Distributed Agency Without a Nervous System:

Plant Intelligence, Memory, and Adaptive Constraint-Management

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Abstract

This paper develops a theory of plant agency as distributed adaptive constraint-management without a nervous system. It argues that plants should not be understood as passive organisms merely reacting to stimuli, nor as conscious agents in the animal sense, but as decentralised living systems that perceive, integrate, remember, prioritise, and respond across body and environment. Plants detect light, gravity, humidity, temperature, nutrients, pathogens, herbivores, neighbours, salinity, drought, flooding, touch, microbial signals, volatile compounds, and mechanical damage. They coordinate responses through calcium waves, electrical signals, hydraulic changes, reactive oxygen species, hormones, volatile organic compounds, RNA movement, root exudates, mechanosensory pathways, and other signalling systems. These processes allow plants to allocate resources, alter growth, regulate stomata, prime immunity, recruit microbial partners, communicate danger, delay germination, flower, defend, and reorganise development under changing conditions.

Crucially, the paper defines plant agency through five capacities: perception, integration, valuation, memory, and action. This does not imply plant consciousness, animal-like intention, subjective experience, or mental deliberation. Rather, plant agency is treated as the capacity of a decentralised organism to sense changing conditions, integrate signals across tissues and timescales, prioritise competing biological demands, retain biologically useful traces of past events, and alter future form or activity accordingly. Plant memory is therefore not autobiographical recollection, but the retention of physiologically useful traces that shape later responsiveness. Stress memory, immune priming, vernalisation, circadian timing, developmental memory, and epigenetic effects are interpreted as forms of biological history without implying human-like remembrance.

Finally, the paper argues that plants are extended organism-environment systems. Roots modify soil chemistry, exudates shape microbial communities, fungi extend resource access, volatile compounds influence neighbouring plants and insects, and seeds carry maternal and environmental histories. Plant agency is therefore not detached action upon an environment, but continuous co-modification of body and surroundings. The paper connects this view to a broader theory of distributed intelligence and Paradox-Negotiation Theory: plants cannot maximise growth, defence, reproduction, water conservation, nutrient acquisition, and symbiosis all at once. They must continuously negotiate incompatible biological demands without collapsing into one rigid behaviour. In this sense, plant agency is not will or intention in the animal sense, but adaptive constraint-management across a living body. The result is a framework for understanding what forms of intelligence become possible when life solves problems without brains.

Keywords: plant adaptive intelligence; distributed agency; plant signalling; plant memory; stress memory; immune priming; root exudates; plant cognition; non-neural agency; constraint-management; embodied cognition; ecological intelligence; Paradox-Negotiation Theory; calcium waves; electrical signalling; mycorrhizal networks.

Contents

1 Introduction: The Problem of Plant Agency

Historically, intelligence has been interpreted through animal-centred assumptions: rapid movement, centralised perception, nervous systems, visible choice, behavioural flexibility, and brain-based coordination. Plants violate almost all of these expectations. They are modular rather than centralised, slow rather than fast, growth-based rather than locomotor, chemically articulate rather than vocally articulate, and environmentally embedded rather than behaviourally detached. The risk is that plant behaviour becomes fragmented into isolated mechanisms: phototropism here, stomatal regulation there, immune priming elsewhere, root exudation somewhere else. What is often missing is a whole-organism theory of how these processes coordinate adaptive life without a nervous system.

Biologically, a plant is not a passive object merely acted upon by light, water, soil, microbes, and weather. It is a living, distributed control architecture that continuously senses, signals, allocates, grows, defends, stores traces of past conditions, and modifies its own environment. Its form is not only a result of development; its form is also a means of action. A root changing direction, a leaf closing stomata, a shoot bending towards light, a seed delaying germination, or a plant releasing volatile compounds after herbivore attack are not mental decisions in the animal sense, but they are adaptive selections among possible biological trajectories.

Conceptually, the central claim of this paper is that plant agency can be understood as distributed adaptive constraint-management. A plant cannot maximise everything at once. Growth can compromise defence. Water conservation can reduce carbon intake. Reproduction can increase vulnerability. Symbiosis can carry pathogen risk. Dormancy can protect future viability while delaying expansion. Plant agency consists in continuously negotiating these incompatible demands across a living body and its ecological surroundings.

2 Beyond Brain-Centred Intelligence

Animal-centred models often treat brains as the default architecture of intelligence. Yet brains may be one evolutionary solution to adaptive agency, but not the only solution. Nervous systems are powerful because they allow rapid integration, sensorimotor coordination, memory, learning, prediction, and action selection. Plants solve many adaptive problems differently. They do not centralise perception in a brain. They distribute sensitivity and response across tissues, organs, developmental zones, signalling pathways, and environmental interfaces.

Importantly, rejecting brain-centrism does not require claiming that plants are conscious. The present argument is not that plants possess subjective experience, animal-like feeling, or a first-person perspective. Instead, it proposes a restricted and operational account of plant agency. A system may display structured adaptive competence without possessing consciousness. In plants, this competence appears as distributed sensing, physiological integration, developmental plasticity, memory-like adjustment, ecological manipulation, and growth-based action.

Philosophically, this distinction is essential. If intelligence is defined only as conscious deliberation, plants will be excluded by definition. If intelligence is defined more broadly as structured adaptive competence under constraint, plants become highly relevant. They show that adaptive systems can perceive, prioritise, remember, and respond without neurons. The absence of a nervous system should not automatically mean the absence of agency. It may indicate a different architecture of agency.

3 Plant Perception as Multidimensional Environmental Sampling

Perception in plants should not be reduced to passive stimulus reception. Plants actively sample a multidimensional environment through light-sensitive tissues, gravity-sensing structures, mechanosensory pathways, humidity responses, chemical gradients, thermal sensitivity, nutrient detection, microbial recognition, pathogen recognition, volatile sensing, salt responses, flooding responses, and damage detection. Their environment is not a simple external container. It is a complex field of gradients, signals, threats, opportunities, histories, and constraints.

Operationally, plant perception may be represented as a vector of sensed conditions:

$$\mathbf{P}_t = (L_t, G_t, H_t, T_t, N_t, W_t, S_t, M_t, P_t, V_t, D_t)\,, \tag{1}$$

where L_t denotes light, G_t gravity, H_t humidity, T_t temperature, N_t nutrient availability, W_t water status, S_t salinity or stress, M_t microbial signals, P_t pathogen or herbivore pressure, V_t volatile cues, and D_t mechanical damage. This notation is heuristic rather than exhaustive. It is meant to show that plant perception is distributed across many channels rather than concentrated in one sensory organ.

Ecologically, the plant does not merely detect these signals in isolation. Signals interact. Drought modifies nutrient uptake. Shade affects growth allocation. Pathogen attack changes hormone balance. Herbivory alters volatile emissions. Soil microbes affect root architecture. Mechanical damage interacts with electrical, calcium, hydraulic, and reactive oxygen species signalling. The plant therefore faces a combinatorial field of conditions, not a linear sequence of isolated stimuli.

4 Whole-Plant Signalling Without a Nervous System

Signalling allows plants to coordinate distant tissues without nerves. Calcium waves, electrical changes, hydraulic pressure shifts, reactive oxygen species, phytohormones, RNA movement, volatile organic compounds, root exudates, and mechanical signals all contribute to plant-wide coordination. These signals differ in speed, range, specificity, reversibility, and biological meaning. Some propagate rapidly after wounding. Others reshape development over hours, days, seasons, or generations.

Schematically, whole-plant signalling can be represented as a distributed network:

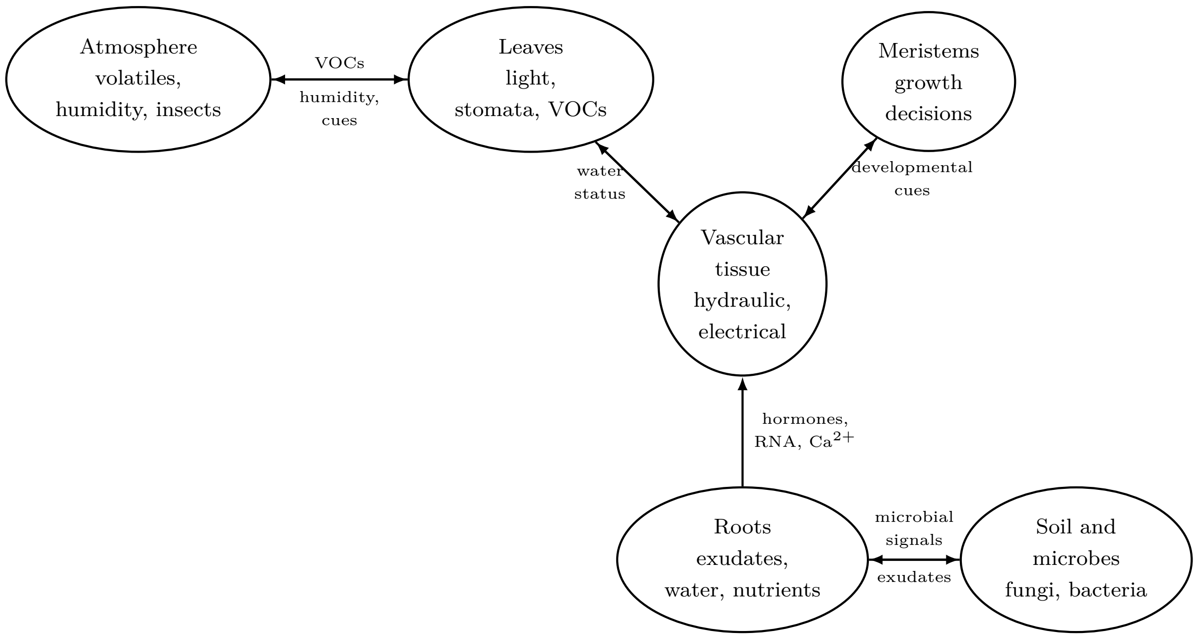

Figure 1: A simplified view of plant-wide coordination through distributed tissues, signals, and environmental interfaces.

Mechanistically, the absence of neurons does not mean the absence of rapid coordination. Electrical signals and calcium waves can move through plant tissues, while reactive oxygen species and hydraulic signals can participate in systemic stress responses. Hormonal networks such as auxin, abscisic acid, jasmonates, salicylic acid, ethylene, cytokinins, and gibberellins help regulate growth, defence, drought response, flowering, senescence, and development. The plant is therefore coordinated by overlapping signalling geometries rather than a single central command channel.

5 Distributed Decision-Making as Developmental Selection

Decision-making in plants should be understood cautiously. Plants do not deliberate, imagine alternatives, or intend outcomes in the animal sense. Nevertheless, they repeatedly select among developmental pathways. A root may proliferate in nutrient-rich soil or avoid toxic zones. A shoot may elongate under shade or branch under favourable light. Stomata may open for carbon intake or close to preserve water. A plant may invest in defence chemistry rather than growth. A seed may germinate or remain dormant.

Developmentally, these selections can be modelled as changes in growth and physiological state:

$$\Delta \mathbf{g}_t = \alpha \nabla L_t + \beta \nabla W_t + \chi \nabla N_t - \delta \nabla Tox_t - \epsilon \nabla Hrb_t + \eta \mathbf{S}_t, \tag{2}$$

where $\Delta \mathbf{g}_t$ is a growth adjustment vector, ∇L_t is a light gradient, ∇W_t a water gradient, ∇N_t a nutrient gradient, ∇Tox_t a toxin or stress gradient, ∇Hrb_t herbivory or damage pressure, and $\mathbf{S}_t$ the integrated internal signalling state. The coefficients represent context-sensitive weighting rather than fixed universal constants.

Practically, this model illustrates why plant agency is better understood as adaptive selection than mental choice. The plant's body changes because developmental pathways compete under constraint. The outcome is not an intention, but neither is it a mere isolated reaction. It is a coordinated alteration of future possibility. Growth itself becomes a form of action.

6 Plant Memory Without Animal Memory

Memory in plants should not be confused with autobiographical recollection. A past drought, heat event, cold exposure, pathogen encounter, herbivore attack, or nutrient condition may change later sensitivity, gene expression, hormone balance, immune responsiveness, flowering behaviour, or growth architecture. Such memory is biological trace retention, not mental recall.

Several forms of plant memory can be distinguished:

Table 1: Forms of plant memory as biologically useful trace retention.

Memory type	**Description**	**Adaptive role**
Stress memory	Prior drought, heat, cold, or salt alters later response	Prepares future stress tolerance
Immune priming	Earlier pathogen or herbivore exposure strengthens later defence	Speeds or amplifies defence response
Vernalisation memory	Cold exposure influences later flowering	Aligns reproduction with season
Circadian memory	Internal timing anticipates day-night cycles	Coordinates metabolism and growth
Developmental memory	Earlier growth conditions shape future architecture	Tunes form to local history
Epigenetic memory	Molecular marks may persist through cell divisions or generations	Carries stress traces across time

Analytically, plant memory can be represented as a state variable that modifies later response:

$$\mathbf{M}_{t+1} = \mathcal{U}\left(\mathbf{M}_t, \mathbf{P}_t, \mathbf{S}_t\right), \tag{3}$$

where $\mathbf{M}_t$ is the memory state, $\mathbf{P}_t$ is perceived environmental input, $\mathbf{S}_t$ is internal signalling state, and $\mathcal{U}$ is an update process involving physiological, molecular, developmental, or epigenetic change. This does not imply subjective memory. It means that past conditions become biologically active in shaping future response.

7 Plant Agency as Adaptive Constraint-Management

Agency in plants can be defined through five capacities: perception, integration, valuation, memory, and action. Perception detects relevant conditions. Integration combines signals across tissues and timescales. Valuation prioritises competing biological demands. Memory retains useful traces of past conditions. Action alters growth, chemistry, signalling, reproduction, dormancy, repair, or resource allocation. These capacities do not require consciousness. They define a distributed architecture of adaptive control.

Formally, plant agency may be expressed as:

$$\mathcal{A}_{plant} = \left(\mathcal{P}, \mathcal{I}, \mathcal{V}, \mathcal{M}, \mathcal{X}\right), \tag{4}$$

where $\mathcal{P}$ denotes perception, $\mathcal{I}$ integration, $\mathcal{V}$ valuation or prioritisation, $\mathcal{M}$ memory-like trace retention, and $\mathcal{X}$ action. This formalisation is intentionally minimal. It does not treat the plant as a mind. It treats the plant as an adaptive system capable of coordinating its future form and activity under constraint.

Comparatively, plant agency differs from animal agency in speed, centralisation, morphology, and action mode:

Table 2: Contrasting animal-centred and plant-centred architectures of agency.

Dimension	**Animal-centred model**	**Plant-centred model**
Control architecture	Central nervous system	Distributed signalling across body
Primary action mode	Locomotion and motor behaviour	Growth, secretion, defence, development
Timescale	Milliseconds to years	Seconds to seasons or generations
Memory	Neural, behavioural, affective	Physiological, developmental, epigenetic
Agency style	Sensorimotor choice	Adaptive constraint-management
Environment relation	Movement through environment	Co-modification of body and environment

8 The Plant as an Extended Organism-Environment System

Environmentally, a plant is not merely located in a niche; it helps construct the niche it inhabits. Roots release exudates that alter soil chemistry and microbial composition. Mycorrhizal fungi extend the effective reach of root systems. Volatile organic compounds influence neighbouring plants, herbivores, and predators of herbivores. Seeds carry maternal and environmental histories. Soil structure, microbial partners, neighbouring vegetation, humidity, light quality, and seasonal cycles become part of the plant's operating context.

Relationally, plant agency is therefore extended. The plant's adaptive space includes tissues inside the organism and processes outside the organism. The boundary between plant and environment remains biologically real, but it is also functionally porous. A root exudate is both an output and a way of reshaping future input. A fungal association is both an ecological relation and an extension of resource access. A volatile warning signal is both a chemical emission and a modification of the behavioural field around the plant.

Consequently, a plant senses the world partly by building itself into it. Its body is not a finished machine executing commands. It is an unfolding structure that discovers, modifies, and is modified by its surroundings. Plant agency is not detached action upon an environment, but continuous co-modification of body and surroundings.

9 Paradox-Negotiation Without Consciousness

Paradox-Negotiation Theory can be applied to plants in a restricted, non-conscious sense. A plant must continuously manage incompatible demands: growth versus defence, root investment versus shoot investment, water conservation versus carbon intake, dormancy versus germination, reproduction versus survival, symbiosis versus pathogen risk, and local repair versus whole-organism allocation. These tensions cannot all be maximised simultaneously. The plant must maintain viability while selecting among competing trajectories.

Dynamically, this can be represented as a constraint-management problem:

$$\max_{\mathbf{x}} \quad F(\mathbf{x}) = w_g G(\mathbf{x}) + w_d D(\mathbf{x}) + w_r R(\mathbf{x}) + w_s S(\mathbf{x}) - w_c C(\mathbf{x}), \tag{5}$$

where G denotes growth, D defence, R reproduction, S survival or stress tolerance, C cost, and w_i context-dependent weights. The point is not that plants solve this equation explicitly. The point is that plant life involves the biological equivalent of weighted constraint-management under changing conditions.

Theoretically, plant paradox-negotiation does not require a felt first-person field. Consciousness, if defined as recursively accessed self-relevant conflict-geometry, is not being attributed to plants here. Rather, plants demonstrate that unresolved biological tensions can be negotiated through distributed physiology, growth, signalling, memory-like trace retention, and ecological feedback. They show that paradox-negotiation can exist below the threshold of consciousness.

10 Objections and Limits

Critically, one might argue that the language of plant agency is anthropomorphic. This objection is important. Plants do not possess brains, nerves, animal-like consciousness, or mental intentions. The present paper accepts that limitation. Its claim is not that plants are conscious subjects, but that they exhibit distributed adaptive agency in a restricted biological sense. Agency here means organised sensing, integration, prioritisation, trace retention, and action under constraint.

Alternatively, one might argue that mechanistic explanations are sufficient. Plants respond through hormones, genes, calcium waves, electrical changes, hydraulic shifts, molecular pathways, and developmental programmes. That is true, but it does not eliminate the need for whole-organism theory. Animal cognition is also mechanistic, yet mechanisms can still coordinate into higher-level functional architectures. The question is not whether mechanisms exist, but how they organise perception, memory, valuation, and response across the plant as a living system.

Finally, one might say that the term "intelligence" is too broad. The reply is that the paper distinguishes plant adaptive intelligence from consciousness, deliberation, and animal cognition. If intelligence means human-like thought, plants are not intelligent. If intelligence means structured adaptive competence under constraint, plants become central examples. The aim is not to erase differences between organisms, but to expand the theory of agency beyond nervous systems.

11 Conclusion: What Life Can Do Without Brains

Ultimately, plants show that life can solve problems without brains. They perceive through distributed tissues, signal through multiple channels, retain traces of past conditions, prioritise incompatible demands, alter their chemistry, reshape their growth, recruit microbial partners, influence neighbours, and modify their surroundings. Their agency is not a hidden animal mind inside a green body. It is a different architecture altogether.

Plant agency should be understood as decentralised, embodied, metabolic, growth based, chemically mediated, and ecologically embedded. It is a form of adaptive constraint management rather than animal-like intention. It is neither mere mechanism nor hidden mentality. It is the capacity of a living organism to build itself while sensing the world, and to sense the world partly through the act of building itself.

Therefore, brains may be one solution to adaptive agency, not the only solution. Plants show another route. They remind us that intelligence does not always announce itself as speech, speed, movement, or deliberation. Sometimes intelligence is slow. Sometimes it is rooted. Sometimes it is the quiet geometry of a living body negotiating light, water, soil, danger, memory, and time.

A Appendix: Summary Framework

Appendix materials summarise the conceptual framework developed in the paper.

Table 3: Five capacities of plant adaptive agency.

Capacity	**Plant expression**	**Agency role**
Perception	Light, gravity, moisture, chemicals, pathogens, touch, neighbours	Detects relevant conditions
Integration	Hormones, calcium, ROS, electrical, hydraulic, RNA, VOC pathways	Combines signals across body and time
Valuation	Growth, defence, reproduction, dormancy, repair, symbiosis	Prioritises incompatible demands
Memory	Stress memory, priming, vernalisation, developmental traces	Alters future response through past conditions
Action	Growth, stomatal closure, flowering, secretion, defence, branching	Changes body, chemistry, or environment

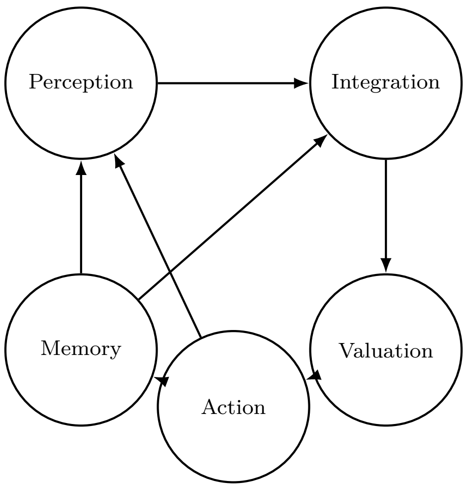

Figure 2: A minimal model of plant adaptive agency as perception, integration, valuation, memory, and action.

$$\boxed{\mathcal{A}_{plant} = (\mathcal{P}, \mathcal{I}, \mathcal{V}, \mathcal{M}, \mathcal{X})}$$

The boxed schema summarises the paper's central claim: plant agency can be modelled as a distributed system of perception, integration, valuation, memory-like trace retention, and action, without attributing consciousness or animal-like intention.

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