audiences for precision forestry output, and are potential sources of additional site-specific precision forestry data. Participants in the "precision forestry information & communication network" represent a complex of workers, contractors, technologists, planners, managers and landowners. An early objective of precision forestry research should be to fully map the communication patterns of all participants in the precision forestry system. Such a study would ensure that all data needs are identified and establish criteria for data formats, etc. that are compatible with existing analytical methods.

Data Needs and Opportunities

In a first-pass effort to identify precision forestry data needs and opportunities, we conducted a number of informal interviews and then held a semi-structured focus group. Our research identified established long-standing spatial information including:

1. Soil surveys
2. Topographic and boundary maps
3. Stream, lake and wetland maps
4. Timber cruise records, stand tables and harvest records
5. Inventory records
6. Permanent plot records, research reports and special studies
7. Contract documents specifying planting stock, planting conditions, fertilizing, thinning, etc.
8. Historic, current and projected future market data for products

In addition to documentary records, experienced foresters develop heuristics and data banks based on memory and observation. Those can be organized by the common human senses:

1. Concepts of place and time
   - Time of year, time of day
   - Location in drainage, proximity to roads, wetlands, streams and other natural features
   - Location with respect to surrounding towns, workforce, markets, contractors, mills, etc.
   - Elevation, slope, aspect
2. Concepts of Ecosystem Integrity
   - Plant and animal communities
   - Endangered and Threatened species management needs
3. Temperature and Relative Humidity
   - Known conditions above the canopy
   - Heat and humidity at head level
   - Heat and humidity at soil level
4. Odor and Taste
   - Odor from crop plants and understory vegetation (e.g., if heat is high, humidity is low and strong turpine smell in air, then fire danger is extreme)
   - Odor from soil microorganisms (e.g., earthy smell is produced by healthy actinomyces; sour smell is anaerobic bacteria in poorly drained soil)
   - Odor from soil when shovel-cut or disturbed by machinery

5. Visual

- Vegetation density within 1 meter of soil
- Vegetation density competing with crop trees
- Vegetation density affecting sunlight – view of the sky
- Plant species and abundance in each quadrant of the view
    a. Special forest products (Mushrooms – morel and chantrel, Beargrass, ornamental species, berries, etc.)
    b. Noxious weeds and host plants for pathogens or detrimental insects
    c. Plant communities indicative of wetlands, dry spots, shallow soils, etc.
    d. Non-crop conifers (naturals)
- Patterns of plant growth indicative of previous disturbance, compaction, skid trails, ancient haul roads, etc.
- Diameter and height of crop trees, variation of diameters and heights among all crop trees in the scene
- Color, needle density, whorl spacing, height to live crown, crown ratio on crop trees
- Patterns of defect (ramicorm branches, disease in bole, sweep from soil slumping, wandering pith, etc.)
- Patterns of disease and insect damage (e.g. early death from armaleria)
- Evidence of disease history from ring patterns and decay of stumps and downed logs
- Soil and duff color
- Amount, size and species of coarse and fine woody debris
- Soil properties on exposed soils from planting holes, equipment traffic, wind throws, mass wasting, etc.

6. Tactile Feel

- Crop species branch and needle flexibility
- Decay status of coarse and fine woody debris
- Ease of soil penetration for planting tool or shovel
- Sound and vibration from walking stick

7. Foot Feel

    1. Sound and vibration from boots walking on duff
    2. Spring and softness from footsteps

An important next step in defining precision forestry will be to conduct focused interviews and experiments to:

1. Link observations with specific forest management and operational decisions
2. Establish a hierarchy for information collection, processing and decision rules
3. Translate natural-language observation terms into technical specifications for appropriate sensors and data processing
4. Validate resulting specifications, criteria and decision rules in actual forest operations
5. Explore the utility of measuring data that is not presently discernable by human senses. For example, we may be able to sense soil properties and population density of beneficial fungi through odor and chemical sensors. We may be able to "see" vegetation status and physiological phenomena at wavelengths substantially below and above the visible range.

Sensor Sets

Although we do not yet have complete understanding of data needs and analysis for practice of precision forestry growing forests, we can explore the state of the art in sensors that might be applied for measurement and data collection. An understanding of the state of the art in relevant sensing technologies will enable better planning of research efforts, timelines and budgets. We may find that some technologies can be applied in relatively short time frames and at low development costs.

The search for relevant sensor technologies is guided by several beliefs and guiding principles about the solution:

1. We should take our initial direction from senior "dirt foresters" who have experienced long tenure on forest properties.
2. Our initial goal should be to enable inexperienced operators and foresters to make site-specific decisions as good or better than their senior counterparts.
3. Sensors exist or can be developed to capture visual, odor, taste, temperature, feel, acoustic, and "scene" data at least as accurately as a skilled forester and operations worker.
4. Sensor sets can be built into familiar tools such as walking staffs, planting tools, etc. such that the incremental ergonomic burden is minimal.
5. Most or all data can be collected in the normal course of planned forest activities. Planned forest operations are sufficiently frequent and traverse the landscape at fine enough of a spatial scale to enable site-specific data collection.
6. Data capture and long-term maintenance will provide context information and improve accuracy and precision of forest planning and management models for use in site-specific precision forestry.

When we first broach the notion of collecting real-time sensor data the image that immediately comes to mind is a forester burdened by a disorganized array of sensors, recording devices, computers and other technical artifacts that get in the way of doing the task at hand. The person on the left in this image is toting a staff with at least eight independent sensors, a global position unit (GPS) and an over-the-shoulder computer. The reality of current sensor technology and micromanufacturing

(MEMS) is that a complete suite of sensors and associated recording/processing devices can be integrated into a familiar wooden tool modeled after a Biltmore stick as carried by the person at the right of the photograph.

The individual sensors we would need to provide real-time capture of data that is now collected by foresters and woods workers includes:

Temperature – thermocouples and thermistors are commonly available on the commercial market. Research needed to specify degree of precision to allow decision-support when temperature is measured at the ground and one or two meters above the ground.

Relative Humidity – low cost miniature relative humidity sensors are commonly available. Research needed to specify degree of precision to allow decision-support when relative humidity is measured at the ground and one or two meters above the ground.

Location and time – Global positioning systems (GPS) provide latitude, longitude and elevation to a high accuracy. They also capture very precise time and date information from navigation satellites. A major challenge to GPS technology is that the technology is relatively ineffective under dense forest canopy or in narrow incised valleys. A number of radio frequency and inertial guidance technologies are available to improve GPS performance in forested landscapes. Research is needed to select the most appropriate technology and define how the technology is to be applied for all forest operations.

Location relative to landscape features – Position data can be matched to layers in a geographic information system (GIS) database to derive information about nearby roads, natural features, communities, workforce, etc. The database may be accessed remotely by radio or cellular network. A limited local area subset of the database may be downloaded to field equipment prior to leaving an equipment base or office.

Slope and Aspect – Macro-scale slope and aspect are readily derived from topographic information in geographic information systems (GIS) once a location is known. Very local slope can be measured with commercially available electronic tilt and angle sensors. Local aspect is measurable with a self-correcting compass.

Odor and Taste – The cost of chemical sensors in coming down and the practical performance is increasing daily. Two technologies are of interest for precision forestry applications. Carbon-polymer matrix devices can be manufactured to react to single organic vapor chemistries. These so-called "electronic nose" devices are only recently coming to the commercial market. For example, the Cryanose 230 (www.cryanosciences.com) is intended for use with fish and other foods. The second technology for quantification of gas composition is based on near-IR spectrometry. Solid-state continuous flow spectrometers are being manufactured on single-chip electronics. A recent example being marked for real-time analysis of grain quality on farm combines is the AFS monitor from Textron Systems.

There are many odorless gases present in the forested landscape that may be of value to practitioners of precision forestry. Chemical sensor may provide a capability that goes well beyond the taste and smell capacity of humans. For example, specific gases may be associated with the population of mychorhizae (an important root colonizer for Douglas fir seedlings) or areas containing morel mushroom colonies.

Substantial research will be required to identify gases of interest for use in precision forestry, and to develop and prove applicable sensors.

Visual Information – Charge-coupled device (CCD) cameras that operate across the full spectral range of visible, ultraviolet and infrared can be used to collect all of the information that a forester or worker sees. Camera devices additionally can detect absorption or reflectance well outside the wavelengths that humans perceive. Many pathogens fluoresce in the ultraviolet range, while crop stress, species differences and many other attributes are readily determined in the infrared spectrum.

A wealth of research information exists in the remote sensing and precision agriculture literature. A substantial research program will be needed to translate and apply research from other fields of application to precision forestry.

Tactile feel – Tactile sensors are available for industrial use, however the technology has not yet been adapted for field and low-cost applications. Research into the actual physical phenomena that foresters are sensing may lead to alternative techniques that simply measure modulus of elasticity, viscoelastic properties or other readily measured property.

Vibration (acoustic and foot fall) – Acoustic and vibration sensors are commercially available in very small packages and at reasonable costs. The state of the art technology includes piezoelectronic triaxial sensors that weigh less than one gram. Research will be needed to identify the frequencies and vibration signatures that are relevant to capturing surface condition and subsurface soil properties.

Another technology that goes well beyond the capabilities of a human is the ground penetrating radar (GPR) sensor and associated processing algorithms. Ground penetrating radar has become an important tool for precision agriculture due to its ability to measure soil mechanical properties, soil moisture and structure at agronomically important depths without the need for soil cores or pits. Substantial research would be needed to adapt the technology for use in precision forestry. As you will learn in the literature review, GPR technology may open a number of new possibilities for improving the management of forest operations.

Information Sciences – Data management and user communication will be among the major challenges to implementation of an integrated precision forestry sensor staff. Very large data sets will be generated during the course of a single day in the woods. At the same time historic and other external data may need to be downloaded to the device to support decisions anticipated during a day in the woods. Long-term data records and interfacing precision forestry site-specific data with other larger scale forest management tools will pose additional data management challenges.

A second information science challenge will be the definition and development of appropriate user interfaces to connect the forester, woods worker and others to the device. Natural language voice communication is preferred. The state of the art in voice communication is fairly well developed for devices talking to humans, but still rudimentary for humans talking to intelligent devices.

"No Inventions Needed"

The discussion indicates that sensor technologies exist at various stages of development or commercial application for most or the entire sensor needs we have identified to-date. Although progress will not be hindered because critical sensors have not been invented yet, there will be requirements for considerable engineering, biology, materials, information processing and other research to appropriately specify and configure sensors appropriate for use in forest operations.

SUB-SURFACE, NEAR-SURFACE PHYSICAL PROPERTIES

Soil properties that contribute to improved crop productivity, are indicative of aeas of environmental concern, or are a source of potential damage to mechanixed forest operations are traditionally assessed by soil boring, soil pits or other labor-intensive methods. Recently, ground penetrating radar (GPR) and ultrasonic sensors have been developed to map subsurface features of intact soils. The technology that is most developed is ground-penetrating radar. Ground-penetrating radar is being applied to precision agriculture to detect soil horizons, soil compaction areas and soil moisture (Freeland, Yoder, and Ammons 1998). The advantages of GPR over conventional soil sampling include:

- Continuous sampling at fine resolutions across the landscape
- Non-intrusive measurement of soil properties such as used when collecting data with soil augers, dug pits, etc.

We believe that similar benefits will accrue from use of ground-penetrating radar in forested landscapes.

Soil moisture data is important for both plant health and making equipment operability decisions. Seasonally wet areas may dry out on the surface, but still be too wet to support mechanized planting, thinning and other forestry machines. Digital ground penetrating radar has been demonstrated by Chanzy (1996) to measure soil moisture in the 10-20 cm (4 - 8 inch) depth range. Optimal determination of soil moisture occurred at a frequency of 200 MHz. Ground penetrating radar can be especially useful when making forest management decisions along river bottom lands where the soil is very non-uniform (Birkhead et al. 1996; Boll et al. 1996). Ancient gravel bars, sand lenses and silt accumulations can be mapped to a depth of 9 meters by GPR systems operating at approximately 500 MHz (Harari 1996; Naegeli, Huggenberger, and Uehlinger 1996).

The cost of road building is highly uncertain in areas of rock outcrops. When the rock is fractured or porous, it can be readily broken and worked by trackhoes and bulldozer equipment. If the rock is monolithic, the cost of drilling and blasting may make road construction infeasible. At times a road segment under construction must be abandoned so a new alignment can be developed around unforeseen rock masses. Ground penetrating radar is commercially used to map fracture patterns in rock quarries and mines (Grandjean and Gourry 1996; Grasmueck 1996).

Post-construction assessment of forest road quality is important for ensuring contract compliance and environmental performance. The depth, density and materials used in road prisms can be non-destructively assessed by use of ground-penetrating radar. Although the techniques are widely used in conventional highways and bridges (Attoh-Okine 1996) the method is not yet proven on low-volume forest roads. Road prism assessment can also be useful for engineers and ecologists who are planning road abandonment and obliteration projects. Very old forest roads frequently include decaying logs and other unstable materials in the fill and prism. Catastrophic mass-wasting events can be triggered if such conditions are not identified and fixed.

Environmental compliance, particularly protection of small mammals, burrowing reptiles and turtles, may be enhanced if the presence and extent of underground burrows could be mapped. Ground-penetrating radar was used by Stott (1996) to map tunnel routes of a burrowing rabbit in a variety of soil types. The Western Pond Turtle, a state threatened species in Washington, nests only in dry, well-drained soils (Hays et al. 1999). Such soils may not be evident from surface evaluations at potential turtle re-establishment sites. Ground penetrating radar may also be applicable to non-destructive determination of the number of turtle eggs in underground clutches. Since pond turtle eggs take from 73-80 days to mature and hatch (Nussbaum, Brodie, and Storm 1983), it would be useful to determine an advanced estimate of reproductive success.

Forest operations must avoid large boulders and tree root systems that may not be visible from the surface. Non-destructive tree root mapping was demonstrated by Hruska, et. al., (1999) as part of a research project in the Czech Republic. Eriksson and Holmgren (1996) have demonstrated the utility of GPR for estimating stone and boulder content of forest soils in central Sweden. If similar performance could be demonstrated in plantations of Washington, the data would benefit both forest operations and research programs. Tree planting machines could be programmed to avoid planting seedlings on top of large boulders, major tree roots or above voids resulting from decayed roots.

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