FOREST PATTERNS AS A MODEL FOR URBAN MORPHOLOGIES

VARIATION AND DISTRIBUTION

Tree species of the Tamborine rainforest, North Tamborine, Queensland, Australia
The rainforest is morphologically diverse, exhibiting patterns of dense strata through its spatial organisation.

What can we learn from the spatial logic of collections of trees in the rainforest? **Evan Greenberg** of the EmTech programme at the Architectural Association (AA) School of Architecture in London and **George Jeronimidis** of the Centre for Biomimetics at the University of Reading combine forces to analyse the rainforest's morphology and its potential as an urban model. They suggest how the sectional height differentiation of trees could present a new way of thinking about urban organisation, accommodating varied microclimates, programmes and the city's infrastructural flows.

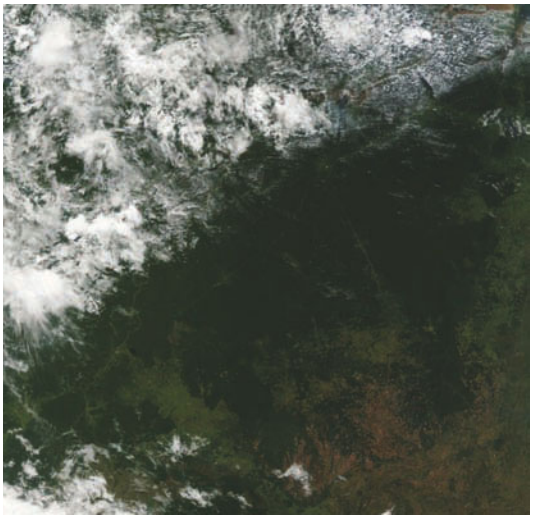
The distribution patterns of trees in the rainforest have developed over thousands of years through cycles of growth and decay, competition and adaptation. Emerging from this dynamic yet homeostatic process, that is, one capable of internal regulation to maintain a state of equilibrium, is a complex global morphology with differentiated microclimates, generated from a finely tuned coordination of flows of various information and energy networks. This spatial logic can be extracted and developed as a new model for city systems, where the distribution of morphological variation at ground level coupled with sectional height differentiation generate productive microclimates capable of environmental negotiation and dynamic spatial and cultural effects.

British biologist D'Arcy Wentworth Thompson states in his seminal work *On Growth and Form* (1915) that 'the form of an object is a "diagram of forces", in this sense, at least, that from it we can judge of or deduce the forces that are acting or have acted upon it'.[1] In biology, all living forms obtain a specific morphology through the collection, negotiation and exchange of energy. This metabolic process is crucial in the development of individual forms, and even more so in the relationship between individuals.[2] The flow of energy and information between individuals creates emergent patterns within the collective, with higher levels of functionality and performance. This association has been well researched in social insects such as termites, ants and bees, where each individual is programmed with a specific set of tasks and interactions, creating highly specialised morphologies with precisely controlled microclimates. Forests are collectives of trees competing for resources and coordinating energy exchange. The morphological outcome of these relations is a highly diverse forest, especially in tropical climates, capable of providing a suitable environment for a vast number of plant and animal species within differentiated productive microclimates.

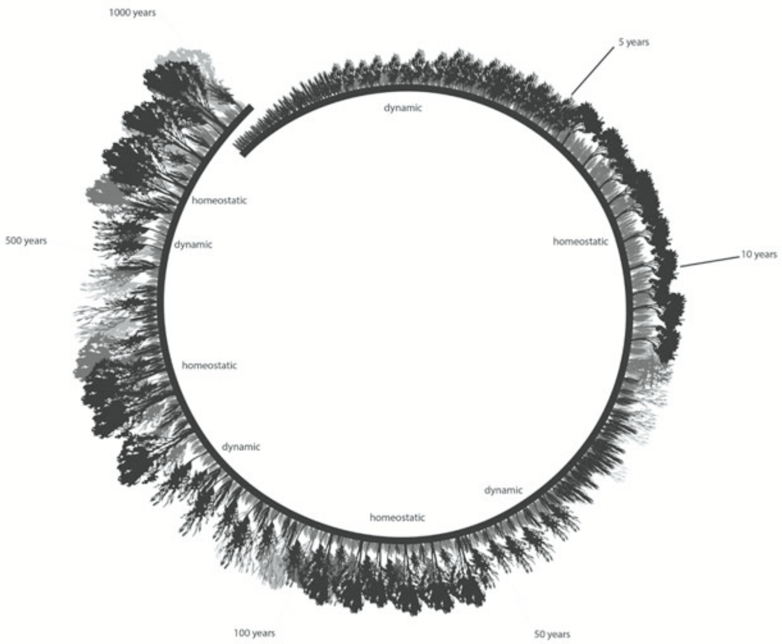
The forest is a highly complex and diversified environment, covering roughly 30 per cent of the earth's land mass.[3] The first forests emerged 360 million years ago through the evolution of water algae and primitive plants in response to continental drift and carbon dioxide availability. By responding to the need for stronger root systems, maximum exposure to sunlight and land reproduction strategies, these organisms evolved into larger plants with advanced vascular systems, roots and leaves, eventually becoming the first trees.[4] Trees evolved in groups, as forest patches, yet individually as singular species, creating layered 'forest communities'.[5] The earliest trees, and specifically seed-producing trees, evolved the ability to reproduce globally over vast land areas, and in time, competition among trees gave way to deeper roots, differential branching strategies, complex flow structures and intelligent leaf organisations.[6] All trees share these characteristics, and all species follow particular mathematical models for growth, adaptation and survival. Within these models, each species follows a predefined genetic rule set modulated by adaptations to environmental pressures while still allowing for response to competitive pressures.

From the study of the evolution of tree populations, it is possible to relate mathematical and functional patterns of the forest to the design of cities and their networks. By understanding the initial genetic rule set of individual trees, and the relationships between the hierarchies in which they exist in the forest, intelligence can be designed into buildings and their arrangement within the city to generate highly performative urban organisations capable of negotiating environmental conditions, managing energy flows, distributing infrastructural networks and creating complex spatial and microclimatic environments.

Trees have an incredibly complex internal organisation focused on the capture and distribution of sunlight and water. They are made of cellulose fibres stiffened in tension, giving them the structural effectiveness to not only stand up, but also to create transportation networks for the flow of water from roots to leaves, and energy captured from leaves to roots. The mathematical branching and leaf arrangement logics present in trees optimise structure and the transfer of materials within.[7] In isolation, a tree will grow with a straight vertical trunk and branch patterns designed to maximise canopy exposure to the sun at specific latitudes.[8] But however calculated the material organisation and mathematical logics of trees may be, they rarely conform to their optimality model, and are in a constant state of morphogenesis. Trees grow in response primarily to gravity and sunlight, and develop specialised tissues, tension and compression wood – depending on species – in order to support unexpected directional growth of branches and achieve shape adaptation of trunks.



Overhead view of the Amazon rainforest
Thirty per cent of the earth's land mass is covered by forests, home to thousands of diverse species living in differentiated ecosystems and microclimates throughout the world. Geneticist and evolutionary biologist Theodosius Dobzhansky concluded in 1950 that the increase in biological diversity from the poles to the equator was a result of multiple small but stable forest habitats.



Phases of sylvigenesis in a tropical rainforest
above: The rainforest is in a constant flux of growth and decay. Its sylvigenesis is a homeostatic process of negotiating numerous flows of energy.

Structural ensembles of a tropical rainforest
opposite: The rainforest is a series of dense layers comprised of three major structural ensembles: trees of the past, present and future.

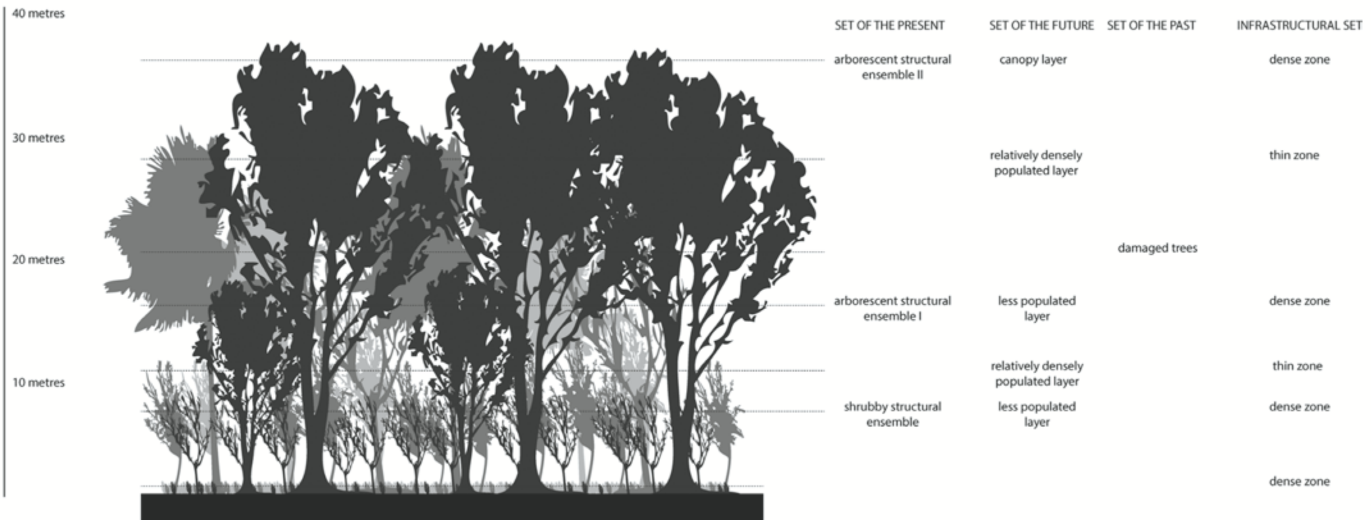
DISTRIBUTION PATTERNS AND THE PERFORMANCE OF THE FOREST

Similar patterns of growth can be observed when looking at a collection of trees in the forest, and more specifically in the rainforest. The constant sylvigenesis, or generation of the forest's global form, is a homeostatic process, distributing various flows of energy within a constant state of equilibrium. While the energy captured by individual trees cannot be redistributed directly to surrounding individuals, there exist explicit interactions between forest hierarchies and individual organisms in relation to energy consumption, employment of resources, recycling of materials and spatial organisations.[9] The competition for light resources, in fact, is believed to have led to the synthesis of the natural adhesive lignin[10] in trees, which is produced within the cell walls and responsible for binding the cellulose fibres together. This allows trees to be structurally stiff, and hence to grow taller and increase canopy size giving them the ability to survive as energy-capturing and energy-distributing organisms.

Competition not only affects morphogenesis of the single organism, but also of the entire forest. Rather than the common view of the existence of four global strata (emergents, canopy, understorey and forest floor), the rainforest can be seen as a series of layers of varying densities, or 'structural ensembles', comprising individuals with three morphogenetic strategies. The first group require no further growth, in that their crowns are exposed to the sunlight necessary for maximum energy capture and conversion, and they have achieved their genetic limit. The second group are typically in the forest understories, and are either expanding or waiting to expand – they will very rapidly fill any 'light niche' that becomes available when a large tree falls down. Finally, there are also damaged or dead trees that do not compete actively as do the other groups, but slow down the growth of neighbouring trees.[11]

As the rainforest is destroyed by wind, earthquakes, animals or other natural phenomena, branches or entire trees fall to the forest floor, damaging some trees below, but also allowing for trees in lower structural ensembles to take advantage and grow into the gaps that result.[12] The first structural ensemble possesses the densest canopy and limits solar access to the ground. While it is true that all trees require sunlight to grow and multiply, the trees in the second structural ensemble survive through the adaptation of chlorophyll distribution and the maximisation of the photosynthesis process. Trees in these underlayers tend to have larger leaves of a darker green or blue colour to make greatest use of the available sunlight. Additionally, some leaves contain red hues that scatter light through the tree canopy, and velvety or satin textures that focus light down towards the forest floor.[13] From a larger ecosystemic view, the effects of the dense canopy on the rainforest create completely new microclimates which are both comfortable and highly productive for many other trees and plants, fruits, insects, birds and other animals.[14] In fact, these conditions are essential in the sylvigenesis of the rainforest through the symbiotic relationships that exist between various species.

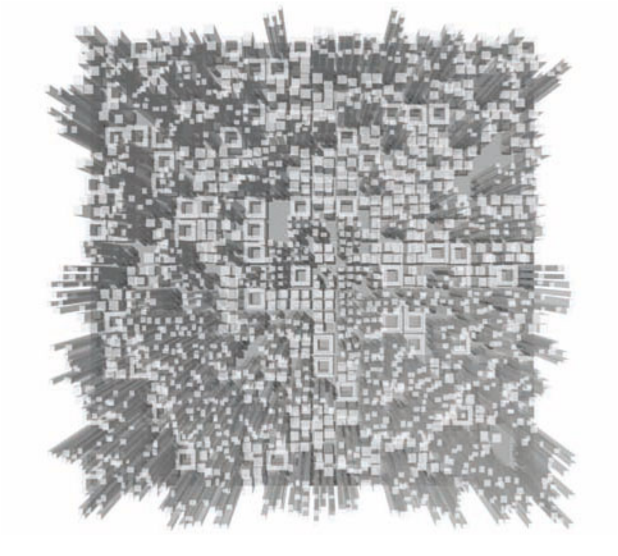
> But however calculated the material organisation and mathematical logics of trees may be, they rarely conform to their optimality model, and are in a constant state of morphogenesis.

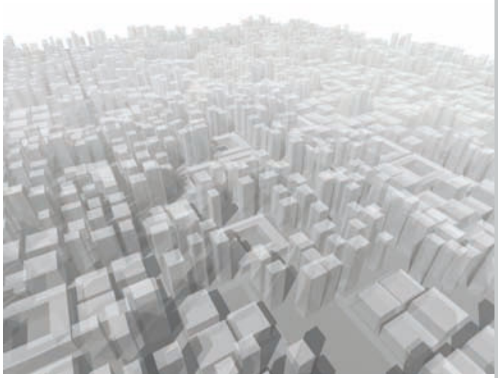


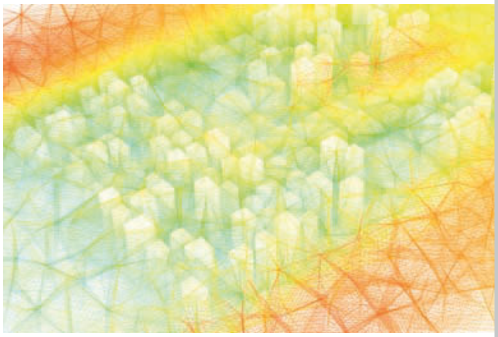
While many forests, particularly in continental and colder climates, contain little variation among species, within the sectional layers of the tropical rainforest lies an exceedingly differentiated population, where often only one individual per species per hectare exists.[15] This hierarchical relationship between global structural ensembles and local diversity is especially evident in rainforests[16] and allows for clever adaptation and extreme robustness under varying conditions. Forest gaps provide intense spots of sunlight exposure that in turn allow for extremely rapid growth. Additionally, the gaps create varied microclimates with differentiated lighting, moisture and wind conditions.[17] Thus the forest responds to environmental pressures at different rates. While gap dynamics and the trees that respond to them are specific to larger events that occur within the forest, all trees must also adapt to seasonal and daily climatic changes. Chemical signals are spread through the air downwind, and trees (although not as frequently as herbaceous plants)[18] can communicate with each other regarding mechanical or predatory damage. Communication also occurs chemically underground between root systems. While trees cannot uproot and move locations, they can induce structural and internal organisational changes to aid defence. The ability to communicate through environmentally distributed signals can often allow trees to expend energy for effective defensive response, reducing the number of late responses to predators and other failures.[19] In the forest, trees also use these signals to anticipate environmental patterns and shed leaves or blossom flowers accordingly in order to conserve energy resources. This response is a global coordination[20] scattered with local specialised events.

So while individual trees are programmed with specific strategies for growth and survival, the rainforest's emergent morphology is a complex result of adaptation to competition among highly differentiated individuals and a finely tuned coordination of flows of various information and energy networks. Through this understanding of the forest's spatial logic, distribution patterns and growth strategies, we can begin to develop similar systems for cities. The city has been referred to as an organism since the late 19th and early 20th centuries by urban planners such as Ebenezer Howard and Patrick Geddes, with a predefined optimal size, cohesive integrated infrastructure and inherent tendency towards homeostasis.[21] And across numerous scales of hierarchy, just like natural systems, cities too have a lifecycle of birth, growth, maturity and decay.

Due to changes at the local, regional and global scales in both human and environmental flows, the infrastructural and information networks within the city are in constant flux. Furthermore, contemporary technology allows individual buildings to communicate through intelligent building material systems embedded with sensing, management and actuation capabilities. Just as trees can react to changes within the forest, buildings can now also sense environmental conditions in real time and react through adjustments to their material makeup. These local building interactions, however, are part of the larger collective system that is the city. A building's ability to filter and modulate the environment has a larger effect on both internal and external climates and incidental effects throughout the entire city.





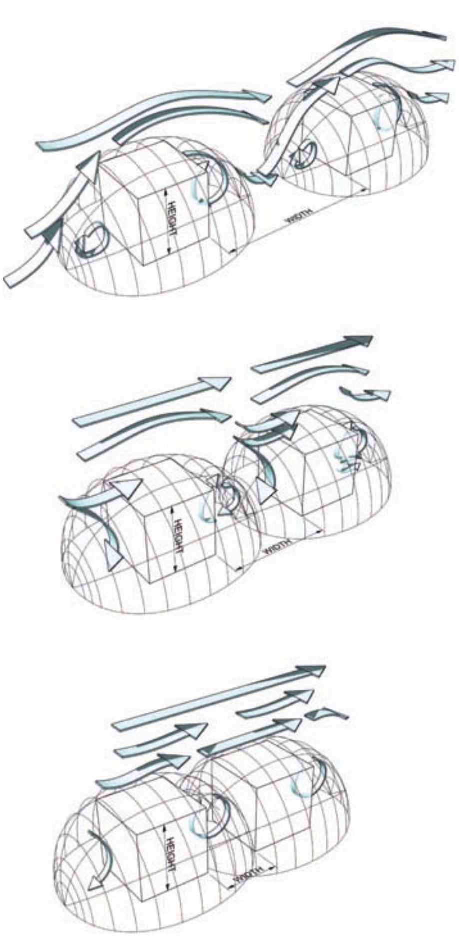


Urban patch utilising the concept of structural ensembles
above and top right: Urban blocks fit within three overlapping height bands (12–24 metres, 18–42 metres and 40–90 metres) in order to generate density differentiation while limiting repetitive block morphologies.

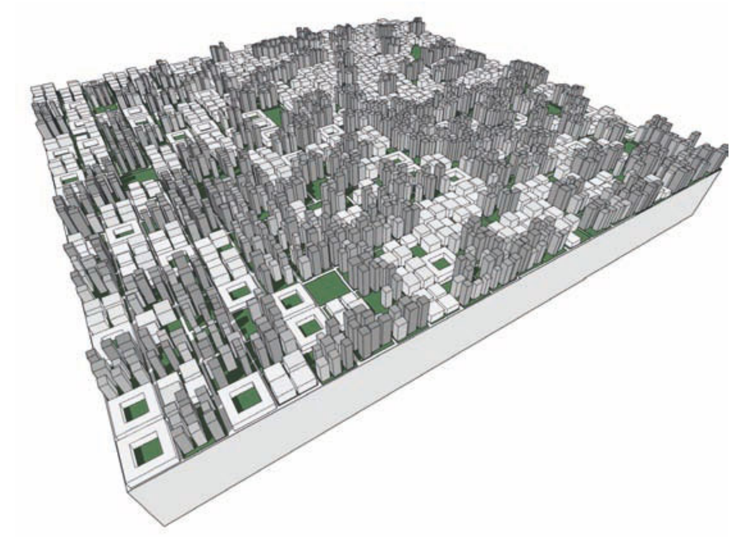
Differentiated air velocities due to morphological variation
bottom right: By varying the planar and sectional distribution of urban block morphologies, a large number of differentiated microclimates emerge three-dimensionally, with varied air velocities and ventilation rates.

Environmental negotiation therefore has a direct effect on morphology and the creation of productive microclimates. This urban form can arise out of the patterns of distribution of city blocks based on the logic of structural ensembles in the rainforest. The specific location of a tree species is governed predominantly by the dispersal and deposition of seeds and establishment of root systems. While these processes are not random, they are also not integral to the observed patterns of the structural ensembles, as each dense layer of the rainforest contains numerous different species acting within its stratum. The emergent effects of the forest are not therefore dependent on their planar position in the forest, but directly linked to their strata, governed by their embodied energy and past, present and future growth strategies.

By designing the city with structural ensembles in mind, city organisations can take advantage of controlled natural lighting conditions and canyon wind flow regimes. Cities are often designed in density gradients, locating specific programmatic districts, 'downtowns' and outskirts. However, by scattering densities throughout, there is the possibility to create numerous microclimates through a series of scales: from neighbourhoods and blocks to urban squares and market streets, down to bus stops and pedestrian walkways. By using a three-dimensional approach to design focused on sectional strata rather than planar zoning, buildings' blocks can be designed by height categories with varying street widths in order to control wind velocity and solar access to create differentiated microclimates at ground level. The emergence of varied solar access patterns can be coupled to patterns of airflow in order to achieve desired light and ventilation conditions. Building heights control solar access at ground level; street widths can then be optimised in order to increase or decrease natural ventilation, affecting the perceived temperatures for pedestrians. By generating sections where large building heights are coupled with narrow street widths (height-to-width ratios above 0.65), or small building heights with very wide streets (height-to-width ratios below 0.5), users at ground level are sheltered from high wind speeds, but also subjected to poor ventilation. On the other hand, designing with height-to-width ratios between 0.5 and 0.65 allows for lower wind speeds and possible natural ventilation.[22] Through a careful choreography of local height differentiations and street dimensions, desired microclimates can thus be achieved. This in turn allows for urban uses in pockets of specificity and intensity not necessarily suitable for a specific regional climate.



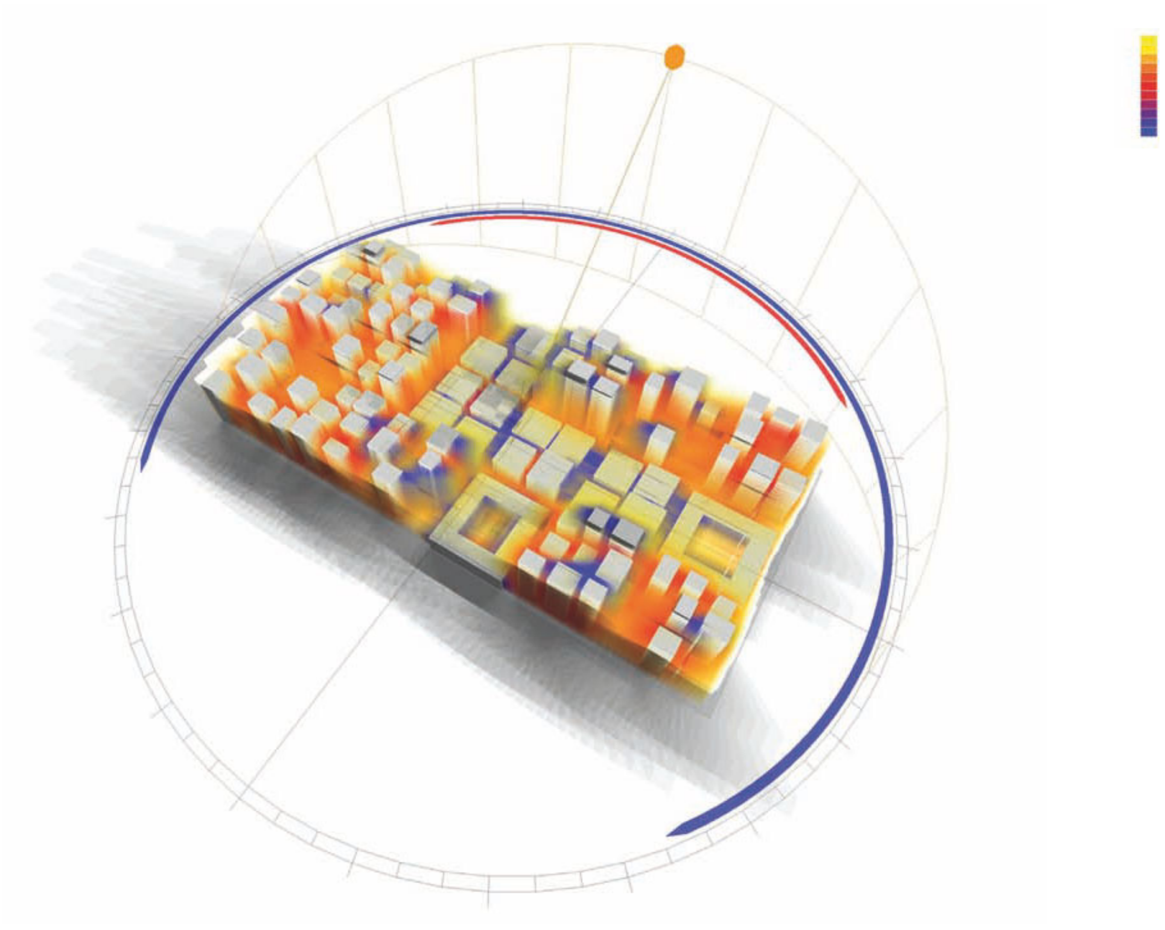
Canyon wind flow regimes
The height-to-width ratio of urban canyons creates changes in wind speeds at ground level while also encouraging or retarding natural ventilation. Top to bottom: An isolated roughness flow with a height-to-width ratio between 0.3 and 0.5 creates wind patterns similar to isolated buildings; a wake interference flow with a height-to-width ratio between 0.5 and 0.65 creates low wind speeds and turbulence, promoting ventilation; a skimming flow does not allow a great deal of wind to enter between buildings, resulting in poor street ventilation.



Height gradients of an urban patch
An urban morphology generated with gradients of heights and densities across blocks can create varied microclimates and unexpected yet productive urban environments.

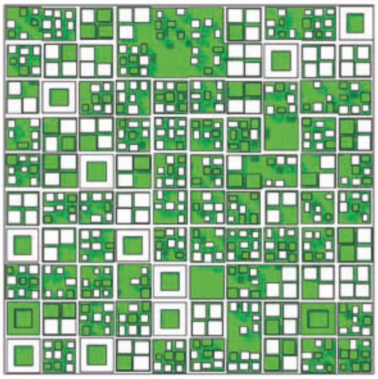
The urban fabric is rich and diverse, and thus becomes a heterogeneous landscape of emergent interactions within a homeostatic environment.

However, the application of different strata to the design of cities must not be limited to environmental effects at street level. Taller blocks, with inherently larger energy demands, have the ability to collect solar energy while providing gradients of self-shading to buildings at lower heights. This decrease of indirect light in certain climates can increase user comfort inside buildings. The availability of useable rooftops, balconies and raised transportation networks is then potentially increased. These spaces become intrinsically linked to the network of green spaces and productive surfaces located in blocks at the ground level. They can be used to generate food resources for the city's inhabitants, immediately linking the productivity of the city to its users. And just as gaps provide varied environmental conditions in the forest, so too can this network of green spaces allow for yet another type of urban microclimate: areas where sun exposure is desired, but also where transpiration occurs to cool the city. The three-dimensional distribution of green spaces throughout the city creates unique morphological relationships between buildings, blocks and transportation networks, and fosters emergent environments, microclimates and interactions that traditionally planned cities may not inherently provide.



Differentiated solar radiation due to morphological variation
Varied morphological distribution throughout a city patch results in large differential gradients of solar radiation not just at ground level, but three-dimensionally throughout.

Sectional height differentiation as a design driver not only dictates formal variation, but also specific organisational effects that accommodate varied microclimates, programmes and, ultimately, infrastructural flows throughout the city. Diverse density gradients derived from varied distribution within strata create new and unexpected associations between networks, nodes and individuals. The urban fabric is rich and diverse, and thus becomes a heterogeneous landscape of emergent interactions within a homeostatic environment. Like the rainforest, the urban environment can benefit from structured differentiation in typology and form; cities equipped with varied microclimates allow for different activities with effective energy usage and information flows. In this way, the city becomes an agent in its own productivity, with the exchange of energy and information leading to the dynamic growth of urban space and culture. ⅅ



Distribution network of urban green spaces
The distribution of differentiated blocks throughout the city creates a series of varied microclimates. By allocating parks, gardens and other productive surfaces three-dimensionally, these microclimates create a new network of green spaces to provide the city with food, energy and social and cultural interactions.

NOTES

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3. Based on data published in 2005 by the Food and Agriculture Organisation of the United Nations: ftp://ftp.fao.org/docrep/fao/010/i0105e/i0105e03.pdf, accessed 19 February 2013.
4. KJ Willis and JC McElwain, *The Evolution of Plants*, Oxford University Press (New York), 2002, p 86.
5. Paul Kendrick and Peter R Crane, 'The Origin and Evolution of Plants on Land', *Nature*, Vol 389, 4 Sept 1997, p 36.
6. Willis and McElwain, op cit.
7. For an in-depth observation on branching logics in trees and other natural systems, see Evan Greenberg, 'Observation, Analysis and Computation of Branching Patterns in Natural Systems', in Andrew Kudless, Neri Oxman and Marc Swackhamer (eds), *Silicon + Skin: Biological Processes and Computation, Proceedings of the 28th Annual Conference of the Association for Computer Aided Design in Architecture (ACADIA),* Association for Computer Aided Design in Architecture, 2010, pp 316–23.
8. Francis Hallé, Roelof AA Oldeman and Philip Barry Tomlinson, *Tropical Trees and Forests: An Architectural Analysis*, Springer-Verlag (Berlin), 1978, p 278.
9. Ibid, p 372.
10. Kendrick and Crane, op cit.
11. Hallé, Oldeman and Tomlinson, op cit, pp 320–5.
12. Ibid, p 320.
13. Martin Ingrouille, *Diversity and Evolution of Land Plants*, Chapman & Hall (London), 1992, p 207.
14. Colin Tudge, *The Secret Life of Trees: How They Live and Why They Matter*, Penguin Books (London), 2006, p 295.
15. AA Federov, 'The Structure of the Tropical Rainforest and Speciation in the Humid Tropics', *Journal of Ecology*, No 54, 1996, p 4.
16. Research has shown that a 2-hectare (5-acre) patch of the Panama rainforest has two and a half times more species than the same size patch in the Vermont rainforest. For more on this subject see Robert H MacArthur, 'Patterns of Communities in the Tropics', *Biological Journal of the Linnean Society*, Vol 1, 1969, p 23.
17. John Kircher, *A Neotropical Companion: An Introduction to the Animals, Plants and Ecosystems of New World Tropics*, Princeton University Press (Princeton, NJ), 1997, pp 57–8.
18. Marcel Dicke and Jan Bruin, 'Chemical Information Transfer Between Plants: Back to the Future', *Biochemical Systematics and Ecology*, No 29, 2001, p 983.
19. Ibid.
20. Colin Tudge, op cit, pp 267, 274.
21. Spiro Kostof, *The City Shaped: Urban Patterns and Meanings Through History*, Thames & Hudson (London), 1991, pp 15–16.
22. Evyatar Erell, David Pearlmutter and Terry Williamson, *Urban Microclimate: Designing the Spaces Between Buildings*, Earthscan (London), 2011, pp 88–9.

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