How does Nature regulate atmospheric composition?

Formaldehyde removal from air

Paper 11586-3 Authors:

Claudia Rivera, Atmospheric Sciences Center, National Autonomous University of Mexico, Mexico City, Mexico
claudia.rivera@atmosfera.unam.mx

Anne-Marie Daniel, NatuR&D, Roy Group Leadership Inc.
North Saanich, BC, Canada
annemarie@naturnd.com

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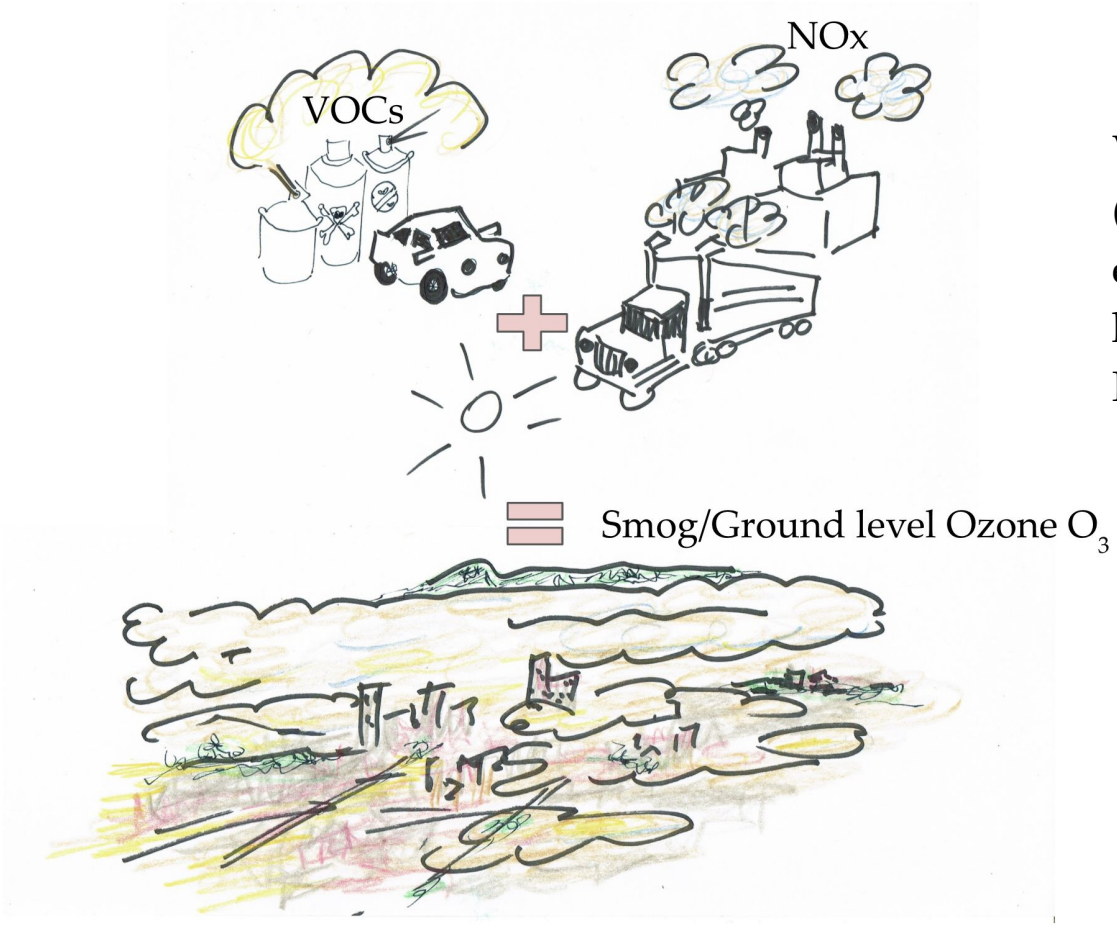
Formaldehyde (HCHO), a common Volatile Organic Compound (VOC) generated from human activity and industry, is everywhere in the indoor and outdoor environments in the Mexico City Metropolitan Area (MCMA).



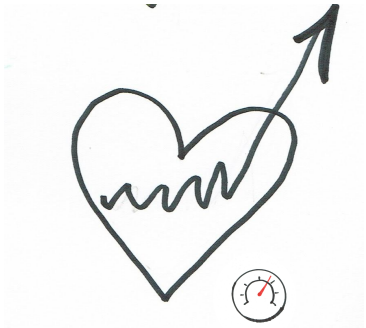
VOCs react with nitrogen oxides (NOx) creating frequent ozone (O_3) events which are hazardous to human and ecosystem health in the MCMA.

Common VOCs are

- benzene
- toluene
- ethylene glycol
- methylene chloride
- tetrachloroethylene
- xylene
- 1,3-butadiene
- HCHO

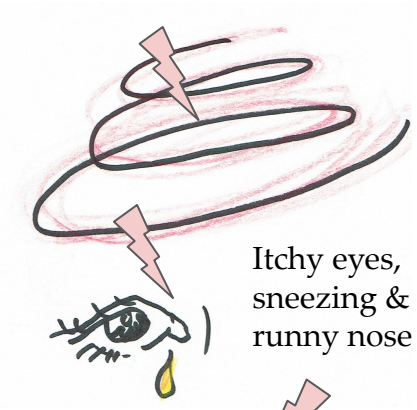
All of these VOCs are hazardous and are known to cause a number of health-related issues including respiratory distress, eye, nose and throat irritation, frequent headaches and nausea. They can also damage the liver, kidneys, and central nervous system.

Sick Building Syndrome, resulting in high worker absenteeism and poor health, has been linked to the presence of VOC loads on indoor air quality.[2]



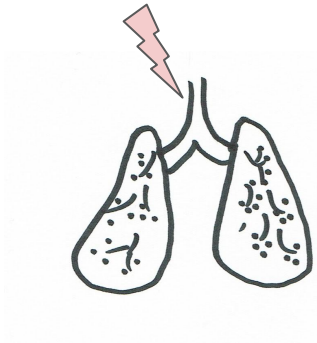
Elevated blood pressure

Frequent headaches



Itchy eyes, sneezing & runny nose

Kidney damage



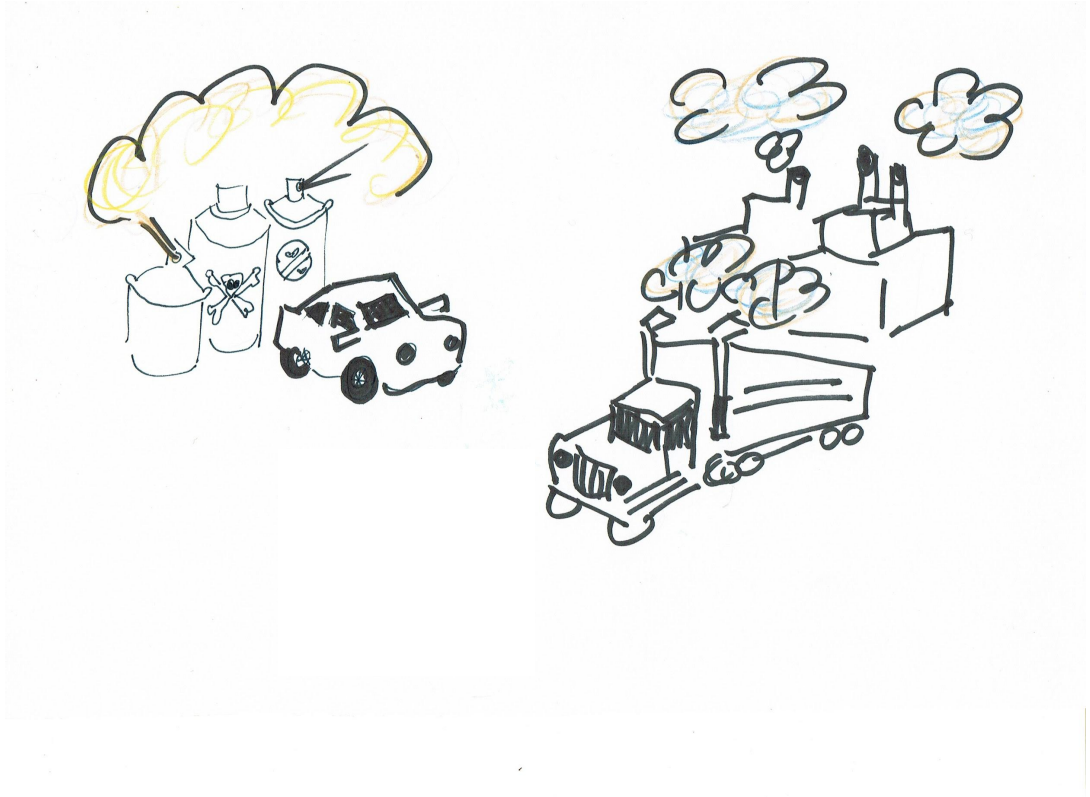
Asthma attacks

Image: Claudia Rivera, MCMA

VOCs from human activity affect sensitive ecosystems by reducing photosynthesis and growth of some plants sometimes resulting in death and consequently, changes in ecosystem diversity, water, and nutrient quality.[3]

The main pathways of human exposure to formaldehyde are industrial fumes, residential housing and occupational indoor settings.[4,5]

In addition, several studies indicate that HCHO is genotoxic,[6] causing gene mutations in mammalian and bacterial cells.[4]



Atmospheric Considerations

HCHO is unevenly distributed in the atmosphere of our planet (Figure 1). Areas with enhanced HCHO abundance in the atmospheric column (hotspots) can be observed over regions where for example forest fires or industrial activities such as chemical production, wood processing or in general burning of fossil fuels occur.

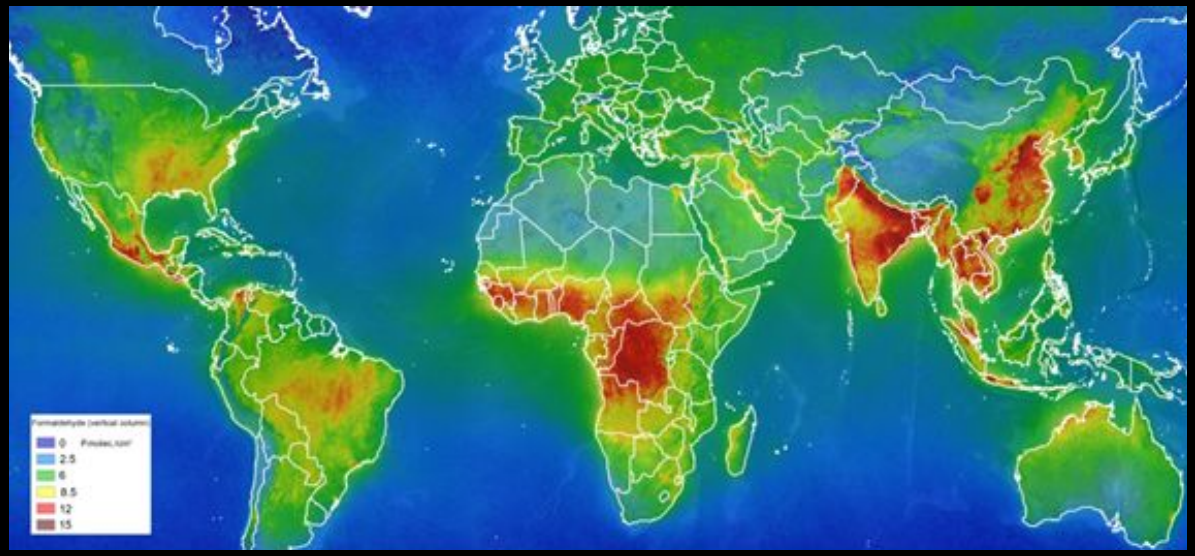


Figure 1. HCHO distribution in the atmosphere. Averaged measurements conducted by the Copernicus Sentinel-5P mission between January and August 2018. [7]

Unhealthy levels of O_3 are most likely to develop on hot sunny days in urban environments.

O_3 can also be transported long distances by wind, so even rural areas can experience high ozone levels.[11,12]

$$\text{Sunlight} + \{[(CH_4)(CO)(NMVOCs)]+(NO_x)\} \rightarrow O_3$$

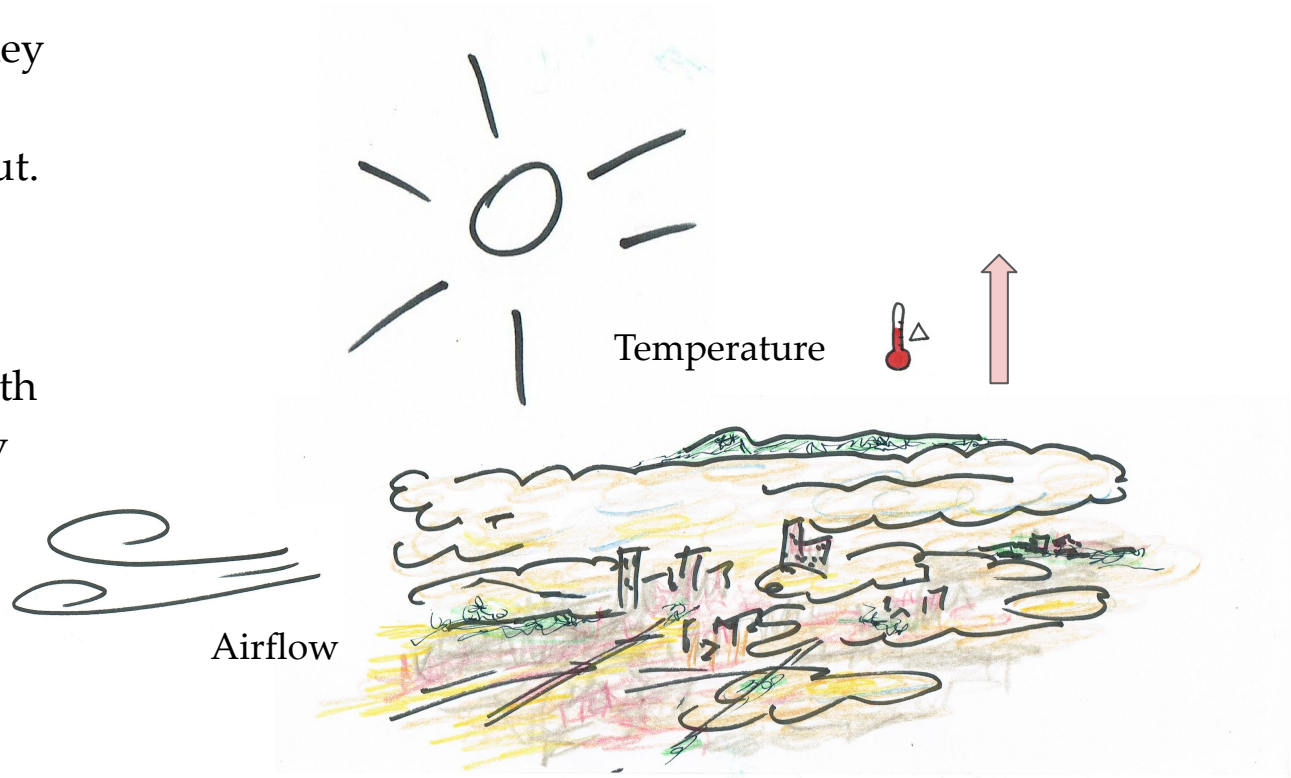
Currently, people living in countries with higher GDPs, spending 90% of their time indoors, are 45-75% less affected[13] by O_3 because they are somewhat protected by sealed space the building envelope provides and the quality of the HVAC system.

They are however, still vulnerable to the presence of the chemical reactions of O_3 with the components of the buildings and furnishings, often emitting HCHO.

Image:Claudia Rivera, MCMA

Temperature and airflow are key factors in atmospheric climate regulation both indoors and out.

Climate change is predicted to have an increasingly negative influence on our air quality with higher temperatures, humidity from flood and storm events, wildfires, particle and pollen loads, and ozone events.[14]



Atmospheric Monitoring Methods in the MCMA

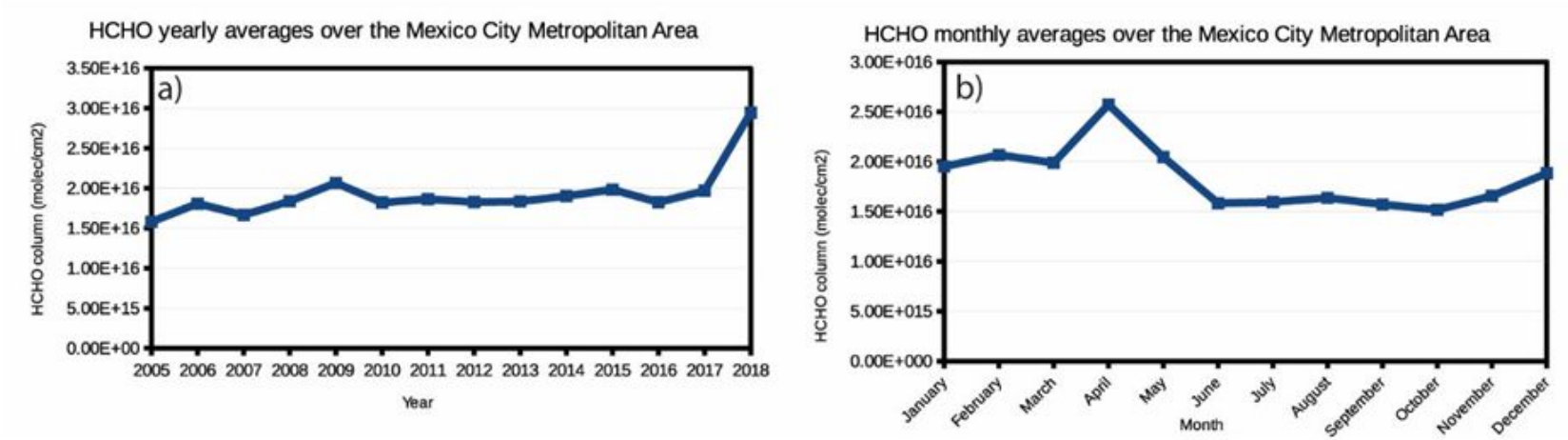


Figure 2. HCHO yearly (a) and monthly (b) averages over the MCMA. An increasing trend of HCHO abundance between 2016 and 2018 over the MCMA can be clearly observed.

Current Technologies

Technology	Materials	Impacts
Mechanical filtration	Ducts made of galvanized sheet metal coupled with fabric and granular carbon filters. In order for the system to filter, air needs to be circulated in the device, typically using an in-line fan, needing an external power supply.	$ Higher costs Need access to external power supply.
Indoor passive panel technologies (ceiling tiles)	Sorptive panels or photocatalytic oxidation (PCO)-based materials in order to remove formaldehyde from air.	PCO based indoor passive panel technologies can generate O_3 and carbonyls as by-products, which results in unwanted exposure of people to those chemical species.
Metal organic frameworks for indoor environment applications	Dual functional adsorbent/catalysts in non-thermal plasma (NTP) catalytic reactors.	During the NTP oxidation reaction, O_3 and several organic compounds are detected as by-products.
A high quality system of passive O_3 removal materials	Activated carbon mats and perlite-based ceiling tiles are 50% effective.	Requires large areas of the home and optimal air transport conditions. The size of the system relative to the area of the building limits the aesthetic quality of the interior. $ Higher costs

Biological Treatment Methods

Technology	Materials	Impacts
• biofilters, • biotrickling filters • membrane bioreactors • bioscrubbers	The microorganisms do the work at ambient conditions. The mix of microorganisms must correspond to the mix of VOCs, therefore a deep understanding of the microbiome being engineered is key. This includes managing the moisture content, pH, substrate composition, temperature and nutrient availability. Organic materials like peat, soil and compost are optimal substrates because of their high-specific surface area, stability and cost.[38]	Lower operating, capital costs and carbon emissions Deep knowledge and capacity in managing microbiomes is created The clean air delivery rate (CADR) is most dependent on the composition of microbiome and aeration of the substrate, the plant itself contributing only by a factor of 2.[39] The presence of vegetation creates aesthetics, carbon sequestration, operation at ambient temperatures and without the white noise associated with HVAC systems.[40]


Image: Eric Salazar Herrera, MCMA

Where is the best point of intervention?

Given the urban sprawl, the strategy of limiting automobile traffic has not achieved the desired results and is not realistic.

Requiring or promoting indoor air quality technology is also beyond the budget of the majority of residents and is not an easy retrofit for the existing buildings.

Addressing indoor air quality on its own does not reduce ozone events or support overall wellness for the community and the ecosystem.

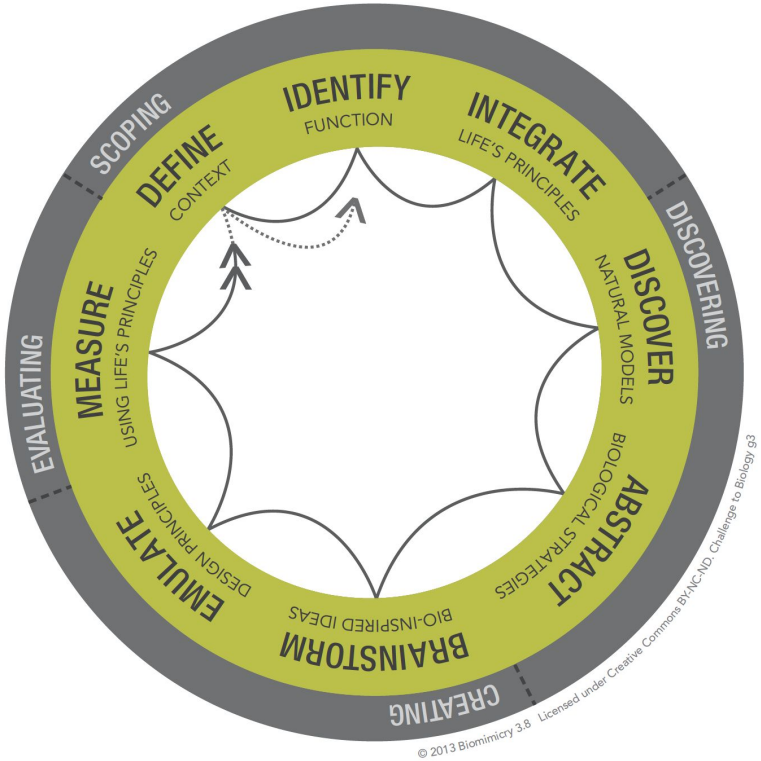
We employ the Biomimicry Thinking Methodology,[1] and ask:

"How would Nature solve this problem?"

BIOMIMICRY THINKING
Biomimicry DesignLens

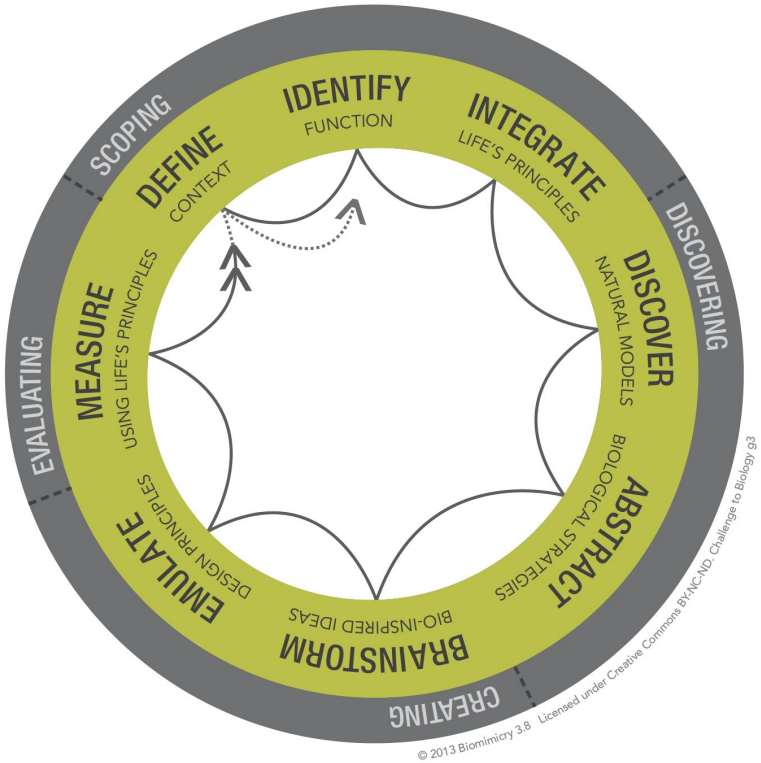
CHALLENGE TO BIOLOGY

Challenge to Biology is a specific path through Biomimicry Thinking. This is useful for scenarios when a specific problem is at hand and you are seeking biological insights for the solution. It is particularly useful for a "controlled" setting, such as a classroom, or for creating an iterative design process. Not surprisingly, the best outcomes occur when you navigate the path multiple times.



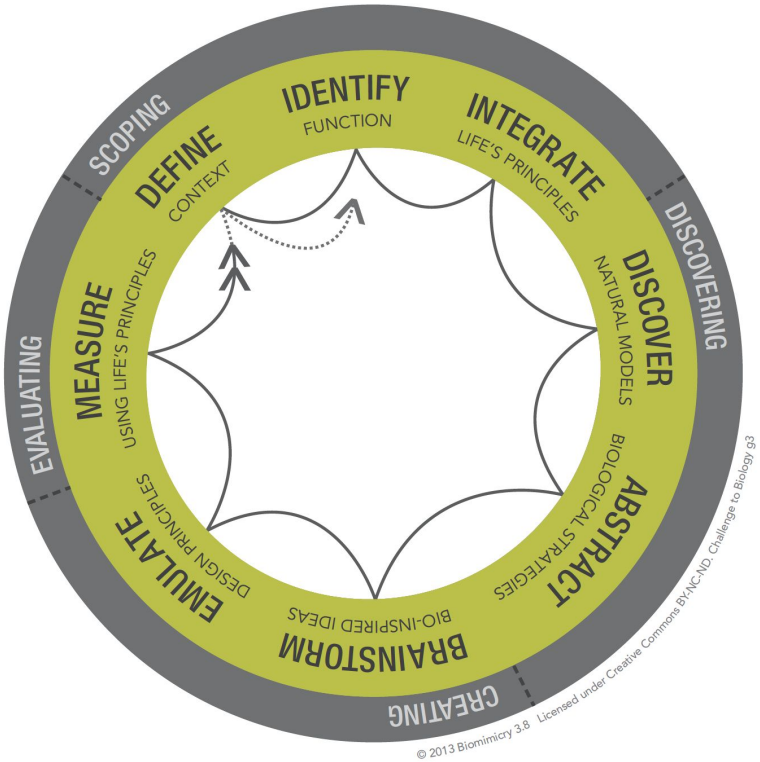
Scoping

- Defining Context
- Identifying Function
- Integrate Life's Principles

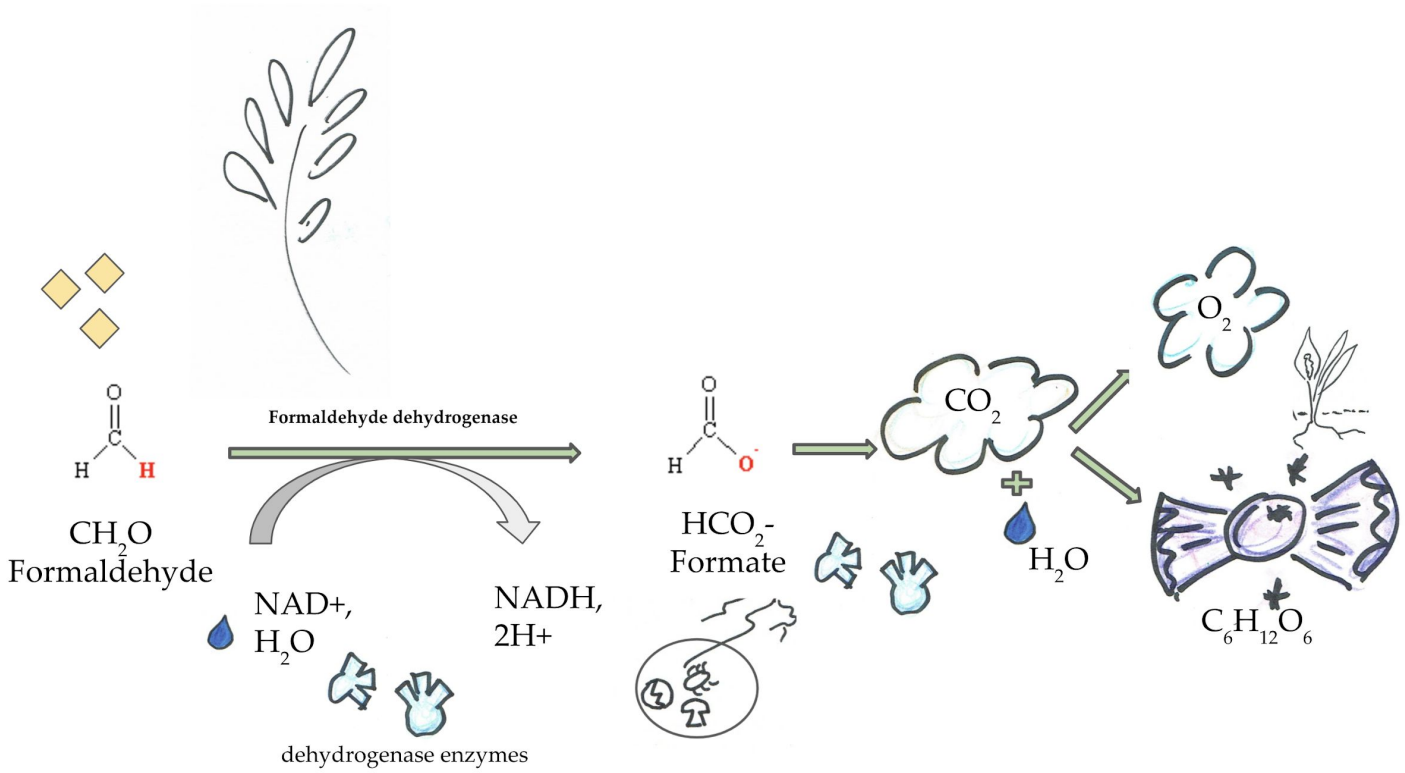


Discovering

- Natural Models
- Abstract Biological Strategies



Biological Pathway of Formaldehyde CH_2O



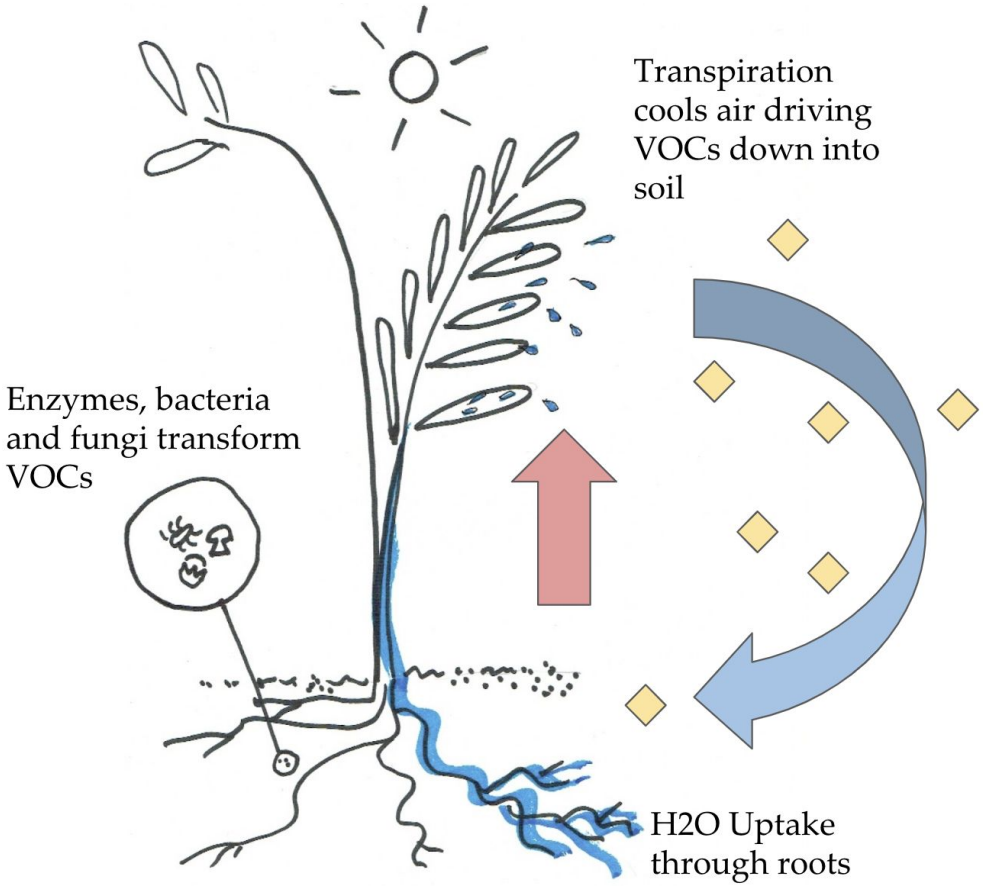
Discover Natural Models:
Plants

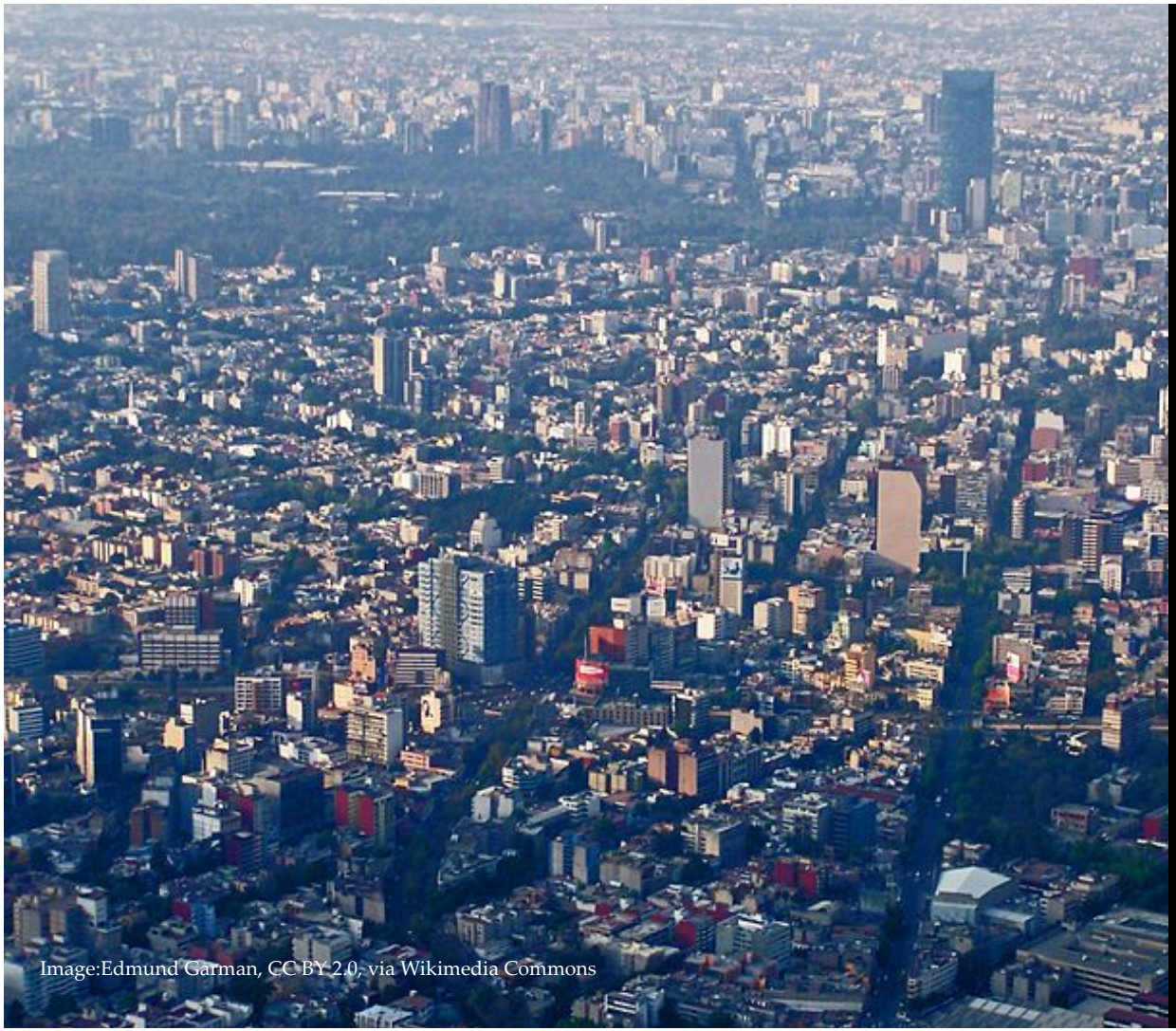
In total twenty five organisms were researched, many of them belonging to several families:

- Asparagaceae
- Araceae
- Solanaceae
- Arecaceae
- Moraceae
- Araliaceae
- Nephrolepidaceae
- Apocynaceae
- Convolvulaceae
- Osmundaceae
- Asteraceae
- Pseudomadaceae

Wolverton[70] reports that plants release water vapor through their leaves to cool the air which creates convection currents to bring down VOCs from the atmosphere to the soil where microorganisms biodegrade them. Enzymes, fungi and bacteria transform VOCs.

Removal of VOCs is accomplished by convection currents and biodegradation of microorganisms.





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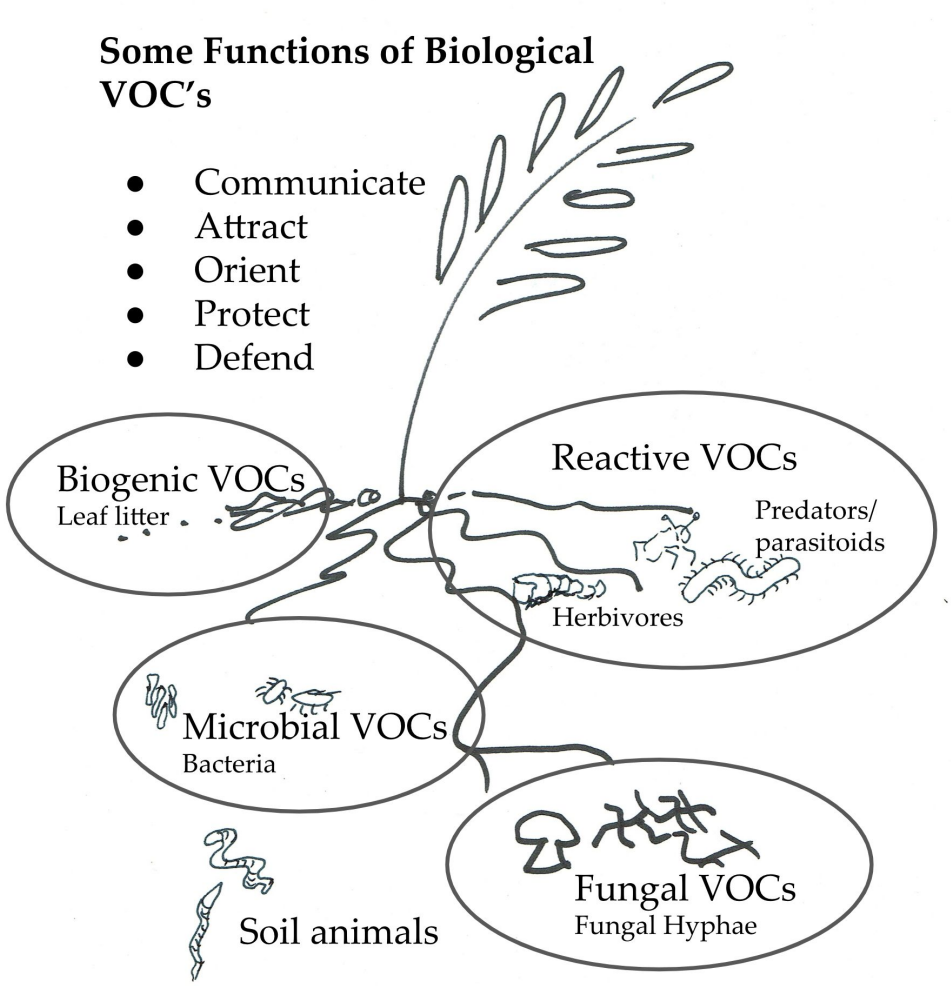
Parks, rain gardens, vertical green walls, green roofs, and general urban vegetation plantings contribute to cooling of the urban climate because they increase surface roughness which improves convection efficiency.

Rainfall is intercepted by the canopy and groundcovers reducing runoff rates, which are then slowed by the root system, allowing for greater absorption and creating more evapotrans-piration potential.

Biogenic VOCs

Most of the processing of VOCs happens via the soil biota.[45,59,72] The fungi and bacteria create many of their own VOCs to help or inhibit plant or animal fitness.

We know very little about the complex dynamics of biogenic VOCs but we do know that they are highly balanced.[45]

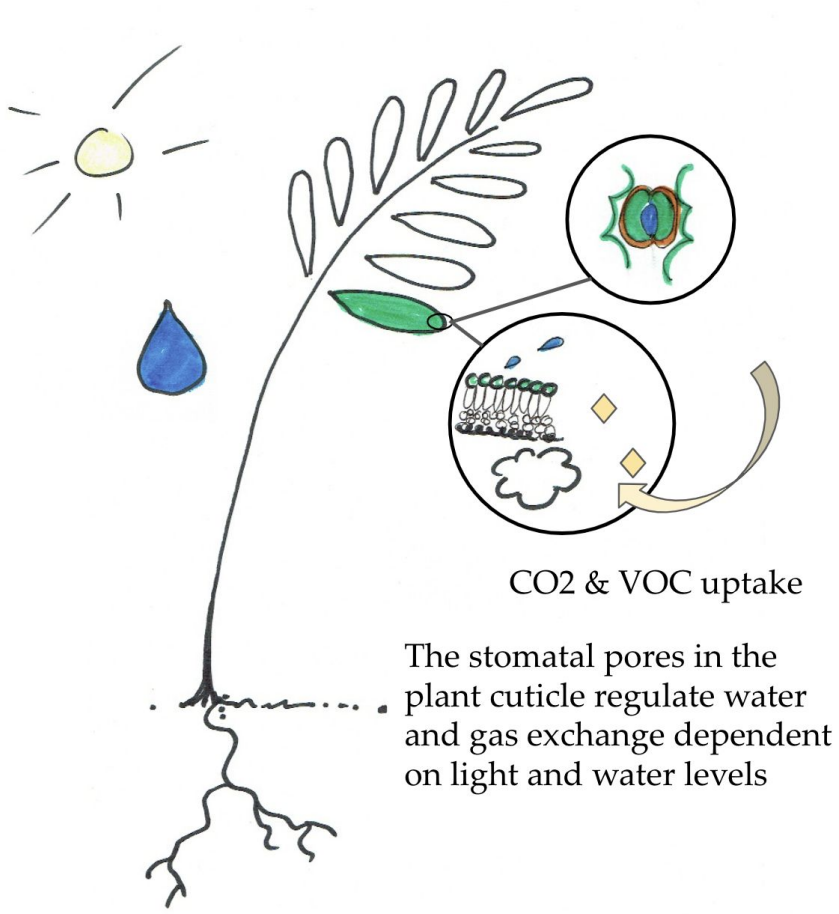


Uptake of HCHO

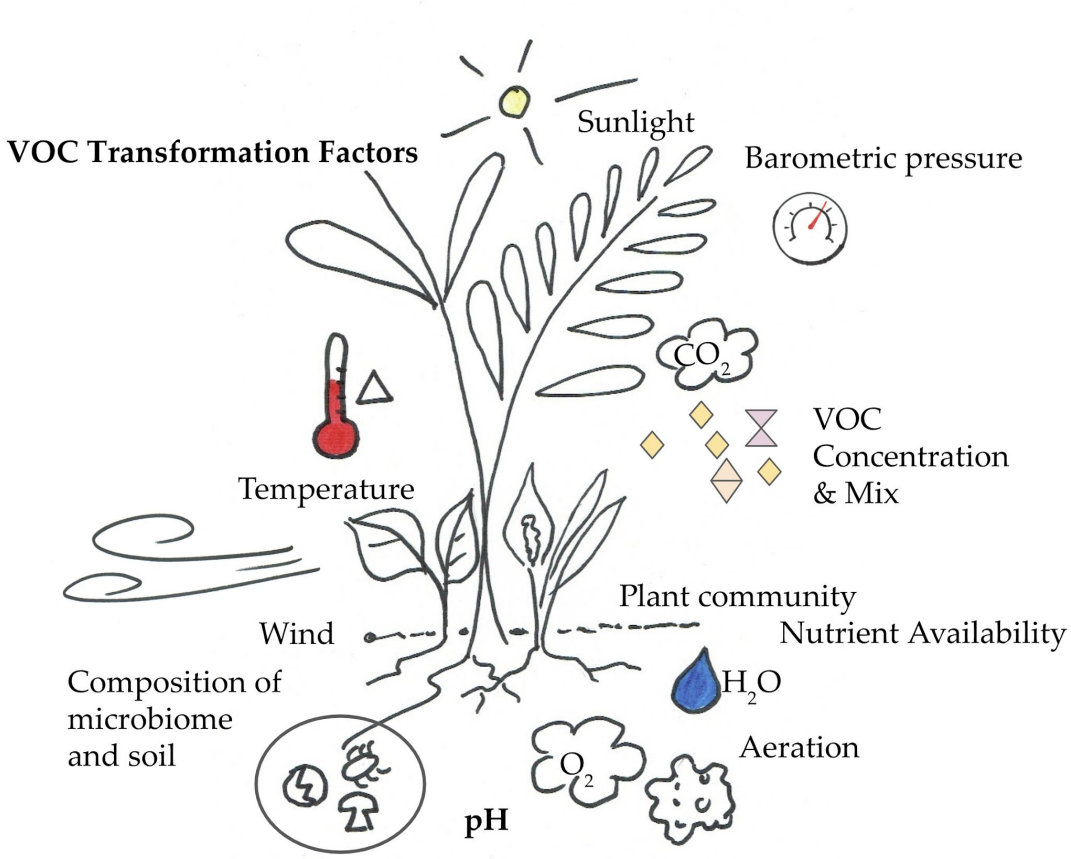
A positive linear relation between the removal of HCHO through stomata and stomatal conductance by *Nerium indicum* is reported.

Plant stomatal movement is induced by light and can therefore affect HCHO removal.

The removal of HCHO by plants may be diffusion-limited rather than reaction-limited.



The rate that the soil either emits or sinks the compounds is affected by many factors.



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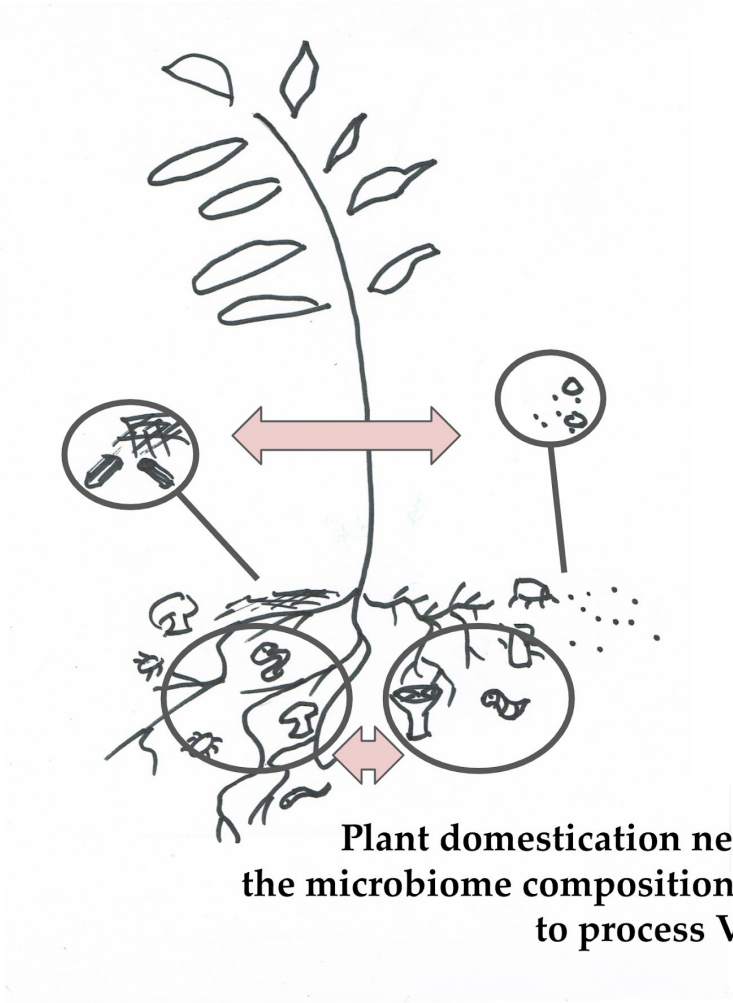
Holobiont Context

Agler et al.[62] conclude that the microbiome must be understood in a holobiont context (host and its associated organisms). Connectivity was observed and microbial hubs identified cross an area pointing to the need for more research into the "functions of host-associated microbiomes".

Microbiomes perform many beneficial ecological functions such as air and water filtration, greenhouse gas sequestration, and supporting our food systems. We don't yet fully understand how the VOCs created by the soil function in keeping life in balance the ecosystem[45].



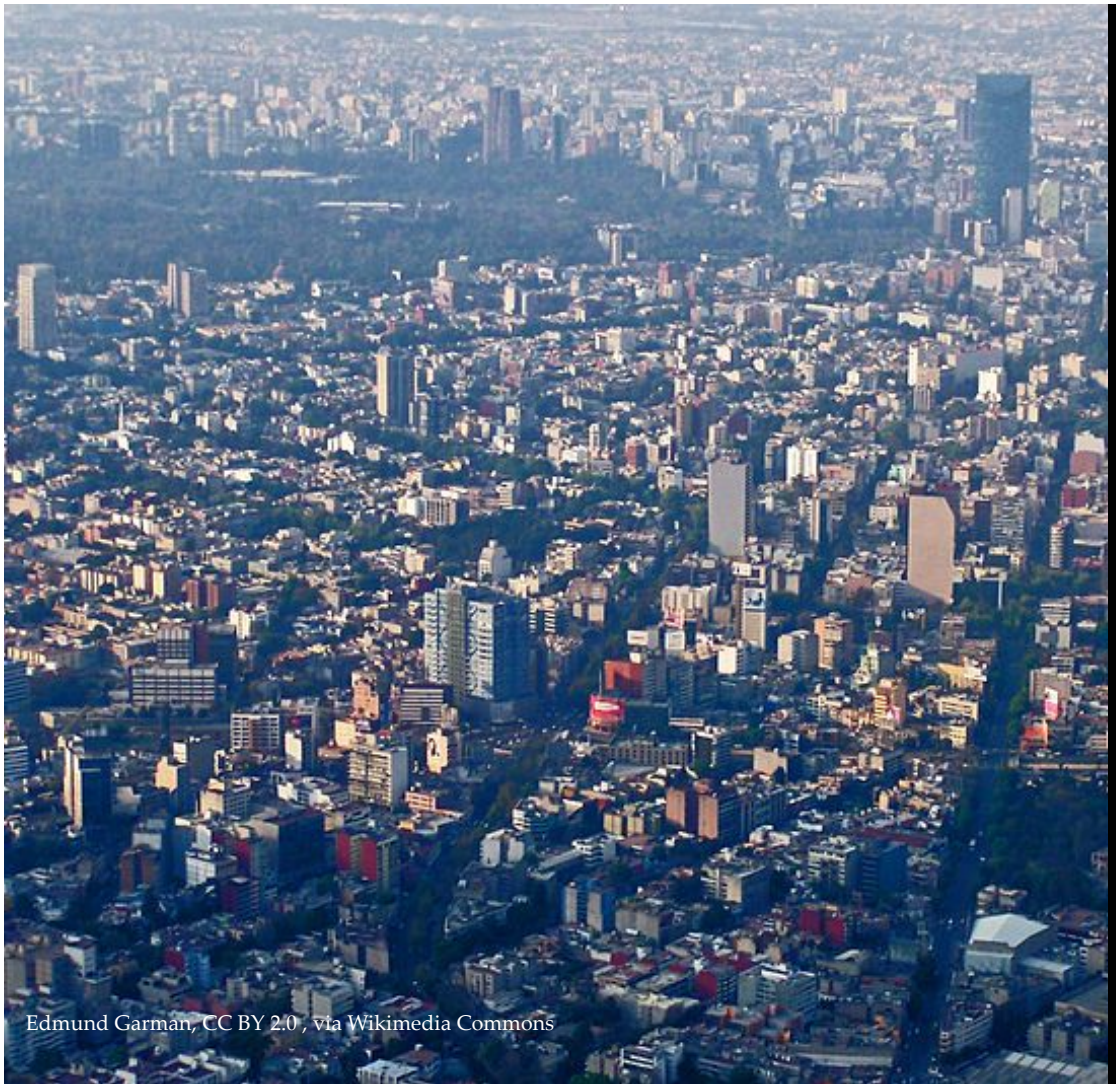
Creates differences in:

- Soil structure
- Environmental conditions
- Chemical ratio C:N
- Microbiome species

Creates changes in:

- Farming and stewardship practices/cultural norms
- Root architecture
- Plant DNA by trait selection & breeding
- Exudate composition

Plant domestication negatively impacts the microbiome composition & functional capacity to process VOCs



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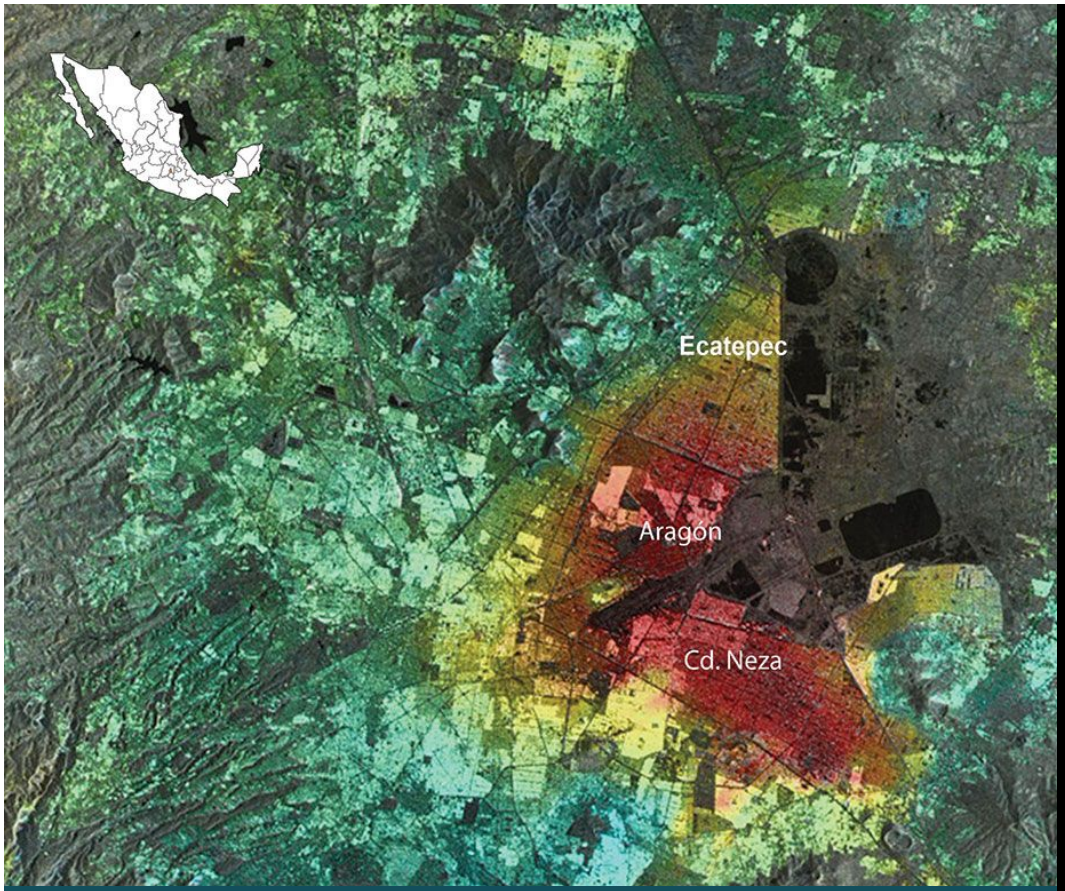
Some Benefits of Natural Spaces

- Processing of some VOCs including HCHO
- Air and water filtration
- Wellbeing of population
- Health of population
- Groundwater recharge
- Food
- Noise mitigation
- Biodiversity
- Cooling
- Beauty
- Climate regulation
- Carbon sequestration



The German Aerospace Center's (DLR) radar satellite
TerraSAR-X imaged Mexico City over 4 months between 9/2009 &1/2010
Red = greatest change
United Nations Office of Outer Space Affairs
https://www.unoosa.org/oosa/en/informationfor/articles/the-force-of-nature-in-mexico--as-seen-from-space.html

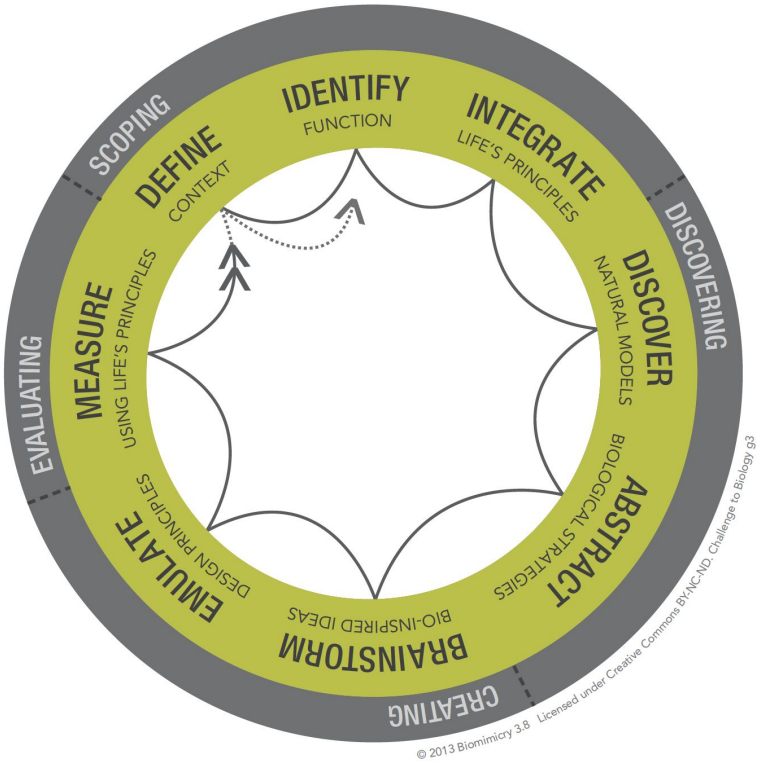
The valley of the MCMA soils facilitate infiltration and underground water circulation due to their composition being mostly made of a sequence of alluvium and volcanic materials.[86]

More water is extracted from the aquifer than is able to be replenished by rainfall, causing compaction and subsidence which affects the stability of the land and water distribution.[87]

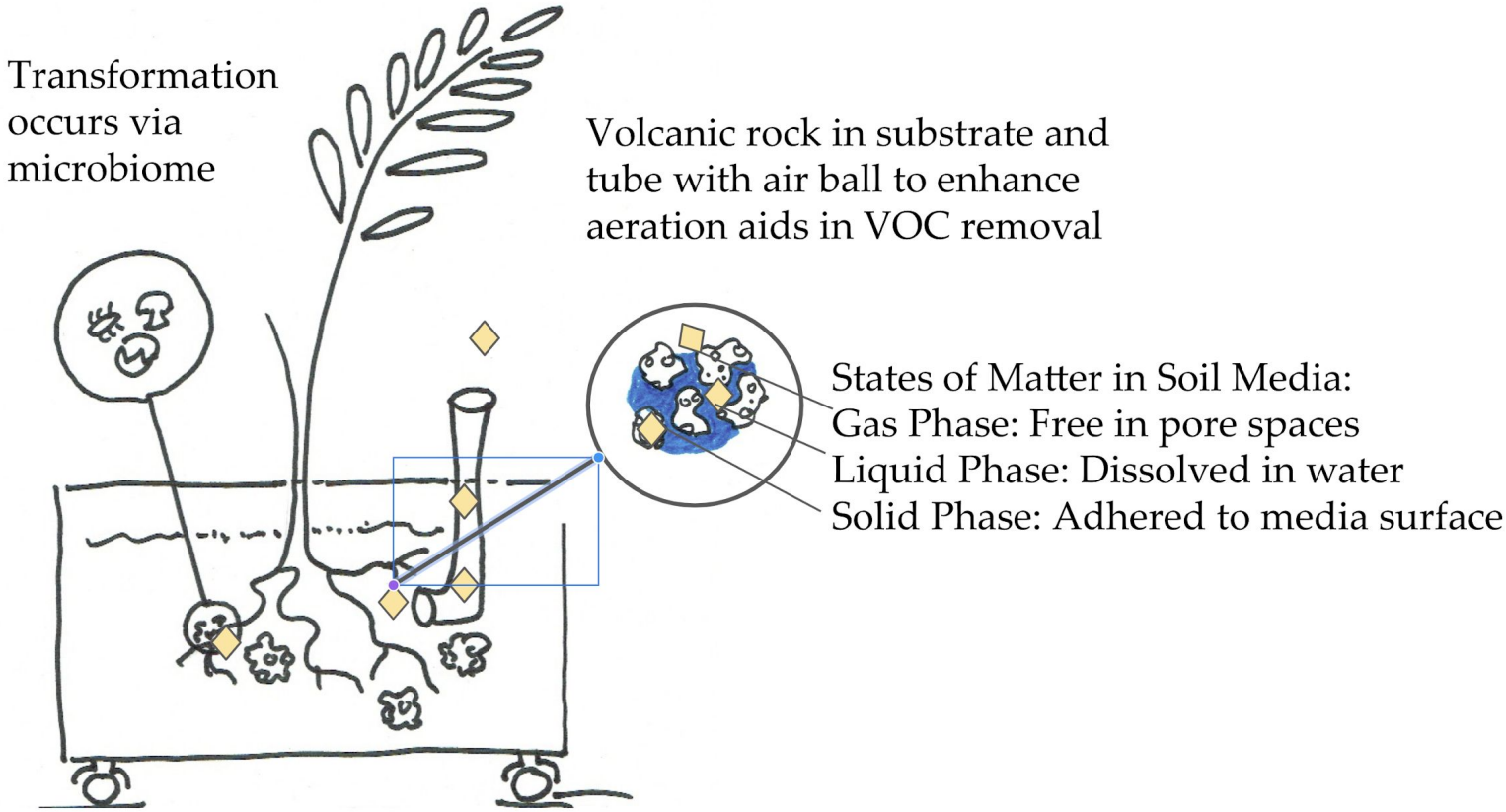
Of interest is the finding that Mexico City's soils are thixotropic, meaning they have the capacity to recover their structure and strength with time.[88]

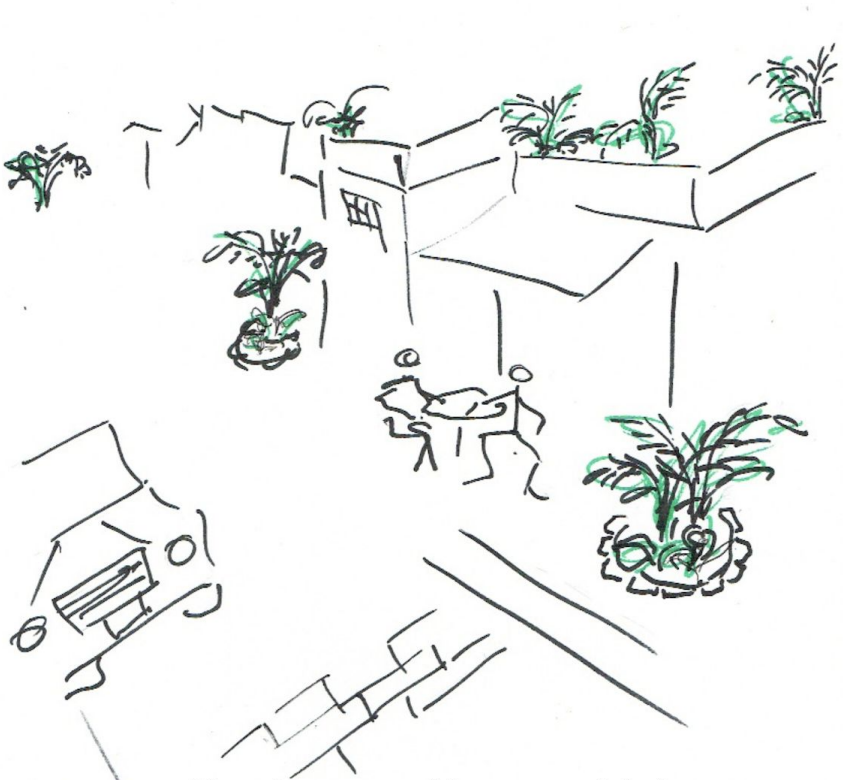
Creating

- Brainstorm Bio-inspired Strategies
- Emulate Design Principles

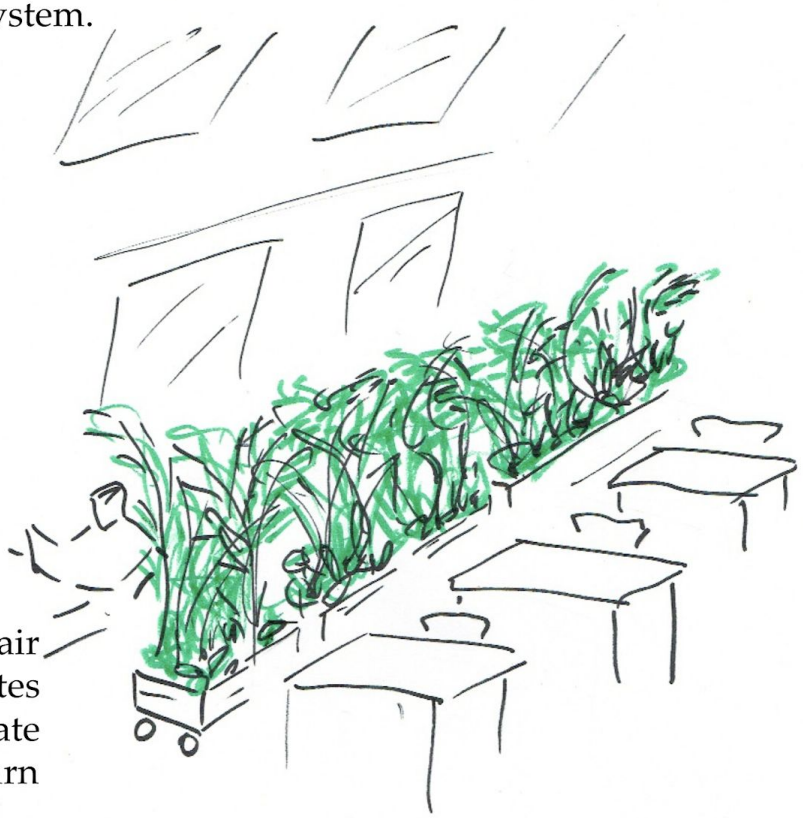


The Prototype





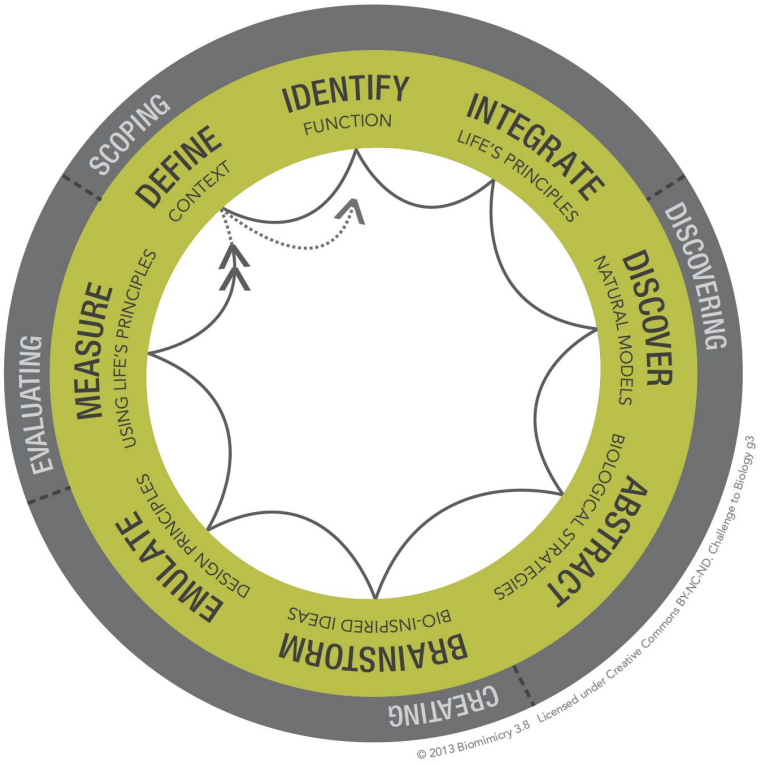
An indoor nursery of native plantings act as living machines, transforming VOCs, improving air quality. Mature plantings are moved outdoors to reinforce the local ecosystem.



Plantings provide natural infrastructure by filtering air & water, removal of harmful gases and particulates from the atmosphere, carbon sequestration, and climate regulation while supporting biodiversity that in turn benefits agriculture.

Evaluating

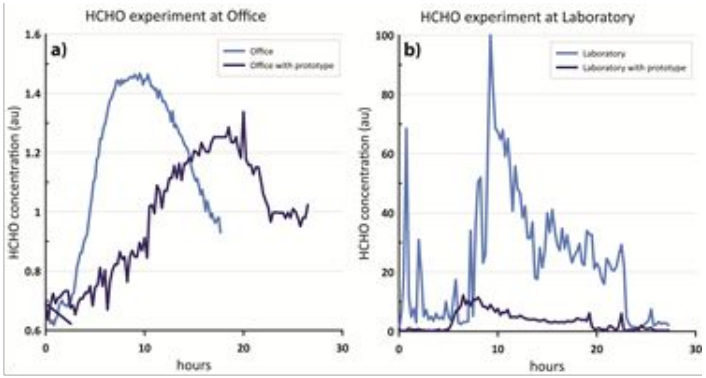
- Measure using Life's Principles



Measurement Techniques

Grove HCHO Sensor

- Target Gases: HCHO, Benzene,Toluene,Alcohol
- Concentration Range: 1~50 ppm
- Conductivity changes with the concentration of VOC gas in air
- Suitable for detecting formaldehyde, benzene, toluene and other volatile components
- Can be used to detect harmful gas in the home environment



Measured values at an administrative office indicate that HCHO abundance is low compared to more polluted environments *(in this specific case an organic chemistry lab)*, however a decrease on HCHO levels is observed after the prototype was deployed.

At the organic chemistry lab, the measured levels of HCHO before the prototype was deployed were two orders of magnitude higher than those of the administrative office. After the prototype was deployed in the lab, the values dropped at least one order of magnitude, and in some cases, reached values as low as the values of the administrative office.

The simplicity of the Grove sensor and the small planter points to the potential of giving control to the average citizen in monitoring and mediating HCHO concentrations in their indoor environments.

Plants are well known for improving indoor air quality and their benefits are often overlooked in green building action.[41] Experimental results presented in this paper indicate that the prototype is able to reduce the abundance of HCHO in indoor air locations.

Although several researchers have conducted tests and previously proposed using plants to remove HCHO from indoor environments,[39,40,59] this “VOC transformer”design offers a strategy that reinforces also the health of the local ecosystem. A holistic solution is a desirable feature.

Research monitoring of green infrastructure features pointed to increased thermal comfort with vegetation at the pedestrian level. A study of planting in ditches has demonstrated significant reductions in street level concentrations of NO_2 and particulates[41].

It is necessary to identify the specific plants of a specific location that facilitate a microbiome able to both function naturally and accommodate additional VOC loads.

Local and indigenous knowledge should be sought in growing site-specific soil microbiomes indoors for relocation outdoors in the urban ecosystem.

Image: Fidel Gonzalez, CC BY-SA 3.0

The MCMA air quality problem needs to be addressed both indoors and outdoors. This city is already overdeveloped with subsidence problems due to overexploitation of groundwater extraction.

The Biomimicry Thinking Methodology[1] was used in this study to address the research question, "How does Nature regulate atmospheric composition? Formaldehyde removal from air."

Benefits of Restoring the Soil Profile & Native Microbiome Using Mobile "VOC Transformers"

- Processing of some VOCs including HCHO
- Air and water filtration
- Wellbeing of population
- Health of population
- Groundwater recharge
- Food
- Noise mitigation
- Biodiversity
- Cooling
- Beauty
- Climate regulation
- Carbon sequestration
- Ecosystem balance
- Sophisticated chemical transformations that render pollutants benign

Popularizing the understanding of local plants as "VOC transformers" for both indoor and outdoor environments and supplying easy-to-use monitoring equipment would help citizens improve air quality, their health, and ecosystem connectivity on private and public property.

Advances in public policy to allow forms of natural or "green infrastructure" in the urban environment[102] show that mimicking Nature at the systems level can lead to effective and affordable strategies for processing of VOCs, which would likely contribute to overall resilience to O_3 events, climate change and a sense of wellness.

Image: Claudia Rivera, MCMA

Image: Claudia Rivera, MCMA

Human and ecosystem health are inextricably linked. Restoring soil as a design intervention supports the central Life Principle to the Biomimicry Thinking Methodology that “Life Creates the Conditions Conducive to Life”.[103]

We hope that this research and design inspires a broader system perspective in designing for air quality, coupled with a deeper awareness of how the health of our soil is a key factor in atmospheric regulation and HCHO removal.

ACKNOWLEDGEMENTS

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Pacific Southwest Region USFWS from Sacramento, US, Public domain, via Wikimedia Commons

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