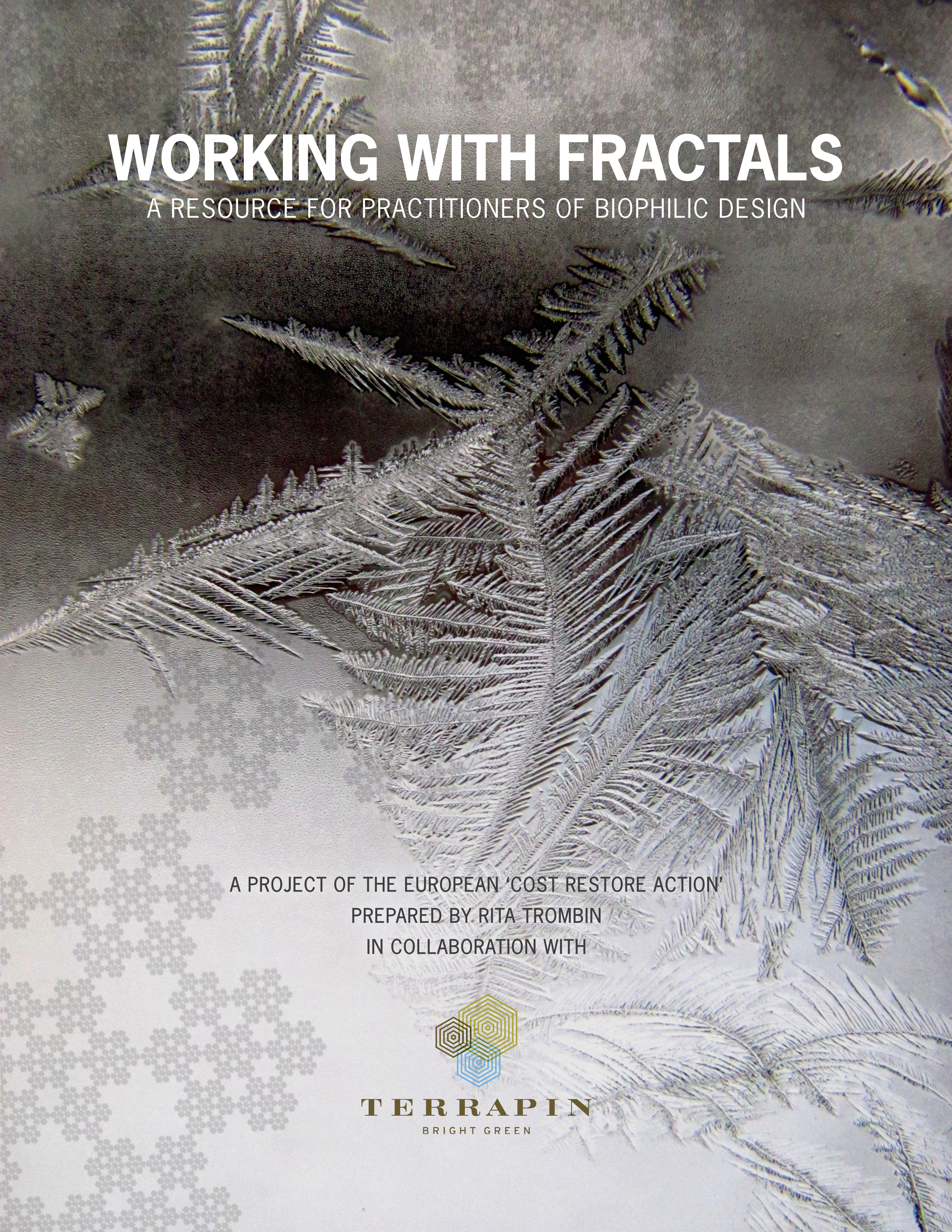

WORKING WITH FRACTALS

A RESOURCE FOR PRACTITIONERS OF BIOPHILIC DESIGN

A PROJECT OF THE EUROPEAN 'COST RESTORE ACTION'

PREPARED BY RITA TROMBIN

IN COLLABORATION WITH

TERRAPIN
BRIGHT GREEN

ACKNOWLEDGEMENTS

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OVERVIEW

Fractals are inherently continuous and complex patterns ubiquitous in nature. Some fractal patterns are understood to stimulate the human experience in positive ways that suggest practical application for the built environment. With the recent surge of interest in fractal geometries – both among peer-reviewed research outputs and as a particularly accessible design attribute for architects and interior designers – Terrapin Bright Green identified the need for a design-oriented document addressing key learning points for design practitioners interested in working with fractals.

In 2014, Terrapin classified fractals under the biophilic design pattern 'Complexity and Order', as to indicate "rich sensory information that adheres to a spatial hierarchy similar to those encountered in nature" which engenders restoration from mental fatigue, stress recovery, enhanced creativity, relaxation and excitement. Today we recognize that fractals, can span beyond a single pattern to help characterize form, light, sound, and even spatial characteristics.

Significant research insights can take an average of 17 years before making it into industry practice. As a joint effort between Terrapin, Cost RESTORE Action, Eurac Research, International Living Future Institute, this project aims help shorten that gap. By identifying the most appropriate data and resources, this work hopes to advance the understanding and discussion of fractals for direct application by the design community and related sectors and industries.

The aim of this paper (PART 1) and toolkit (PART 2) is to:

- Appreciate the value of fractal patterns and incorporate them within their projects.
- Illustrate that nature-based fractal patterns can lead to significant positive health benefits.
- Encourage product and material selection featuring fractal patterns to optimise associated health benefits.

PART 1: FOR THE LOVE OF FRACTALS

THE HISTORY AND SCIENCE OF FRACTALS FOR INDOOR ENVIRONMENTAL HEALTH

PART 2: WORKING WITH FRACTALS

A TOOLKIT FOR DESIGNERS

PART 1
FOR THE LOVE OF FRACTALS

THE HISTORY AND SCIENCE OF FRACTALS
FOR INDOOR ENVIRONMENTAL HEALTH

FRACTAL FLUENCY, A TRADEMARK OF NATURE

FRACTAL DESIGN, ARCHITECTURE AND ART IN HUMAN HISTORY

Fractals have permeated cultures spanning across many centuries and continents, classical art and vernacular architecture from the column capitals of ancient Greece, Egyptian, Aztec, Incan civilisations, the art of Ancient Mayans, Islamic and Hindu temples, Angkor Wat in Cambodia, the Eifel Tower in Paris, and the structures of Santiago Calatrava. Fractals are also evident in such well known works as those of Botticelli, Vincent van Gogh, and Jackson Pollock. Their visual properties were also explored by mathematicians when Benoit Mandelbrot published *The Fractal Geometry of Nature* (1982) in which he catalogued nature's statistical fractals and discussed them using mathematical methods for their replication.

Fractals constitute a central component of human daily experience of the environment (Taylor & Spehar, 2016). While extensive research has documented the negative effects of environments that do not have a complement of rich experiential aesthetic variety (Mehaffy & Salingaros, 2013), their proliferation in art and design has continued to grow and diversify, creating architecture, interiors and products designed for human needs (Taylor & Spehar, 2016). Over the past two decades, interdisciplinary teams have confirmed that the aesthetic qualities of nature's fractal patterns can induce striking effects on health.[1]

What is perhaps most intriguing is that the appeal of fractals is potentially innate and not learned, as adult-like preferences for fractals have been detected in urban-raised children as young as three years old (Robles et al., 2020).

FRACTALS AS NATURAL PHENOMENA

Nature is characterized by a particular type of statistical geometry, different from Euclidean geometry, called fractal geometry (Mandelbrot, 1982). Humans evolved in complex and sensory rich natural environments, where all of natural structure are fractals on a hierarchy of scales, from the large to the microscopic. At present, the majority of global population live in built urban environments characterised by minimalist/Euclidian architecture (e.g., straight lines, right angles, empty planes, rectangles, cubes, cylinders, etc.) resulting in spaces that do not adequately nurture and revitalise. Abundant research in environmental psychology suggests that humans need fractal scales, rich patterning, spatial layering, and interlocking geometries that are typical of nature. From an evolutionary standpoint we could venture to surmise that humans are instinctively drawn to fractal features for their survival value. Within a contemporary context, a good habitat is one in which people can function at their optimal potential (Kellert & Calabrese, 2015); thus, when nature's trademark for complexity and order is applied to architecture and design, restorative, nourishing and satisfying spaces, products and materials result.

ENTOMOLOGY & TAXONOMY

DEFINING FRACTALS

The term fractal comes from the Latin *frāctus*, meaning 'broken' and 'to break, shatter'. The French mathematician Benoit Mandelbrot (1924–2010) coined this term as a means to describe a 'never-ending pattern' ubiquitous in nature. The term was suggested in Mandelbrot's 1967 book *How Long is the Coast of Britain: Statistical Self-Similarity and Fractional Dimension*, and indicates the consecutive magnifications of self-similar patterns.

Fractals are self-similar patterns over a range of magnification scales (Fairbanks & Taylor, 2011; Mandelbrot, 1983), resulting in visual stimuli that are inherently complex and organised. A **fractal dimension**, abbreviated as 'D', is the parameter that indicates fractal complexity or the scaling hierarchy between the patterns at different magnifications. This D value lies across a range from 1.1 to 1.9, with D=1 and D=2 indicating no fractal properties. For example, a smooth line (containing no fractal structure) has a D value of 1, while a completely filled area (also containing no fractal structure) has a D value of 2.

STATISTICAL AND EXACT FRACTALS

Given the prevalence and variety of fractal patterns across nature, art and science, this paper focuses on fractal patterns most accessible for design application: statistical and exact.

Statistical fractals repeat the qualities (i.e. density, roughness, complexity) of the pattern at different scales with an apparent randomness to their construction, revealing the organic signature of nature's design. **Exact fractals** repeat a pattern at increasingly fine scales and appear exactly the same at different magnifications, revealing the cleanliness of precise mathematical shapes. See Table 1 for distinct characterisation of these two types of fractals.

WHY PEOPLE NEED FRACTALS

FRACTAL FLUENCY, HEALTH AND THE ALLURE OF NATURAL GEOMETRIES

The experience of fractals has quantifiable health benefits, including reduced stress, improved cognitive functioning, enhanced creativity and problem solving, heightened appreciation for nature and positive emotions (see table 3). The benefits of fractals specifically, and of nature more generally, have been shown to occur within minutes, even seconds (Smith et al., 2020; Lee et al., 2015). As people increasingly find themselves surrounded by urban landscapes, they become disconnected from nature's fractals and its stress-reduction qualities. This **nature deficit** can lead to an unhealthy build-up of stress, placelessness and sick building syndrome.

Prolonged stress mobilisation in humans produces a plethora of harmful consequences, such as increased blood pressure, energy depletion, heightened release of stress hormones, decreased cognitive ability, and reduced immune function. The World Health Organization declared stress to be the "Health epidemic of the 21st Century" with associated illnesses ranging from depression to schizophrenia (Smith, 2012). Stress-related illnesses cost countries such as the US over $300 billion (€267.3 billion; £242.4 billion) annually (Taylor & Spehar, 2016). In the UK, poor mental health costs employers up to £45 billion (€49.6 billion; $55.7 billion) each year. However, for every £1 spent on supporting people's mental health, employers get £5 back on their investment in reduced presenteeism, absenteeism and staff turnover (Franklin, 2020).

Taking this escalating concern as an interdisciplinary challenge, the designers who embrace the opportunity to reintroduce fractals and other biophilic patterns to the human habitat could radically improve the health and wellbeing of the built environment (Smith et al., 2020).

TABLE 1. CHARACTERISTICS OF COMMON FRACTALS

Design Aspect	Randomness	Symmetry	Ubiquity in Nature	Fractal Fluency	Examples
STATISTICAL	✓		✓	✓	trees canopy, branches, bark, wood grain; clouds; waves and tributaries; fire, ferns
EXACT		✓		✓	geometric art and ornament, as found in architecture, textiles, hardscaping

Just as trees roots and branches, rock fissures, wood grain and river tributaries are fractal structures, so too are the human lungs, circulatory system, brain, skin and so on. Throughout evolution, the prevalence of mid-complexity statistical fractal patterns (D=1.3–1.5) in nature is theorised to have played a critical role in leading the human nervous system to adapt and efficiently process them with so little cognitive effort (Aks & Sprott, 1996; Taylor et al., 2011; Albright, 2015; Taylor & Spehar, 2016; Taylor et al., 2018). Analogous to a language fluency, this ability to detect and understand fractal patterns accurately and effortlessly is referred to as **fractal fluency**. Several behavioural experiments, (e.g., Robles et al., 2020; Taylor et al., 2018; Taylor & Spehar, 2016; Hägerhäll et al., 2008, 2015), coupled with qEEG and fMRI techniques, have studied this effortlessness in the mental processing of mid-complexity statistical fractal patterns.

The ability to grasp nature's complex sense of order (Gombrich, 1984) has the advantage of fluidly reallocating cognitive energy to serve more novel stimuli that human survival depends upon, such as safely crossing a street or solving a new problem. A positive visual preference or aesthetic pull of fractals over simple Euclidean patterns occurs among 95% of people (Taylor, 1998), and it's due to the ease with which fractals can be processed.

Designers, intuitively or by training, tend to create fractal patterns that are exact/geometrical rather than statistical/organic. Environments that have been found as non-healing do not have fractal scaling relationships can be too austere or Euclidian to engender a positive biophilic health response. By contrast, these can be stressful environments and can induce anxiety and depressive behaviour, and ultimately pathology in their users and residents (Salingaros 2012). Repeating lines in colinear, curvilinear, parallel and radial patterns in design, facilitates visual perception by tapping into the highly organized neuronal system for representing contour orientations (Albright, 2015). Whether fractal aesthetics are generated by nature, mathematics and art, preference for mid-complexity statistical fractals remains universal (Spehar et al., 2003).

PARAMETERS OF FRACTAL PREFERENCE

The universal preference for 'statistical' fractals peaks at low to moderate degree of complexity, while universal preference for 'exact' fractals peaks at a higher complexity. The high level of symmetry in exact fractals enables greater tolerance for visual complexity compared to statistical fractals (Abboushi et al., 2019). Four factors influence complexity in exact fractals:

1. Fractal dimension (D)
2. Symmetry
3. Recursion
4. Number of elements introduced at each recursion

Fractal dimension. The Euclidean simplicity and symmetry of exact fractals increases tolerance and peak preference for medium-high complexity exact fractals (D= 1.5–1.7) (Abboushi et al., 2019). Medium-high exact fractals can enhance visual preference and mood, particularly in less complex Euclidean interior spaces (Abboushi et al., 2019; Taylor et al., 2018).

When complex fractal patterns are experienced within a low-complexity interior space, the visual preference can shift to those available higher D values (1.5 to 1.7, medium-high range), suggesting that a low complexity environment enables a tolerance and preference for higher complexity statistical fractals such as found in artworks or casted light patterns unique within that space (Abboushi et al., 2019). A good example of this scenario is museums with an abundance of geometrical rooms and white walls adorned with highly complex artworks that captivate.

Symmetry. Patterns with symmetry and geometry, such as common among exact fractals, can be visually appealing as they balance interest and comprehensibility. Mirror symmetry is generally considered one of the most predictive factors when judging whether a geometric pattern is 'beautiful'. A lack of radial and mirror symmetry can be overcome by including more recursion and higher fractal dimensionality.

The orderliness of exact fractals allows a pattern to approach the maximum use of space at a particular dimension while retaining its elegance. Patterned tiles and carpet, wall coverings and textiles, artefacts and ornaments found in many cultures (Eglash, 2002) are evidence of this spatial orderliness and symmetry.

Recursion. Fractals generated by a finite subdivision rule bear a striking resemblance to both nature and human ornament. In mathematics, the finite subdivision rule is a recursive way of dividing a polygon or other two-dimensional shape into smaller and smaller pieces. In a sense, subdivision rules are generalisations of regular exact fractals. Instead of repeating exactly the same design over and over, they have slight variations in each stage, allowing a richer structure while maintaining the elegant style of fractals (Cannon, et al., 2001).

TECHNOLOGY & FUTURE DIRECTIONS

SOFTWARE AND OTHER INDUSTRY TOOLS FOR FRACTAL DESIGN

Since the 1980s architects and designers started using computer technology to analyse and simulate the complexity observed in nature and apply it to structural building shapes and urban organizational patterns. From the standpoint of both design and experience, industries have different equipment requirements and appropriate technologies. Also, for each industry there might be different opportunities and methods to integrate fractal patterns in design. People experience space as a balance of all its elements, so when implementing fractal patterns, it is key to take into account of the context as a whole. Ultimately, individual preference will determine what is the best application of fractal patterns to serve one's own needs.

Grasshopper (Rhinoceros 3D) is more readily accessible to designers for parametric (or algorithmic) design. It presents a visual programming language interface to create and edit geometry. Fractals is a plug-in that allows users to create three different types of mathematically generated fractal patterns. It can be leveraged to determine whether an image or design possesses fractal qualities and contribute to an iterative design strategy.

Other software can produce 2D and 3D forms based on fractal design. Some of these are: Mandelbulber, Mandelbulb3D, ChaosPro, Fractal Zplot, QuaSZ, Fractal ViZion, Fractal Scope, Ultra Fractal, Apophysis, Fractal Science Kit, Incendia Fractals, Fractal Extreme. These programs allow for different forms to be increased in complexity, based on fractal principles, offering options of high quality rendering, colouring, lighting and animation. These programs are frequently used by designers working with digital art.

MATLAB scripts for creating and analysing fractals are still nascent and relatively inaccessible to the common practitioner. MATLAB box-counting technique is the most broadly used to analyse fractal complexity (D values). This technique is reliable and robust particularly with computed fractal figures and it is useful to quantify the topologic dimension of images, therefore calculating their D values (i.e. roughly how much fractal the image is). Importantly, this fractal D value may vary according to several parameters like the image resolution and the threshold for the digitalisation. In other words, box-counting method can provide an aesthetic, not absolute, account for the aesthetic experience of the image itself.

Virtual Reality can be used to test navigation and visual preference in spaces with fractal design elements (Juliani et al., 2016). This approach can be used by designers to test the experience of 'being in

CURIOUS FACTS ON FRACTALS

1 Why is identifying familiar likenesses in the clouds such a ubiquitous pastime? Our pattern recognition processes are so enhanced by fractal cloud patterns that our internal visual system becomes "trigger happy" and we imagine shapes that aren't actually there (Taylor & Spehar, 2016).

2 Pioneering research on stress-reducing fractals was funded by NASA with the aim of maintaining the health of astronauts during long missions away from Earth's scenery (Taylor, 2006). How might we design with fractal geometries to benefit everyday terranauts?

3 Animals naturally forage for food in a fractal pattern (Viswanathan et al., 1996). For instance, short trajectories allow a bird to look for food in a small region and then to fly to neighbouring regions and then onto regions even further away, allowing efficient searches across multiple scales. The human eye adopts the same motion when 'foraging' for visual information.

4 One of the earliest known descriptions of fractal patterns in nature comes from the great artist and scientist Leonardo da Vinci: "All the branches of a tree at every stage of its height when put together are equal in thickness to the trunk [below them]." In the 15th century da Vinci speculated about a logical relationship between tree branches at different heights, based on their volumes.

the space'. Paired with qEEG techniques (Hägerhäll et al., 2008) it can be used to assess brain activation while moving through the space (e.g., whether a pattern entices relaxation or excitement). Eye tracking is also used to test: how long an element takes to capture attention (time to first fixation), how long it keeps attention for (fixation time), and how many times attention is moved away to come back to it (revisits). Pupil size can also be tracked as this change according to arousal.

With the rapid advancements in 3D printing technology, intricate patterns can be printed ('contour-crafted') as physical objects. In the future, 3-dimensional printers will be able to will print whole rooms, allowing assembly into buildings, making fractal architecture a practical proposition (Taylor at al., 2018).

PROS AND CONS OF TECHNOLOGICALLY GENERATED FRACTALS

Software scripting supports quick pattern generation and facilitates repetition to confirm the direction to take a design through replication and testing. The connection, sensitivity and intuition of pattern sketching by hand might be lost with scripting. Computers and printers cannot fully replicate the multisensory human experiences of swirling wind, warm crackling fire and lapping waves. Although computers can fill virtual worlds with the rich patterning of fractals, in the physical world they are almost exclusively the trademark of nature (Taylor at al., 2018). To keep in alignment with the concepts of biophilia, the pursuit of a purely mathematical or technological approach is not recommended.

In addition, fractal fluency and dimensions in particular may offer the numeric metric convenient to designers and engineers, particularly when developing fractals targeting human health benefits such as in green buildings – it might be premature to factor these values in green building rating systems but if nature is fractal in its totality, it is conceivable that our buildings could be too one day. Software may be the key to making that feasible but there is no silver bullet solution to fractal design technology.

FUTURE RESEARCH

Among available research, few studies have factored the user environment into the data. One study of note suggested that having a quality view to nature can negate the value or purpose of a decorative man-made fractal design (Abboushi et al., 2018). Research that limits the study to fractal patterns viewed on a computer screen located directly in front of study participants can be translated to the indoor environment, but are not sufficient for understanding the human response to fractals when the context and external factors (e.g., view, daylight) are not considered. More research is needed on fractal experience in a variety of everyday environments and several questions are worth exploring.

1. What is the extent to which fractal preference differs between natural landscapes and the built environment or, framed another way, what factors of the built environment change preferences for fractal complexity?

2. From a health and experiential standpoint, what are the critical junctures of the built environment where a fractal intervention is most desirable, as a type of 'urban acupuncture', or unnecessary – such as when a quality view to nature trumps a technologically engineered fractal pattern?

3. With the proliferation of handheld smart devices and surge in citizen scientists, is it a realistic and useful endeavour to develop an app (e.g. with a QR code) to scan and analyse the fractal qualities of design patterns we encounter? Such data could be catalogued and used by designers to narrow down materials selection on a project. Or would such a catalogue of patterns, calculated fractal dimensions and preferences, encourage an 'unnatural' fixation to detail?

4. How might modular and pre-cast practices support the constructability of fractals in at the building scale? What role might technology play in ensuring that growth is fractal at the urban planning scale?

These and other research inquiries would help the industry understand the value and priorities of fractals on health and wellbeing in the built environment.

1. Example studies include Abboushi, Elzeyadi, Taylor & Sereno, 2019; Aks & Sprott, 1996; Albright, 2015; Bies, Blanc-Golhammer, Boydston, Taylor & Sereno, 2016; Cutting & Garvin, 1987; Field & Brady, 1997; Hägerhäll, Purcell & Taylor, 2004; Hägerhäll et al., 2008; Hägerhäll et al., 2015; Geake & Landini, 1997; Juliani, Bies, Boydston, Taylor & Sereno, 2016; Knill, Field & Kersten, 1990; Marlow et al., 2015; Spehar, Clifford, Newell & Taylor, 2003; Smith et al., 2020; Spehar & Taylor, 2013; Spehar et al., 2015; Spehar, Walker & Taylor, 2016; Street et al., 2016; Taylor, 1998, 2002, 2006; Taylor & Spehar, 2016; Taylor & Sprott, 2008; Taylor, Spehar, von Donkelaar & Hägerhäll, 2011; Taylor et al., 2017; and Taylor, Juliani, Bies, Spehar & Sereno, 2018.

PART 2
WORKING WITH FRACTALS
A TOOLKIT FOR DESIGNERS

For millennia humans have intuitively used complex fractal patterns in design and architecture. Yet, for much of the last century, built spaces have been designed with neutral and geometrical shapes.

Only since the turn of this century has science been used to demonstrate how qualities of fractal patterns in nature can have positive impacts on human perception, health, cognitive performance, emotion and stress. The nascent evidence-base is being tapped to help guide the creation of products, built spaces and experiences that are healthy, beautiful and engaging.

This toolkit provides a high-level conceptual framework for thinking about designing with fractals in a way that promotes restorative and satisfying indoor environments. This toolkit includes seven resources:

- Defining Fractals
- Human Relationship to Fractals
- Evidence Base
- 8 Insights to Designing Biophilic Fractals
- Biophilic Fractal Design Applications
- Biophilic Schools Case Study
- Appendices: Recommended Reading
  Bibliography

For designers familiar with using fractals, this resource offers a lexicon for talking about it and the science for supporting broader adoption.

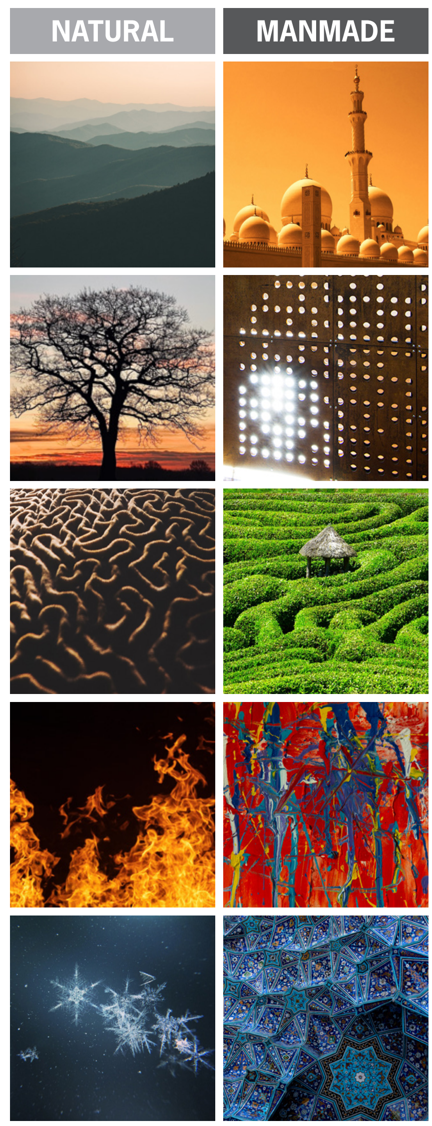


FIGURE 1. With a general understanding of fractals, it becomes easy to identify parallels between natural and human-made designs. Photos from Pixabay.

CRITIQUE YOUR ENVIRONMENT

- In your daily environment, try identifying where statistical and exact fractals occur at home, when commuting to work, in the office, in your project(s), or while at the grocery or the park.
- Are the instances of fractals more prominent in any one of these locations?
- Which spaces or places in your daily experience could potentially benefit from fractal patterns?
- How might this awareness inform your approach to design?

FIGURE 2. Naturally occurring statistical fractals are one of the reasons waterfalls, experienced up close or at a distance, so easily and repeatedly capture and hold our attention. Photo credit: Marcelo Irigoyen/Unsplash

DEFINING FRACTALS

- Fractals are self-similar patterns over a range of magnification scales. They are characterised as being either statistical or exact. Statistical fractals are found in nature, displaying randomness and an organic signature. Exact fractals are created by humans, displaying cleanliness, symmetry and scaled replication.
- Fractal dimension (*D*) or complexity indicates the scaling hierarchy between the patterns. This *D* value can range from 1.1 to 1.9 (*D*=1 and *D*=2 indicate an absence of fractal properties).
- Fractals are ubiquitous in nature. Their organised complexity allows for many intricate processes to occur in nature and within the human body.
- Until the recent past, fractal patterns occurred in design, architecture and art with great frequency. Modern-built spaces, however, tend to be either oversimplified and Euclidian or overtly complicated an disorderly – conditions both known to induce stress.

HUMAN RELATIONSHIP TO FRACTALS

- Humans have evolved to thrive in complex, yet coherent, fractal environments. Analogous to a language fluency, fractal fluency is the human ability to detect and understand fractal patterns easily and accurately. We also perceive fractal environments as having the highest aesthetic value.
- The universal visual preference is for medium-complexity fractals (D= 1.3–1.7).
- Fractals can have quantifiable health benefits for stress reduction, cognitive performance, creativity, problem solving, mood and navigation. See table 2 for a general summary of the health benefits associated with fractal patterns.

EVIDENCE BASE

There is extensive research in fractals, but these select studies focus on distinct human health responses to the experience of fractals in our physical environment and view shed.

<table>
<tr><th>STRESS REDUCTION</th><th>COGNITIVE PERFORMANCE</th><th>EMOTION, MOOD & PREFERENCE</th></tr>
<tr><td>Reduced stress up to 60% and positively impacted heart rate, blood pressure and galvanic skin responses particularly for statistical fractals TAYLOR, 2006; JOYE, 2007</td><td>Induced state of alertness; enhanced ability to concentrate and hold attention (particularly fractals D=1.3; peak in brain beta response in parietal area) HÄGERHÄLL ET AL., 2008, 2015</td><td>Superior ability and ease in navigating through the environment; liveability and vitality JULIANI ET AL., 2016; MEHAFFY & SALINGAROS, 2015</td></tr>
<tr><td rowspan="4">Induced stress-reducing, restorative experience, wakefully relaxed state. Deep relaxation, daydreaming and light mediation state (particularly for statistical fractals D=1.3) peak in brain alpha response in frontal lobes) TAYLOR ET AL., 2016, 2017; HÄGERHÄLL ET AL., 2008, 2015</td><td>Effortless looking' characterised by increased engagement and prolonged concentration SMITH ET AL., 2020</td><td>Balances between relaxation and excitement, especially compared to Euclidean patterns ABBOUSHI ET AL., 2019</td></tr>
<tr><td>Reduced cognitive effort JULIANI ET AL., 2016</td><td rowspan="3">Increased visual preference and performance, regardless of the generation method (i.e. among naturally occurring, computer-generated and man-made fractals) TAYLOR ET AL., 2018; TAYLOR & SPEHAR, 2016; SPEHAR ET AL., 2015; SALINGAROS, 2012; HÄGERHÄLL ET AL., 2004; SPEHAR ET AL., 2003; TAYLOR, 1998; AKS & SPROTT, 1996</td></tr>
<tr><td>Increased pattern recognition abilities TAYLOR ET AL., 2018, 2017A, 2017B</td></tr>
<tr><td>Enhanced performance in visual tasks TAYLOR & SPEHAR, 2016; TAYLOR ET AL., 2018</td></tr>
</table>

TABLE 2. Summary of health benefits associated with mid-complexity fractal patterns. Results are primarily from early research based on computer screens.

FIGURE 3. Blue Ridge Pastures, by Gary R. Huber of 3D Nature LLC, is a computer-generated, fractal landscape (CC BY-SA 2.5).

8 INSIGHTS TO DESIGNING BIOPHILIC FRACTALS

As a general rule, when introducing fractal patterns in the design process, it is important to empathize, define, sketch, prototype and test with teammates and the client. During this process, consider the following eight perspectives that may influence the direction of your design.

Try combining your latest understanding of fractals with that of biophilic design. For more on the science, opportunities and health impacts of biophilic design, see the 14 Patterns of Biophilic Design (Browning et al, 2014).

1. ENABLE ACCESS TO LOCAL NATURE

The best design guidance for incorporating fractals may be to support visual and physical access to outdoor spaces and experiences where statistical fractals occur naturally. Secondary to immediate access is to assess what pre-existing site characteristics can be 'borrowed' for integration (e.g. daylight, views) or inspiration (e.g. natural material patterns, sequences).

2. IDENTIFY PRIORITIES AND EXPERTISE

Determine which design problem the fractal design solution is solving. Question your experiential narrative and how fractals help in telling the design story. Decide whether the pursuit of a science-based design model is essential to your project's experiential goals and messaging.

- If not essential, intuition and the other insights listed here within are a good next steps.
- If essential, work with research scientists who can provide health-specific guidance, metrics and methods for developing and testing appropriate fractal design solutions.

3. CREATE FOR UNIVERSAL APPEAL

If creating statistical or exact fractals, target a medium range of complexity (*D*=1.3–1.7) for greatest potential visual preference. Recognize that fractal extremes (low *D*=1.1–1.2 or high *D*=1.8–1.9) may be unhelpful or potentially harmful to certain user groups. This approach is applicable to most designs, regardless of the generation method.

4. ERR ON THE SIDE OF CAUTION AND SIMPLICITY

As we experience space in its wholeness, a fractal design feature or product will be perceived differently on its own from when it's experienced in its final context. Thus, the aim can be to either introduce greater complexity to a minimalist space or add order to an already complex experience. Be judicial with applications. Over-indulgence for fractals can sometimes lead to visual interference, such as moiré patterns, which usually run counter to the experiential goal.

EXACT FRACTALS

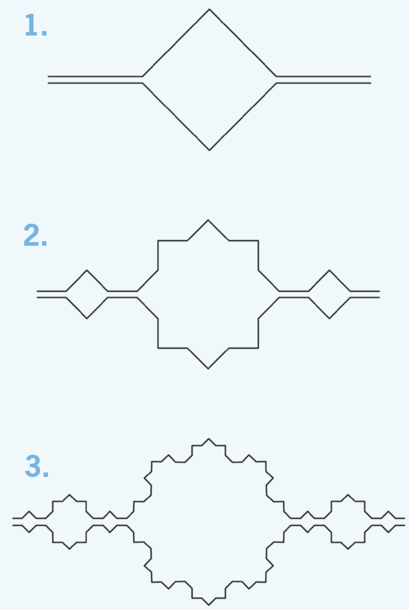


FIGURE 4. With each recursion, the fractal increases its resemblance to both nature and human-made ornament.

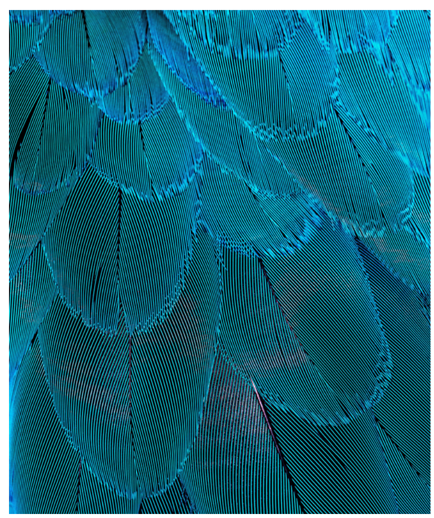


FIGURE 5. Bird feathers are richly biophilic and fractal. When transcribed into design, judicial applications of such inspiration can spice up a space, add intrigue and inspire. Over-utilization (e.g., quantity or layering) can have a dizzying moiré effect known as 'visual toxicity'. Photo credit: David Clode/Unsplash.

5. DESIGN FOR HUMAN SCALE

Viewing distance and exposure time do not significantly influence visual preference for fractal complexity. Scaling the design to the human experience and in balance with other drivers of the design aesthetic or experience will play an important role in the experiential success of the design solution.

For instance, the scale of fractals on the wall panels in an elevator will differ from the scale of fractal artwork suspended in a 10-story atrium. This sounds intuitive, but is sometimes overlooked in the design process – can the fractals be seen and appreciated from primary vantage point(s)?

6. LOCATE FOR OPTIMAL IMPACT

The experiential impact of fractal patterns can occur within minutes or seconds of exposure. Consider placing fractal designs in locations where the most people will benefit and where relevant health outcomes are desired, even if not tracked or measured.

7. DESIGN FOR A MULTISENSORY EXPERIENCE

Fractal patterns can be visual, tactile or auditory; continuous, temporal or ephemeral; and spatial or organizational experiences. While research on multisensory fractals is uncommon, there is ample evidence indicating that multisensory experiences of nature yield a more meaningful user response than the engagement of any single sense on its own.

8. START WITH NATURE BEFORE TECHNOLOGY

Computer software can fill virtual worlds with rich fractal patterning, yet in the physical world statistical fractals are almost exclusively the trademark of nature. Computers and printers cannot fully replicate the multisensory human experience of swirling wind, warm crackling fire and lapping waves.

Automated processes without adequate scientific analysis also run the risk of generating incorrect *D* values or non-fractal patterns that are often incorrectly trusted as being a valued fractal quality. Thus, the pursuit of mathematical or technological approaches to generating fractal patterns is not recommended in isolation.

Even when a technological solution is anticipated necessary for fabrication, the connection with nature will be more profound and intuitive when the design challenge is first approached by active exploration of nature followed by hand sketches or mock-ups. Software scripting then supports quick pattern generation and facilitates repetition to confirm the direction to take. Introducing a degree of randomness into the scripting will also help to retain that perception of being sourced from nature.

APPLICATIONS FOR BIOPHILIC FRACTALS

- Architectural geometries
- Architectural components *(partitions, acoustic materials, railings, millwork, metalwork)*
- Windows *(mullions, frit, fins, films)*
- Materials *(wood, stone, tile)*
- Textile design *(upholstery, carpet, wall coverings)*
- Hardware design *(grates, grilles, accent panels)*
- Environmental graphic design *(wall graphics, decals)*
- Lighting and shadow design
- Product form *(furniture)*
- Art and sculpture
- Floor plan, spatial navigation
- Roof line
- Street hierarchy, urban growth patterns
- Water feature
- Sound and sensory scape *(water flow, bird song, aromas)*
- Landscape *(interior, exterior, artworks)*

BIOPHILIC FRACTAL DESIGN APPLICATIONS

MOHAWK & INTERFACE CARPETS

Collaborative Science-Design Approach: Mohawk took an interdisciplinary approach to fractal design by engaging Anastasija and Martin Lesjak of 13&9 Design and scientist Richard Taylor of Fractals Research and the University of Oregon. The collaboration yielded 'Relaxing Floors' – carpet tiles based on statistical, mid-range fractals (D=1.3–1.5) refined by specialized software to generate fractals with parameters known to have universal aesthetic appeal and to generate stress-reduction.

Interpretive Approach: Interface's design team, led by David Oakey, started by abstracting nature. The output was an 'Urban Retreat' carpet tile design analogous of moss and paving stones, visually communicating a transition from one zone to another.

Though distinct approaches, each pattern is a great example of biophilic fractal design.

1

2

FIGURE A. (1) Relaxing Floors by 13&9 Design in collaboration with Fractals Research for Mohawk Group, photo © Sandra Mulder; (2) Urban Retreat carpet tiles by Interface®

WESTIN GEN 5 PROTOTYPE ROOM

When re-envisioning what the Westin guest room experience should encompass, the design team wanted to use a holistic approach to their wellness brand. The lighting strategy needed to be both circadian-effective and experientially engaging. The signature ceiling light panel was intentionally designed to resemble the protective and embracing underside of a tree canopy. The fractal perforations help to create a dynamic and memorable nature-based experience unique to Westin.

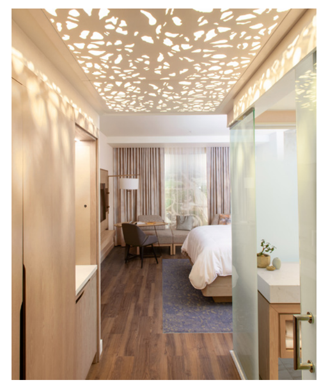


FIGURE B. (a) inspiration; (b) fractal design output; (c) in context at Westin Hotel prototype guest room with fractal lighting plane. Image courtesy of Marriott International

25 PARK ROW, NEW YORK CITY

Façade complexity and order – with a tiered hierarchy of windows and mullions – is fundamental to the aesthetic and living experience of this Lower Manhattan high-rise. The window scrims and Juliet balconies were intentionally designed as an exact fractal abstracted from the contours of a Calla Lily flower. While the fractal scrim adds ornament to the building façade, the indoor experience of the window ornament and passive manipulation of light and shadow is uniquely dynamic and ever changing throughout the day and year.

10

1 2 3 4 5 6 7 8 9

FIGURE C. (1) inspiration; (2–8) iterative fractal design process; (9) fabrication output; (10) installed scrims at 25 Park Row, NYC. Images courtesy of COOKFOX Architects

BIOPHILIC SCHOOLS CASE STUDY

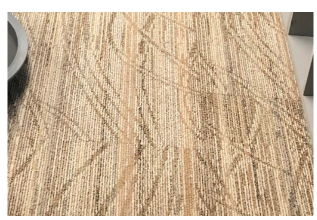
FRACTAL DESIGN AT GREEN STREET ACADEMY

This inquiry-based study was the first research to investigate the impacts of a biophilia-enhanced learning space on learning outcomes for middle school mathematics students in an urban school (West Baltimore, US). The study presents findings of data collected from a control classroom and a biophilic classroom.

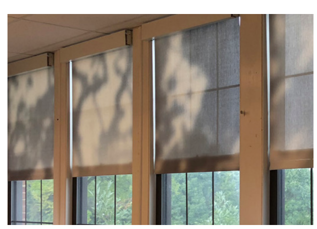
The results showed that students in the biophilic classroom were less stressed than students in the control classroom and their test scores were three times better than of those of students in the space in the year prior to changing the classroom. Quantitative and qualitative assessments including surveys, interviews, biometric and cognitive tests, all indicated that the biophilic enhancements of the classroom were strongly associated with reduced student stress and enhanced learning outcomes.

The biophilic classroom was enriched with views to nature, dynamic and diffuse daylight and biomorphic fractal patterns:

DesignTex wallpaper frieze was custom designed with characteristics based on the natural fractals of palm leaves.



Interface carpet tiles are designed to mimic the curving collinear fractal pattern of waving prairie grass.



Mecho shades were imprinted with a dappled tree shadow. The tree pattern was intended to easily blend in with the outdoor landscape view. The custom product is now a standard option.

Images courtesy of Craig Gaulden Davis Architects. Data Source: Determan, J., Akers, M.A., Albright, T., Browning, B., Martin-Dunlop, C., Archibald, P. & Caruolo, V. (2019). The impact of biophilic learning spaces on student success. https://cgdarch.com/knowledge/

APPENDICES

RECOMMENDED RESOURCES

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Fractals in psychology and art, by Richard Taylor, University of Oregon, (February 3, 2016) https://blogs.uoregon.edu/richardtaylor/2016/02/03/human-physiological-responses-to-fractals-in-nature-and-art/

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Due to the complexities of transcribing fractal science to design application, this publication provides a high level introduction to the topic. The nuances associated with characterizing fractals for specific health benefits is limited to the peer reviewed journal entries cited here within. The toolkit is a guide; the authors and owners cannot attest to the efficacy of products created as a result of using the information provided in this publication. If such efficacy is essential to the success of a project, the designer is encouraged to seek expert consultation.

For more information on fractals or biophilic design, contact the author (rita.trumpet@gmail.com) or Terrapin Bright Green (biophilia@terrapinbg.com). To download or share additional publications at no cost, visit us at TerrapinBrightGreen.com/publications.