ON THE RADAR

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Plant-based Sensors

A Technology Primer

BY ANTHONY BENJAMIN

TYPE Sensor	**CHARACTERISTICS** Vantage/range, Resiliency, Undetectability, Persistence	**RISK FACTORS** Intrusive, Clandestine, Dual-use[1]
DOMAIN Land	**COUNTRY** United States	

- Plant-based sensors are physiology-based mechanisms—either already present or artificially engineered to create “smart” plants—capable of reporting the presence of specific chemical, pathogen, and radiation stimuli on land.
- Plant-based sensors are comprised of two elements. The first includes the plant’s physiological mechanisms and physical responses that are either genetically modified or left untouched (“natural”) and react to a specific compound or environmental condition. The second element is comprised of remote, man-made technology that monitors the smart plants' reactions and provides data that is interpretable to an operator.
- Plant-based sensors are a highly unobtrusive solution compared to alternate means of monitoring conventional and non-conventional weapons development and presence.
- Successful plant-based sensors create long lasting, self-sustaining, and reproducing populations that continually collect intelligence, but these populations would be hard to remove if they ever caused environmental or diplomatic issues.

Introduction

Plant-based sensors are physiology-based mechanisms—either already present or artificially engineered to create “smart” plants—capable of reporting the presence of specific chemical, pathogen, and radiation stimuli on land. Physiology-based mechanisms that are artificially integrated into plants by gene-editing techniques are a part of a broader effort to create bio-sensors. Plant-based sensors are comprised of two elements. The first includes the plant’s physiological mechanisms and physical responses that are either genetically modified or left untouched (“natural”) and react to a specific compound or environmental condition. These smart plant physical reactions must then be remotely measured to determine the presence or lack of stimuli. The second element is

[1] In this case, the term "dual-use" is used to describe a technology with civiilan and military applications (as opposed to dual use for conventional/nuclear applications).

comprised of remote, man-made technology that monitors the smart plants' reactions and provides data that is interpretable to an operator.

The technology necessary to monitor plant physiology-based mechanism, responses, and physical reactions already exists. For example, a number of existing technologies can monitor plant growth, leaf coverage, chemical composition, visible and infrared light reflectance and the temperature of plants and soil.[2] These measurement devices are necessary to collect data from reporting smart plants unobtrusively and remotely. These biosensors represent a novel and promising long-term intelligence source that is resilient, stealthy, unobtrusive, and easy to distribute. Biosensors can be genetically modified to detect multiple and diverse stimuli and can be integrated into many different plants found in varying biomes and regions. Modified plants could be distributed by means of wind or wildfires, water, animals, or mechanical and non-mechanical human activity. For example, seeds of modified plants could have parachutes similar to those of poplar seeds, which have been found to travel up to 30 km; alternatively, seeds could have floating capabilities allowing them to disperse through rivers.[3] Bio-sensor projects seek to substitute costly and intrusive monitoring efforts for conventional and nuclear weapon presence and development. Currently, genetically modified plants have been able to sense and report single types of low concentration airborne molecules, such as TNT.[4] The ability of these plants to devote resources to sense and report multiple complex chemical compounds and radiation long-term while surviving in wild environments has not been established.

State of Play

Past research in the field of molecular biology provides a foundation for biosensor development by establishing a vast database of plant reactions to their environment. Scientists and engineers are now exploiting and editing these known reactions to report on environmental conditions. Examples of these reaction mechanisms include electrochemical plant cell responses to high energy radiation that ionizes DNA and gene expression-linked proteins that conform to small molecules that can range from specific amino acids to cocaine.[5] While these types of findings in molecular biology are not new, these biosensors can now be usefully tailored for use in warfare in general and nuclear detection in particular.

In 2011, laboratory and greenhouse-based genetically modified tobacco plants successfully detected low concentrations of airborne TNT molecules.[6] These plants are able to sense and report traces of TNT while surviving in airports under regular care. In the plants' engineered mechanism, TNT corresponds to a protein that

2 Nikolaos Katsoulas et al., "Crop Reflectance Monitoring as a Tool for Water Stress Detection in Greenhouses: A Review," *Biosystems Engineering* 151 (November 2016): 374-398.

3 W. Carter Johnson et al., "Modeling Seed Dispersal and Forest Island Dynamics," in *Ecological Studies Forest Island Dynamics in Man-Dominated Landscapes*, R.L. Burgess and D.M. Sharpe, eds. (December 1981), 215-39; Jeremy H. Groves et al., "Modelling of Floating Seed Dispersal in a Fluvial Environment," *River Research and Applications*, 2009, no. 25 (2009): 582-92.

4 Mauricio Antunes et al., "Programmable Ligand Detection System in Plants through a Synthetic Signal Transduction Pathway," *PLOS ONE* 6, no. 1 (January 2011): 1-11.

5 Roy Tarnuzzer et al., "Vacancy Engineered Ceria Nanostructures for Protection from Radiation-Induced Cellular Damage," *Nano Letters* 5 no. 12 (2005): 2573-77; Joseph Wang, "Microfabricated Electrochemical Sensor for the Detection of Radiation-Induced DNA Damage," *Analytical Chemistry* 69 no. 7 (1997): 1457-60; Brian Baker et al., "An Electronic, Aptamer-Based Small-Molecule Sensor for the Rapid, Label-Free Detection of Cocaine in Adulterated Samples and Biological Fluids," *Journal of the American Chemical Society* 128 no. 10 (February 2006): 3138-39; Antunes et al., "Programmable Ligand Detection System in Plants through a Synthetic Signal Transduction Pathway," PLOS ONE 6, no. 1 (January 2011): 1-11.

6 Antunes et al., "Programmable Ligand Detection System," 7.

is linked to the activation of genes that produce visual responses. The engineered mechanism is modular, so this detection system can be adjusted to detect and report most small molecules. However, these plants and similar explosive-detecting plant systems have not been regularly adopted. Currently, explosive detecting plants' response time competes poorly with conventional explosive detecting methods, such as special canine units, mass spectrometry, and x-ray machines.[7] Additionally, for preventing immediate terror strikes in public areas, intrusiveness and presence of explosive detecting tools can be a deterrent while the effort to develop hidden detectors is not necessary.

Researchers at Johannes Gutenberg University have found physical and chemical evidence of artificial smoke use in World War II in the rings of trees.[8] The use of artificial smoke by Nazis to hide the Tirpitz battleship left severe damage to trees in a two-and-a-half-mile radius from the Kåfjord. The deployed smoke screens in 1944 caused years of stunted growth and contamination in the surrounding trees. This effect of warfare on the environment and similar acts may provide further insight for the scope of plant-based sensors and suggest the use of retroactive determining technologies for detection of chemicals, explosives, nuclear materials, and pathogens through longer living plants.

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More recently, the transformational CRISPR genome editing technique discovered in 2011 has provided cheap and simple opportunities to modify plant genomes.[9] This discovery has led to the rapid development in the field of study surrounding plant-based sensors. In 2017, the Defense Advanced Research Projects Agency (DARPA) posted a funded opportunity announcement requesting research project proposals for genetically modified plant-based sensors as a part of its Advanced Plant Technologies (APT) program, and projects are expected to begin in mid-2018.[10] DARPA hopes to develop a variety of plants capable of competing in natural environments while also being able to detect and report many specific stimuli to monitor chemical, pathogen, and nuclear weapon developments.

DARPA requires its funded projects for plant-based sensors to be split into a laboratory phase, greenhouse phase, and integrative complex environment phase that together will take four years to complete.[11] After successful biosensors sensors are created, the genetically modified plants, or smart plants, would go through a series of biosafety committees to assess potential environmental damage resulting from their permanently modified genome and to avoid violating international environmental treaties. Department of Defense employment of APT would shortly follow, which can be expected optimistically within a decade. Commercial use

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7 National Research Council, Opportunities to Improve Airport Passenger Screening with Mass Spectrometry (Washington, D.C.: The National Academies Press, 2004), 1-42.

8 Claudia Hartl et al., "Warfare Dendrochronology - Trees as Witnesses of the Tirpitz Attacks," European Geosciences Union General Assembly Conference Abstracts 20 (April 2018): 12769.

9 Blake Wiedenheft et al., "Structures of the RNA-guided Surveillance Complex from a Bacterial Immune System," *Nature 477* (September 2011): 486-89.

10 "Broad Agency Announcement: Advanced Plant Technology (APT), HR001118S0005," *Defense Advanced Research Projects Agency Biological Technologies Office*, November 21, 2017, https://www.fbo.gov/index?s=opportunity&mode=form&id=b6cd364110ee04f9654b617249db8143&tab=core&_cview=1.

11 Ibid.

in the United States would require the Department of Agriculture and Animal and Plant Health Inspection Service to investigate and improve the technology.

Taking advantage of inert plant processes and modifying plant genomes to detect low concentrations of specific compounds is not a novel idea and has been performed in the laboratory before. Any state could replicate these experiments; however, it has not been proven if smart plants can directly detect conventional weapon compounds or nuclear radiation while surviving in the wild. Only recently, the US has sought out proposals from the public to develop this possibility.

Effects on Situational Awareness

Vantage and Range[12]

Plant-based sensors allow for the collection of local ground-based data that would otherwise require personnel and equipment to intrude on the party being monitored. Biosensors would be designed to be highly tailored to their environment and their desired stimuli. They would passively persist in an environment and detect desired stimuli while subtly reporting this data. In principle, biosensors can continuously report the presence of stimuli or lack of stimuli and cover large areas of land at low cost. Data generated by biosensors can be detected by conventional satellites, drones, and ground-based sensors that are already proven effective plant composition monitors for detecting visible and infrared radiation reflectance for farming and measuring spatial variability, or diversity, and growth for biologists and environmentalists.[13] In some environments, seasonal change would effectively decrease the operating time of a plant-based sensor each year. This concern entirely depends on the climate severity of the designated environment and the deployed modified plant's life cycle.

Speed

Plant-based sensors are a worthwhile research topic for national security because the sensor vantage points provide essential insight into early stages of development of explosive, chemical, and nuclear weapons. This provides the monitoring party additional time to plan and coordinate pre-emptive attacks, build coalitions, and prepare for conflict. The speed of collection and analysis of data depends on the mechanism a biosensor uses, which can vary from weeks to hours. Unlike other electrical devices, such as gamma ray detectors or neutron counters, plant-based sensors could not instantaneously provide information.

Resiliency

Successful plant-based biosensors would survive and reproduce in their selected environments for long-term monitoring of an area. Biosensors can be genetically modified into a plethora of host plants capable of living in most biomes. Any plants that are defective or killed are easily replaced by natural reproduction or cheap deployment as seeds. It would be very difficult for opposing parties to completely and discriminately inhibit or destroy deployed smart plants because of their numbers and ability to reproduce.

Reproducing plants with biosensors would create a vast network of data gatherers in a desired area after a few generations; however, the reliability of future generations of smart plants is not determined. The ability of future

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[12] To learn how this project defines the italicized terms, please visit the *On the Radar* website glossary, https://ontheradar.csis.org/glossary.

[13] Iftikhar Ali et al., "Satellite Remote Sensing of Grasslands: From Observation to Management," *Journal of Plant Ecology* 9, no. 6 (2016): 649-71; Guijun Yang et al., "Unmanned Aerial Vehicle Remote Sensing for Field-Based Crop Phenotyping: Current Status and Perspectives," *Frontiers in Plant Science* 8 (2017): 1-26.

generations of smart plants to detect and report specific stimuli could be jeopardized and reduced by pollution, radiation, natural selection, and cross-pollination with non-modified plants.

(Un)detectability

Plant-based sensors are a highly unobtrusive solution compared to alternate means of monitoring conventional and non-conventional weapons development and presence. Smart plants would be genetically modified native species in their target environment and thereby indistinguishable from plants that are not genetically modified. If smart plants were detected by an adversary, attribution of the smart plant design and deployment would be difficult.

Precision

Plant-based sensors provide a qualitative assessment of specific stimuli in an environment. The determination of signatures of specific nuclear weapons relevant activity would be difficult because of biosensor novelty and biologic limits. Furthermore, although stimuli presence is known, the source of stimuli would be ambiguous. Plant-based sensors may not be able to determine the scale of chemical, explosive, nuclear, or pathogen weapon presence and development, but reporting plants would give enough evidence to elicit further investigation and caution.

Persistence

Deployed plant-based sensors constantly and passively monitor their surrounding environments. Smart plants have the potential to continuously live in their deployed environments and reproduce to become long-term data gatherers.

Risk Factors for Strategic Stability

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Intrusiveness

Plant-based sensors are designed to operate in enemy territory and in close proximity to the site or area being monitored. Plant-based sensor output can be collected by satellites, drones, or other non-intrusive devices from a distance. Although in adversary territory, engineered plant sensors are indistinguishable from other natural native plants and do not raise concerns for local populations or adversaries being monitored. This technology provides an opportunity to determine radiation, chemical, and explosive presence or manufacturing with evidence that would otherwise only be attainable from on-sight inspection and sample collection.

Destructiveness

Plant-based sensors do not actively destroy or damage adversary resources. Deploying gene-edited plant-based sensors would make permanent changes to that plant species' genome, and specific effects on the environment may be unknown for months or years after deployment. It would be incredibly difficult and damaging to remove smart plant-based sensors from their deployed area completely; genetically modified plant-based sensors would resemble natural native plants and deployed plants would become integral to their adoptive ecosystems.

Predictivity

Plant-based sensors provide a new and covert way of gathering land-based and on-site evidence of specific weaponry. The party that employs this technology would be able to determine the existence of chemical, explosive, nuclear, and pathological weapons in their early and manufacturing stages. This insight would give the monitoring party supporting evidence and confidence to take actions against the monitored party earlier and before the monitored party uses the weaponry.

Dual-use

Plant-based sensors are able to detect and report the presence of specific chemical compounds, nuclear radiation damage to smart plants, and changes in the environment from nuclear radiation. These insights help determine the presence of nuclear, chemical, and explosive weapons in many stages of their life cycle. Plant-based sensors also have many commercial applications. Plant monitoring has helped farmers increase productivity and has helped ecologists detect industrial pollution and other environmental risks. The advancement of gene-editing techniques can ease these processes and expand the detectable environmental factors.[14] For example, the company Plant Route has been developing biotechnology to not only detect explosives but to also detect heavy metal pollution from mining sites.

Clandestine

Use of plant-based sensors is enticing because of the ability to collect data in circumstances where outside monitoring would usually be blocked or hindered by the party being monitored. Plant-based sensors would be deployed on adversary territory; an adversary aware of deployed plant-based sensors would remove them, block their ability to report, block their ability to detect, or avoid the limited range of detection these plant-based sensors would have. However, successfully deployed modified plants would be very hard to identify in an environment, and their existence may be unknown. Adversaries who discover plant-based sensors being used against themselves in their territory would not be able to immediately identify who deployed the smart plants because the biologic material would not necessarily have any human or technologic trace.

Concluding Remarks: Risk versus Reward

The deployment of plant-based sensors would fill the intelligence gap between satellite and drone imaging used for intelligence, surveillance and reconnaissance and on-site inspection by military personnel, with the former often described as lacking the necessary details and the latter being too intrusive. Plant-based sensors would detect and report local stimuli that give early insight into chemical, explosive, pathogen, and nuclear development and use. While this reporting may not be quantitative or indicate a specific source, it could prompt actors to act with caution and further investigate the source of stimuli earlier than otherwise.

Plant-based sensors are designed to assimilate to their environment, and their reporting is remotely detectable by specific instruments that are currently fully developed. The targets of this technology most likely won’t think to test these specific instruments on their local ecosystems for self-reporting plant-based sensors. A case-by-case

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[14] Yang et al., *Unmanned Aerial Vehicle Remote Sensing*; Lingli Wang et al., "Satellite Remote Sensing Applications for Surface Soil Moisture Monitoring: A Review," *Frontiers of Earth Science in China* 3 no. 2 (2009): 237-47; Ellis F. Darley, "Use of Plants for Air Pollution Monitoring," *Journal of the Air Pollution Control Association* 10 no. 3 (1960): 198-99.

analysis of targets' sensor capabilities and the likelihood of detecting smart plants deployed against them would be required to develop tailored biosensors that would report stimuli subtle enough while still being distinct from their specific environment. A target party detecting an anomaly in its territory caused by tailored smart plants would have to investigate the anomaly, successfully assign it to human intervention, ascertain the role of the smart plants, and then determine the intervening party before taking confident escalatory and destabilizing actions. A target party that is aware of smart plants deployed against itself would have to reverse engineer a plant-based biosensor to understand what stimuli it reports before successfully giving deployed smart plants false information.

Successful plant-based sensors create long lasting, self-sustaining, and reproducing populations that continually collect intelligence, but these populations would be hard to remove if they ever caused environmental or diplomatic issues in the future. Additionally, target parties would interpret the deployment of these smart plants as an extreme infringement to their security. More specifically, the deployed smart plants' capabilities would be unknown, and their risk to security could easily be overestimated and labeled as biological warfare, a malicious threat to targeted ecosystems and an attack on farms. Therefore, the utility of plant-based biosensors depends on their ability to remain covert. There are many stages of research and development needed to convert this well-established proof of concept to a large, self-sustaining scale. Furthermore, the ethics of plant-based sensors and gene-editing are still unclear. However, the rapid advancement and understanding of gene-editing and the plant genome make plant-based sensors an appealing way to monitor weapon development and use to help secure strategic stability.