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Leveraging Digital Disruptions for a Climate-Safe and Equitable World: The D^2S Agenda

"We shape our tools, and thereafter our tools shape us"

—Often attributed to Marshal McLuhan

In 2019, millions of young people took to the streets demanding "systems change not climate change." Their call echoes the words of the Intergovernmental Panel on Climate Change (IPCC) Special Report, which stated that "Limiting global warming to 1.5 °C would require rapid, far-reaching and unprecedented changes in all aspects of society" (1). Keeping the rise of global average temperature to well below two degrees Celsius will require cutting greenhouse gas (GHG) emissions in half by 2030 and reaching net zero emissions by 2050 (1). Society must completely decarbonize over the coming 30 years. The message from

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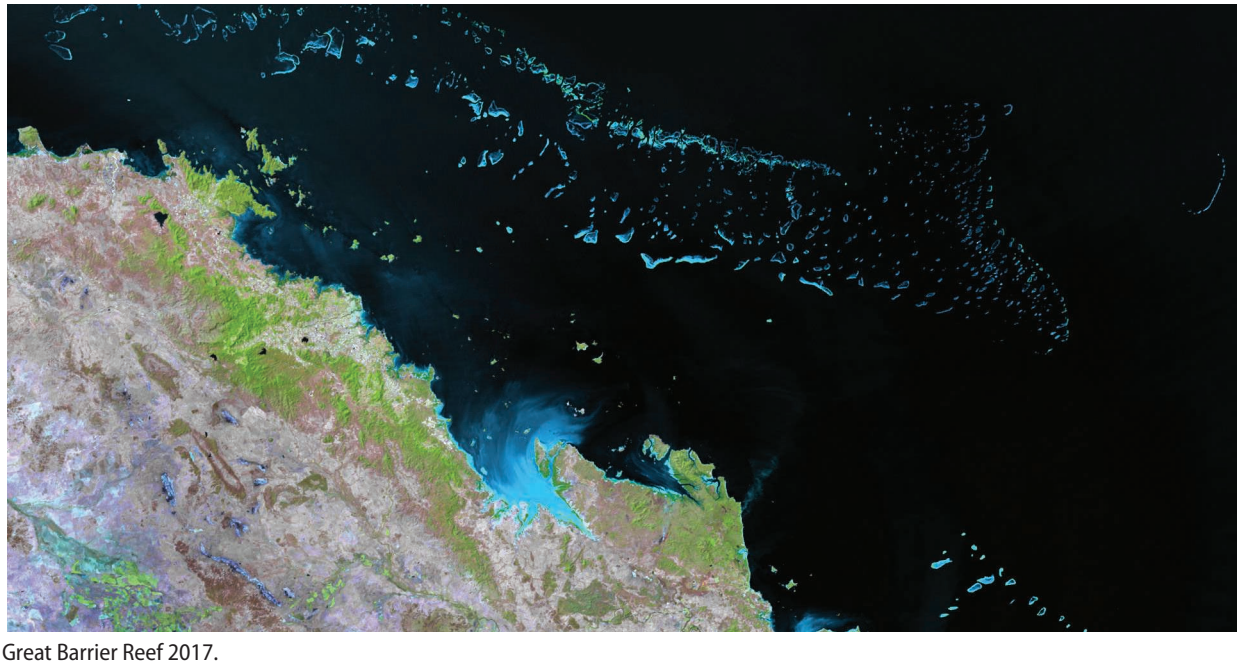


U.S. NOAA NESDIS

Great Barrier Reef 2017.

grassroots activists, scientists, and political leaders across the globe is clear: to avoid the worst impacts of the climate crisis and to achieve the United Nations Sustainable Development Goals (SDGs), we need rapid societal transformations [2]–[7].

Rapid and widespread societal transformations are already underway. Big data, the Internet of Things (IoT), Artificial Intelligence (AI), blockchain, and other digital technologies are disrupting social systems and driving societal transformations at a scale and pace unparalleled in history. However, it is not clear where these digital disruptions will lead humanity. Many risks and uncertainties are emerging, including threats to individual rights, social equity, and democracy. Many of the risks are amplified by "the digital divide" — the differential rate of Internet penetration and access to digital technologies around the world [8]. As the commercialization of AI, blockchain, and derivative technologies expands, the disparity between those who benefit and those who do not will grow unless proactive action is taken.

Yet, massive opportunities exist for leveraging the capabilities of the digital age to steer society towards net-zero carbon emissions and a more equitable global society. To seize the potential and minimize the risks, the climate and digital communities must work together to: anticipate the systems changes that are unfolding as a result of the digital revolution, imagine new systems changes that could be realized from digitalization, and identify the actions that must be taken now to steer these powerful levers of change to help build the world we want.

A new report, *Digital Disruptions for Sustainability Agenda* (the D^2S Agenda) [9], developed by Future Earth's Sustainability in the Digital Age initiative, explores these issues. The D^2S Agenda was developed over the course of a year, engaging over 250 experts from around the world through workshops, online consultations, and desk-top research. This article provides an overview of the analysis and findings outlined in the D^2S Agenda.

We begin with an overview of the research on how to change systems and drive societal transformations. We then describe the process used to develop the D^2S Agenda and provide a summary of the research and innovations outlined in it. The final section outlines near-term actions needed to establish the enabling conditions to drive the transformative systems changes needed for a climate-safe and equitable world.

Systems Change and Societal Transformations

History shows that rapid societal transformations are possible and even common. The Industrial Revolution, the Green Revolution, women gaining the right to vote, the collapse of the Soviet Union, and the end of apartheid in South Africa are all examples of societal transformations spurred by disruptions caused by technological advances, social movements, market signals, and/or government policies. In previous centuries, rapid transformations have occurred over several decades. More recently, the time for societal transformations to occur can be measured in years rather than decades. For example, over just a few years, Microsoft and Apple brought computing to a large fraction of humanity, Google transformed access to information, Facebook transformed how people connect with each other, and eBay and Amazon transformed how people conduct business.

How have such transformative systems changes come about so rapidly? More than 20 years ago, renowned systems scientist, Donella Meadows, argued that making fundamental changes to a system requires identifying and pushing on influential "leverage points" [10]. These are points within a complex system, such as an economy, an ecosystem, or a community, where a small shift in one place can produce major changes everywhere. Meadows showed that the strongest leverage points are those that alter the rules of the system, the power structures and dynamics that uphold existing rules, and the mindsets that define them (see Figure 1) [10].

Digital technologies are disrupting social systems and driving societal transformations at a scale and pace unparalleled in history.

This insight has not yet been effectively applied to the climate crisis. Climate strategies often treat climate change as a carbon management problem, focusing on technical solutions for reducing emissions by sector [11], [12], rather than driving changes in the socio-economic systems that underpin all sectors. Although technical strategies that focus on cutting emissions by sector are essential, they are not high-leverage drivers of systems change. Instead, they fall into the low-leverage "parameters and structures" category of system-change levers depicted in Figure 1. Systems scientists suggest that information flows and controls are stronger levers for

systems change ([10], see also [13], [14]). The digital revolution demonstrates the transformative power of these middle-range levers, as it radically alters information flows and controls throughout society and drives ongoing transformations in economic, governance, and cognitive systems. The digital revolution has also created opportunities to push on the third and most influential set of levers of system change highlighted by Meadows: rules, power structures, and mindsets.

> **It is not clear where these digital disruptions will lead humanity.**

Rules include both formal laws and regulations imposed by governments and informal social and cultural norms that reinforce carbon-intensive lifestyles [15]. Power refers to who makes the political and economic decisions that steer economic development patterns. Mindsets encompass the value systems, worldviews, and beliefs that underly human behaviors. Changing mindsets is the most influential leverage point, but it is among the most difficult levers to push, especially when tackling such wicked systemic challenges as the climate crisis.

Building the D^2S Agenda

We developed the D^2S Agenda to identify opportunities created by the digital age to push the most influential leverage points for systems change. Many studies have explored how big data, AI, and other digital technologies can be used to reduce emissions or increase climate resilience in any given sector (e.g., [16], [17].) In contrast, our team explored how digital transformations are driving changes in the social systems underpinning all carbon-intensive sectors. The premise of the D^2S Agenda is captured well by the aphorism "We shape our tools, and thereafter our tools shape us," often attributed to the philosopher and media theorist, Marshall McLuhan, who foresaw the transformative power of the digital age over half a century ago.

The D^2S analysis started with the question: what are the systems that sustain our unsustainability? In particular, what are the systems that are keeping society on a carbon-intensive and increasingly vulnerable development path? Initially, we explored these questions through an online consultation with almost 200 experts from around the world using Futures CoLab (www.futurescolab.org), a collaboration of Future Earth and the M.I.T. Center for Collective Intelligence. The participants emphasized the importance of the informal rules, power structures, and mindsets that are embedded within three dominant social systems: economic, governance, and cognitive.

The D^2S team then explored how existing digital capabilities are disrupting the rules, power structures, and mindsets within these three social systems. We identified four key "digital disruptors" (see Figure 2) — unprecedented transparency, intelligent systems, mass collaboration, and mixed reality — that are enabling and scaling systems change across current economic, governance, and cognitive systems.

In each of the three key social systems, economic, governance, and cognitive, the D^2S research team identified levers of systems change through which the four digital disruptors are shifting existing rules, power structures, and mindsets. For each lever, we explored both the risks and the potential for positive transformative impacts. We also asked what it would take to steer and scale each lever to drive positive, systemic changes. From this analysis, we identified priority research questions and innovation needs for driving transformative change in each social system. In the following sections, we describe the digitally

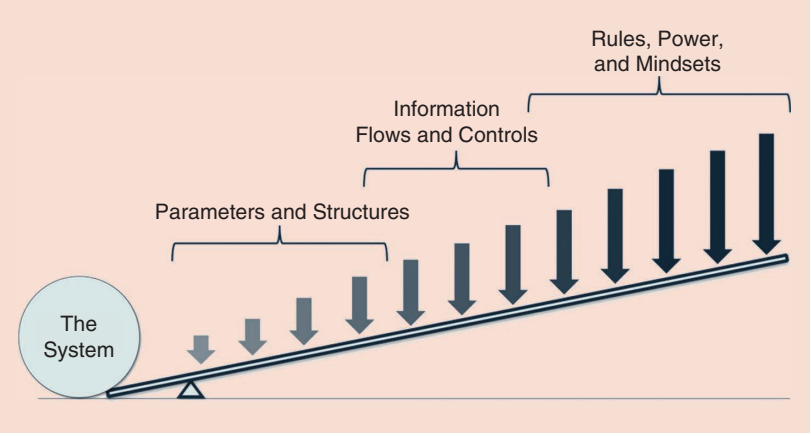


FIGURE 1. Leverage points for systems change. In 1999, Donella Meadows identified 12 leverage points to bring about change in a complex system (adapted from [10]). In the D^2S Agenda, these were grouped into three main categories: 1) physical and institutional parameters and structures; 2) information flows and controls; and 3) rules, power structures and dynamics, and mindsets.

empowered levers of change most relevant to each system and outline the research and innovation agenda, outlined in the D^2S Agenda. These are summarized in Figure 3.

Research and Innovation Agenda

Economic Systems

The prevailing neoliberal economic paradigm and linear models of production and consumption are increasing inequalities, perpetuating vulnerabilities, and accelerating environmental degradation (18, 19). The intellectual underpinning of neoliberalism is Adam Smith's "invisible hand" — the idea that the market provides for the needs of society without much government intervention. In the digital age, the invisible hand has morphed into a "digital hand" (20), where transactions and even intentions and decisions are increasingly mediated by computers. It is still unclear what the implications of the digital hand will be for people and planet. But the digital hand clearly has a powerful influence on consumer and citizen behaviors, and thus has the potential to steer society towards a more sustainable and equitable development trajectory.

Digital Platforms

The digital age has given rise to new business models built on digital platforms (21), which have enabled a new economy based on sharing, giving, or obtaining access to goods and services (18), (22). Platforms work through the interplay of technologies (data, algorithms, interfaces), businesses (operators of the platforms), and users — where users include individuals, corporations, governments, and civil society (23). Platforms enable users to market personal assets, experiences, or skills at a scale previously inaccessible to individuals or small enterprises (e.g., Airbnb, Uber, *Huffington Post*). As a result, platforms can shift economic power to individuals, away from traditional institutions, such as hotels, taxis, and newspapers. However, platforms also lead to a concentration of power in the hands of the few platform operators, who position themselves as the gatekeepers and mediators of data, content, and value (24). The platform economy has given rise to "surveillance capitalism," which uses consumer data to

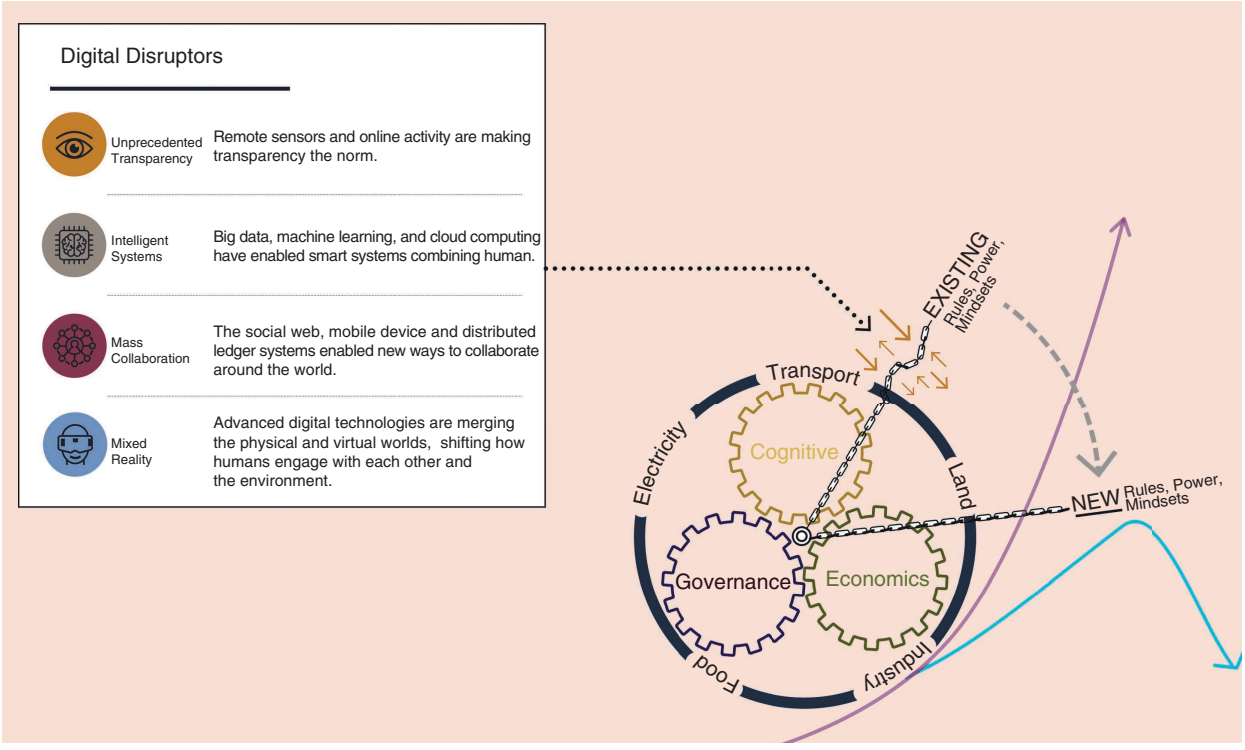
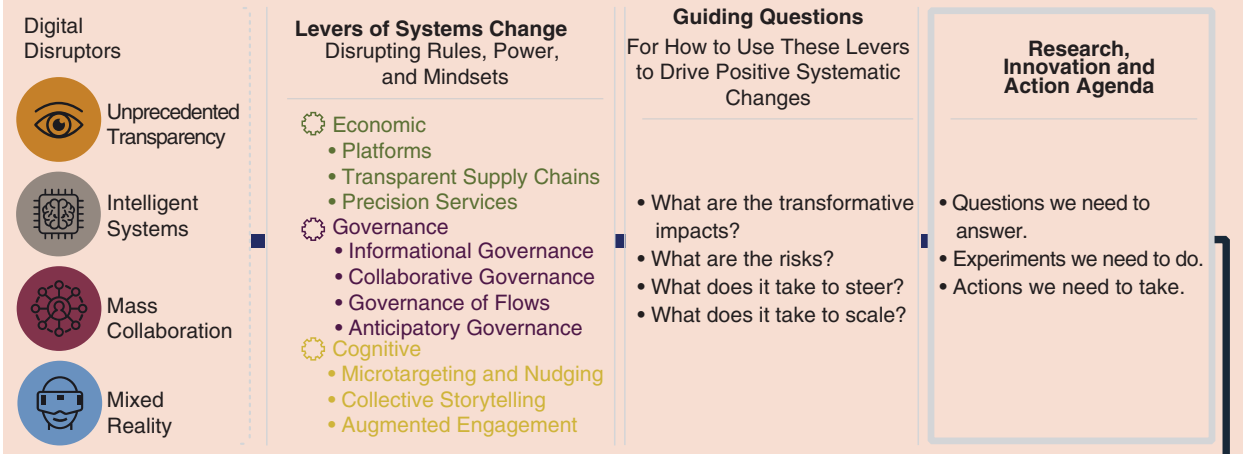


FIGURE 2. Four digital disruptors and systems change. The D^2S Agenda identified four digital disruptors that have the potential to impact influential leverage points of systems change. The outer circle represents the proximate sources of GHG emissions that are contributing to the high emissions pathway. The gears inside this circle represent the social systems cutting across all emitting sectors. The black chain that is connected to the center of the gears represents that these social systems are constrained by the rules, power structures, and mindsets embedded in them. The premise of this report is that the digital disruptors are disrupting the rules, power structures, and mindsets, and open up the potential to steer us to a lower GHG emissions path — represented by the blue arrow.



D^2s Agenda: Research, Innovation, and Action

Examples of questions that need to be answered, experiments that need to be done, and actions that need to be taken to disrupt, steer and scale:

Economic Systems	Governance Systems	Cognitive Systems
Research		
• How can we help embed democratically determined public values (e.g. keeping temperature rise <2°C) into digital platforms? • Will increased transparency of social and environmental externalities of supply chains lead to transformative shifts in business practices and consumption norms? • What are the social and environmental outcomes of existing digital nudges? Is digital nudging a lever for shifting production and consumption behaviors at a global scale? • How can vulnerable populations leverage precision services to customize climate mitigation and adaption solutions?	• How can trust and accountability be fostered where decisions are based on collective and artificial intelligence? • What social and political conditions enable informational and anticipatory governance systems that lead to inclusive sustainability outcomes? How can we leverage the digital age to scale these and overcome constraints such as algorithmic bias and unequal quality and coverage of data? • Under what technical, institutional, and political conditions does Measurement, Reporting and Verification (MRV) lead to inclusive sustainability outcomes? How can these be enabled and scaled in the digital age?	• Why do some narratives become embedded in societal discourse while others do not? How do they shape societal change? How has the emergence and reach of new narratives changed in the digital age and how does this vary with social and cultural context? • How can we minimize and mitigate the risks of using digital technologies to manipulate cognitive biases while using these mechanisms ethically to foster a new shared narrative on net-zero carbon emissions and global equity? • How are changes in individual and collective mindsets connected? How have these links shifted in the digital age? Do they provide an opportunity to steer and scale inclusive collective action on climate change?
Innovation		
Develop analytic and legal systems and institutions that credibly use new data streams and crowdsourcing to quantify and expose the cost of environmental and social externalities.	Develop a new tool box for climate governance that leverages digital disruptors to better tap into the capacity of people across networks of states, businesses, governments and civil society.	Build a network of targeted engagement strategies that leverage mixed reality tools and intelligent systems to co-create new meta-narratives across populations and geographies.

Cross-Cutting Actions (For Enabling Conditions)

- Establish a social contract for the digital age.
- Promote inclusion as a touchstone of the digital age.
- Expand open access to high-public-value data.
- Establish foundational standards for the digital sector.
- Expand public-private partnerships to build our digital future.
- Reduce environmental impacts of the digital age.
- Foster cross-sectoral collaboration and innovation.
- Invest in targeted communication, engagement, and education.

FIGURE 3. Overview of the D^2S Agenda. This diagram outlines the analysis process for developing the D^2S Agenda (top) and a summary of some of the priority research, innovation, and actions identified (bottom).

"predict and modify human behavior as a means to produce revenue and market control" [25].

With stronger and more widespread governance, digital platforms could become powerful levers to help steer society towards a climate-safe and equitable world. Consider, for example, the ways digital platforms influence human behaviors and social norms. Platforms today inscribe norms and values in their choice architecture [21] and have demonstrated their ability to rapidly shift social norms at scale through simple changes in their interfaces and selection options. For example, when Google engineers added walking, biking, and public transportation to the map application's travel-time calculation options, they digitally nudged user behaviors and helped to shift social norms. When Facebook added an "other" option to gender identification, it influenced social norms by disrupting the conventional limit of only binary options [21].

Transparent Supply Chains

Vast amounts of new data — from satellites and other remote sensors — are increasing the transparency of the environmental and social costs of supply chains and enabling new opportunities to internalize these costs, which are typically unaccounted for in economic activities. Interest in supply chain transparency for sustainability management has grown and supply chain transparency initiatives have proliferated [26], [27]. However, the sustainability and equity outcomes of these programs are not well assessed, raising the question of how best to design and implement them to be positive catalysts for potentially transformative change [28].

Precision Services

Enhanced transparency and intelligent systems are enabling the precise targeting of services. Precise targeting methods are more valuable and cost-efficient than traditional, more generic approaches [16], [29]. Precision agriculture, precision disaster risk management, precision medicine, and precision insurance are all examples of leveraging big data, IoT, machine learning, natural and social science research, and knowledge co-production to provide services narrowly targeted to solving unique problems in their specific context. For example, precision medicine refers to the tailoring of medical treatment to the individual characteristics of each patient. It recognizes that people respond to medical ailments and treatments in different ways based on the unique characteristics of each individual. Precision medicine uses massive datasets of genomic, genetic, and health records in combination with machine learning to target treatments that match the needs of individual patients [30].

Precision services are already emerging as valuable for managing climate risks. Climate-related risks have typically been difficult for governments, investors, and businesses to plan for and manage [31], [32]. However, advances in climate and data science make it possible to customize climate risk information for specific locations and activities. Big data and AI are increasingly being used to improve climate projections (e.g., oneconcern.com), map vulnerabilities, and build resilience [16], [33]. These new, lower-cost precision services offer novel opportunities to vulnerable communities where climate services were previously unavailable [34]. However, whether these services ultimately empower vulnerable communities will depend on many factors, including: what data is available, who owns and controls access to the data, how information and knowledge are derived from the data, and whether communities have access to the technology needed to use the data.

Massive opportunities exist for leveraging the capabilities of the digital age to steer society towards net-zero carbon emissions and a more equitable global society.

Research Questions

- How can we embed democratically-determined public values (e.g., keeping temperature rise well below two degrees) into digital platforms? How do we determine the public values that should be incorporated into the design of the "platform society" and who is responsible for doing so?
- How can we effectively manage and regulate an economy dominated by digital platforms to achieve inclusive and positive sustainability outcomes? Who is responsible and accountable for the outcomes resulting from the "platform society," such as the circulation of misinformation and the implications of choice architecture?
- Will a massive increase in public visibility of the social and environmental externalities of supply chains lead to transformative shifts in business practices and consumption norms? Can big data, data analytics, and machine learning provide

salient, credible, and legitimate information — that is ethically derived — to steer development, planning, and business decisions towards a sustainable and equitable world?
- What are the social and environmental outcomes of existing digital nudging of consumers? Is digital nudging a powerful lever for shifting production and consumption behaviors and norms at a global scale?
- How can vulnerable societies leverage precision services to develop customized climate mitigation and adaptation solutions?

Innovation Needs

- Develop analytic and legal systems and institutions that credibly use new data streams from satellite imagery, digital sensors, and crowdsourcing to quantify and expose the cost of environmental and social externalities.
- Improve the ability to track and monitor carbon and other environmental goods and services using big data and remote sensors.
- Develop new business models that ethically and legally leverage individual and social data to steer society towards sustainable consumption patterns, while strengthening human agency.
- Develop new models that support co-developed, knowledge-intensive precision services for vulnerable populations currently disconnected from the digital world.

Governance Systems

Current governance systems — the structures, processes, rules, and traditions that determine how people make decisions, share power, and ensure accountability — have so far failed to steer the world towards climate stability and equity [35]. Historically, the dominant focus of climate governance has been on establishing a single global agreement, defined through the United Nations Framework Convention on Climate Change (UNFCCC), that would be state-centric and top-down. However, many are recognizing that top-down steering must be combined with bottom-up self-organization to drive the deep societal transformations needed to keep global temperature rise well below two degrees [2], [36], [37].

Combining bottom-up and top-down approaches will require redesigning the top-down approaches while bottom-up approaches are strengthened and expanded. Digital innovations are already empowering bottom-up governance and are reshaping the global environmental governance landscape to be more distributed [38], though this also brings challenges and can lead to fragmented governance architecture with uncertain outcomes [39]. Nobel laureate Elinor Ostrom reflected positively on a shift to what she called a polycentric governance structure that could address these challenges [40]. Polycentric systems have multiple centers of authority at various scales as opposed to a monocentric top-down system. Each unit within a polycentric system exercises considerable independence to make their own norms and rules. Ostrom's research, spanning diverse cultures, showed that, under the right conditions, polycentric governance systems can overcome the challenge of collective action characterized by Hardin's "Tragedy of the Commons" [41].

Although the digital age has disrupted the rules and power structures of traditional governance systems, the outcomes have not always led to a net benefit to society. This is in part because the digital revolution expanded so rapidly that governance systems have been unable to keep pace with both the risks and opportunities. Climate governance strategies illustrate this lag, as most are still based on models designed for the analogue world of the twentieth century. We urgently need a new tool box of strategies for climate governance that leverages the four key digital disruptors to better access the increased availability and use of data, advances in AI, and new means for involving the capacity and expertise of a wider diversity of people in decision making. Below we describe three digitally empowered levers that could help important components of a new climate governance toolbox.

Informational Governance

Increased access to data from satellite imagery and other remote sensors, as well as to data on individual and social behavior, is rapidly shifting how information is used and by whom in environmental governance regimes. These trends are giving rise to "informational governance," which explores the use of information and information technologies to foster innovations in governance mechanisms and institutions, as well as changes to the roles different institutions play in governance [42], [43].

Informational governance appears to be disrupting the power structures of some traditional climate governance systems, but it is too early to know how these will influence sustainability outcomes over the longer term [43]–[45]. For example, digital measurement, reporting, and verification (digital MRV) of GHG emissions has shown promise for improving the accuracy of transparency programs, potentially leading to greater accountability and ultimately stronger sustainability outcomes [46]. However, transparency alone does not assure improved

environmental governance, especially in the absence of trust [47]. For informational governance to be an effective lever of transformation towards a climate-safe and equitable world, society needs a better understanding of the social and political contexts within which transparency is used a governance mechanism, as these determine whether and under what conditions they will lead to positive outcomes [47].

Governance of Flows

Global society can be viewed as a system of nodes (nations, corporations, communities) and flows (of goods, services, information, power). Traditional governance structures are designed to govern the nodes of society and not the flows among them. While material flows are governed through the World Trade Organization (WTO), it has had limited effectiveness with regard to sustainability issues, in large part because it requires equal treatment of "like products" without a mechanism for accounting for how the products were made [48], [49]. As a result, WTO does not regulate the "virtual flows" of goods, services, and information. An example of a poorly-governed virtual flow is "embedded carbon"— the carbon emitted in the production of goods and services — often referred to a product's carbon footprint [50]–[52]. Other virtual flows that fall into a governance gap are "teleconnections" or "telecoupling," the flows of information in one region that influence production and consumption decisions in another region of the world [53]–[55]. Enhanced transparency, intelligent systems, and mass collaboration have opened up new opportunities to govern flows. Yet, more still needs to be done to ensure that these schemes lead to positive outcomes for the climate and people.

Collaborative Governance

Collaborative governance refers to decision-making and management that engage people across public, private, and civic spheres [56]. Collaborative governance approaches have proven difficult to scale due to challenges of coordination and problem-solving among multiple different authorities and heterogenous actors [57]. Digitally empowered mass collaboration, enhanced transparency, and intelligent systems could help to overcome some of these constraints. New collaborative governance structures have been proposed, such as a big data-driven "transnational sustainability agency" [58] or digital "global participatory platforms" [59], [60].

Governments and citizens are already experimenting with putting these concepts into practice. For example, BitNation is an organization that is building a decentralized voluntary "nation," with the explicit intent to "disrupt the nation-state oligopoly through offering more convenient, secure, and cost-efficient government services" [61]. This includes services such as World Citizenship ID and a Refugee Emergency Response [62]. Blockchain is emerging as a potential tool for overcoming the barriers to scaling collaborative governance [63]. While there are many technical and social challenges to realizing this vision, these new digitally empowered tools for collaborative governance could unlock new strategies for governing the climate commons and scaling climate actions [57]. At this stage, the concept of governing a "citizenship" beyond the nation-state is so novel that the rules and regulations surrounding its use are poorly understood or lacking altogether [64].

Anticipatory Governance

Futures analysis, alternatively referred to as foresight, entails the identification of and reflection on alternative potential futures using a range of available methods [65]. Given the high degree of uncertainty and high risk associated with climate change, there is a proliferation of the use of both qualitative and quantitative futures analysis methods for climate change mitigation and adaptation [66], [67]. However, a deeper understanding of the implications of this proliferation for climate governance is still lacking [66].

> **Many conditions are needed to enable society to unleash positive digital disruptions and steer them towards transformative system changes.**

Although the use of futures analysis to inform decision-making is not new, it has taken on new meaning in the digital age. In today's world, everything is becoming "smart." We have smartphones, smart homes, and smart cities. This begs the question: Should society build smart governance systems to tackle the climate crisis? If so, how can this be done in an equitable and ethical manner? Digitally empowered intelligent systems create new opportunities for anticipating future human behavior, weather patterns, or economic trends that could steer society towards a low-carbon and potentially less vulnerable world. However, these mechanisms risk undermining democracy if not implemented effectively [68]. To leverage the opportunities while managing

the risks, standards and frameworks are urgently needed to ensure that algorithms governing society are transparent, ethical, and equitable, both in how they are developed and how they are used.

Research Questions

- Under what social and political conditions does the expansion of informational, collaborative, and anticipatory governance systems lead to inclusive sustainability outcomes? How can we leverage big data, IoT, AI, and other digital technologies to enable and scale these new governance structures and overcome constraints such as algorithmic bias and unequal quality and coverage of data?
- How can trust and accountability be created in a world where decisions are based on collective and artificial intelligence?
- How can transparency in climate governance be enhanced by emerging technologies? Will enhanced transparency in GHG emissions and reduction compliance deliver environmental benefits and citizen empowerment?
- Where is the line between unprecedented transparency for accountability and surveillance for control? What standards, policies, and norms are needed to avoid crossing that line?
- Under what conditions does measurement, reporting, and verification (MRV) lead to inclusive sustainability outcomes? What institutional and political constraints must be addressed for MRV to be effective in different governance systems? How can these be enabled and scaled in the digital age?

Innovation Needs

- Develop a new tool box for climate governance that leverages the four digital disruptors to make use of greater availability of data, advances in AI, and new approaches to access the capacity and expertise of people across networks of states, businesses, local governments, and civil society.
- Foster polycentric governance systems, leveraging unprecedented transparency, mass collaboration, and intelligent systems, to build complementary top-down and bottom-up approaches that reinforce, rather than counteract each other at different scales.
- Improve the ability to track and monitor carbon and other environmental goods and services using big data and remote sensors.
- Explore methods to integrate new digital data streams — from satellite imagery, digital sensors, and crowdsourcing sites — to enable more credible and legitimate MRV systems that support inclusive sustainability outcomes.

Cognitive Systems

Psychologists and economists have shown that human cognitive systems, and thus human behaviors, influence and are influenced by social and cultural norms [69], [70]. In the hyperconnected digital age, people's interactions are embedded in machine systems. Machines, powered by big data and AI, increasingly mediate human cognition and social, cultural, economic, and political interactions [71]–[73]. As a result, human cognition and human behaviors are now shaped by linked human-machine networks [74]. Within these networks, digital disruptors are already shaping social norms in ways that could have significant implications for the climate and social equity [21], [23], [75]. Understanding the behavior of human-machine networks is essential for governing society today, while reaping the benefits of the power of these networks and minimizing the risks they pose to society. Here we explore three digitally empowered levers to influence cognitive systems and accelerate and expand sustainable actions.

Nudging and Microtargeting

Human decisions are constrained by a range of cognitive biases. For example, we are biased towards maintaining the status quo, prioritizing the present over the future, preferring pre-existing beliefs over new ideas, and avoiding losses over securing equivalent gains [76]–[78]. To counteract or exploit these inherent biases, political, commercial, and public campaigns often use "nudges," a technique that emerged from behavioral economics [79]. Nudges influence behavior through small changes in how choices are presented, without altering the range of choices. People tend to be more susceptible to nudges than attempts to persuade using rational arguments or facts. People are also more open to personalized messages, especially when suffering from information overload. Digital capabilities have amplified the power and reach of nudging and microtargeting by personalizing influence at scale. Nudging and microtargeting are now embedded in the daily lives of much of humanity, influencing behaviors and social norms [80]. It is incumbent on society to develop mechanisms to regulate digital microtargeting and nudging to prevent malicious, or unethical manipulation [81], and to advance democratically determined values, such as reducing GHG emissions, by advancing low-carbon and climate resilient choices [76], [79].

Collective Stories

Narratives define our individual and collective realities. Stories unite us

and give us purpose [82]. In the digital age, the way we create and share stories is rapidly changing. Collective narratives capable of global impact, which historically have taken decades and even centuries to form, now emerge in just a few months. For example, in less than a year, #MeToo emerged and transformed accountability for sexual harassment. In a matter of months, #FridaysforFuture expanded from one person to a global movement. The power to change narratives at scale today is unparalleled in human history. But how to create authentic narratives that can scale deep societal transformations is still an open question. Research suggests that inaccurate information — "fake news," which often triggers strong reactions of surprise, disgust, or fear — travels six times faster and can reach up to 100 times more people than accurate information [83]. Thus, one of the biggest challenges to achieving sustainability in the digital age is the increasing difficulty in distinguishing fact from fiction.

Given the potential for narratives to shift mindsets, and the unprecedented speed with which new narratives can be developed and spread in the digital age, collective storytelling is potentially a powerful lever for systems change. But pushing this lever effectively will require research to better understand critical issues such as the sources, spread, and uptake of fake news, and more broadly why some concepts and narratives become embedded in societal discourse and influence behaviors, while others do not.

Augmented Engagement

Virtual reality and augmented reality have been characterized as the ultimate "empathy machine" [84]. While many question the true impact VR and AR can have on building empathy and shifting behavior [85], they are increasingly being explored in a range of sectors from education to public health [86], [87]. When coupled with AI and mass collaboration, AR and VR (referred here collectively as "augmented engagement"), offer new ways to engage the public on the risks and solutions to climate change. Much research and experimentation are needed to better understand the potential role of augmented engagement for tackling climate change. However, early research [88] suggests that immersive augmented engagement strategies can help to 1) build understanding of complex issues such as climate change [86]; 2) engage emotional response to simulated changes through visual, auditory, and haptic stimuli [85]; and 3) elicit action [87].

Augmented engagement can also be weaponized through manipulative tools such as "deepfakes," which are a form of disinformation that use machine learning algorithms to create audio and video of real people saying and doing things they never actually said or did. These are rapidly becoming indistinguishable from reality [89] and much more widely accessible. It is now possible to make a fake video of a person speaking in just a few minutes from just a few images of the person's face [90].

While augmented engagement could be an influential lever for driving societal transformations towards a climate-safe and equitable world, more research and innovation are still needed. For example, we need to better understand how augmented engagement strategies compare to analogue strategies in shifting human mindsets and norms, how mixed reality tools and intelligent systems could be used to co-create meta-narratives across populations and geographies, and how to decipher and hinder the spread of false information.

Research Questions

- What are the connections between changes in individual and collective mindsets, and how do these translate to collective action? How have these links shifted in the digital age? Do they provide an opportunity to steer and scale inclusive collective action on climate change?
- How effective and efficient is digital nudging for influencing behavior and mindsets at scale? What are the implications for sustainability outcomes? Can nudging be legally and ethically mandated at a global scale? If so, how would the mandated nudges be determined?
- Why do some concepts and narratives become embedded in societal discourse while others do not? How do they shape societal change? How has the emergence and reach of new concepts and narratives changed in the digital age across the wide range of social and cultural contexts?
- How has the digital age changed the power of social movements to shift individual beliefs and social norms, and to shape policies?
- How can we minimize and mitigate the risks of using digital technologies and platforms to exploit cognitive biases and amplify specific worldviews? Can these digital levers be used ethically to foster a new shared narrative centered around net-zero carbon emissions and global equity?
- Can augmented experience change human mindsets and norms at scale?

Innovation Needs

- Build a network of targeted engagement strategies that leverage

mixed reality tools and intelligent systems to co-create new meta-narratives across populations and geographies.
- Explore methods that leverage unprecedented transparency, mass collaboration, intelligent systems, and mixed reality to build collective narratives that draw on emotions and create credible and legitimate shared views of reality.
- Develop automated programs to monitor the sources, spread, and uptake of fake news. In parallel, develop transdisciplinary initiatives to empower individuals to evaluate the veracity of news.

Enabling Conditions

For any of the levers of change outlined above to be effective at driving the societal transformations needed to build a climate-safe and equitable world, a number of near-term actions are needed. One of the most important is closing the digital divide. Over half of the global population is online, with over 4.1 billion Internet users in 2019 [8]. But access varies widely by region and population (see Figure 4). For example, Africa and Asia have a 28% and 48% Internet penetration rate respectively, much lower than Europe's rate of 82.5% [8].

Two main drivers of the digital divide are the educational and economic disparities between countries [92]. The economic benefits of the accelerating rate of technology uptake also vary by region. Projections indicate that the economies of some regions (e.g., North America and China) stand to gain more of economic benefits from the AI boom than other regions (e.g., Africa and Latin America), due to their high rates of access, investment, and adoption [17].

As commercialization of AI, blockchain, and derivative technologies rapidly expands, the disparity between the digital haves and have-nots will likely grow, unless, as a society, we make eliminating the digital divide a global priority for sustainable and equitable growth. To close the divide, it will be important to disseminate low-cost solutions. One example is mobile broadband, which requires less investment in hardware than fixed broadband and provides the highest rate of growth in Internet users [93].

Closing the digital divide is essential, but it is only one of many conditions needed to enable society to unleash positive digital disruptions and steer them towards transformative system changes. We identified eight priority actions to create the enabling conditions for leveraging the digital age to achieve a climate-safe and equitable world. These actions are described in the Montreal Statement on Sustainability in the Digital Age (this issue). They include:

- Establish a social contract for the digital age.
- Promote inclusion as a touchstone of the digital age.
- Expand open access to high-public-value data.
- Establish foundational standards for the digital sector.

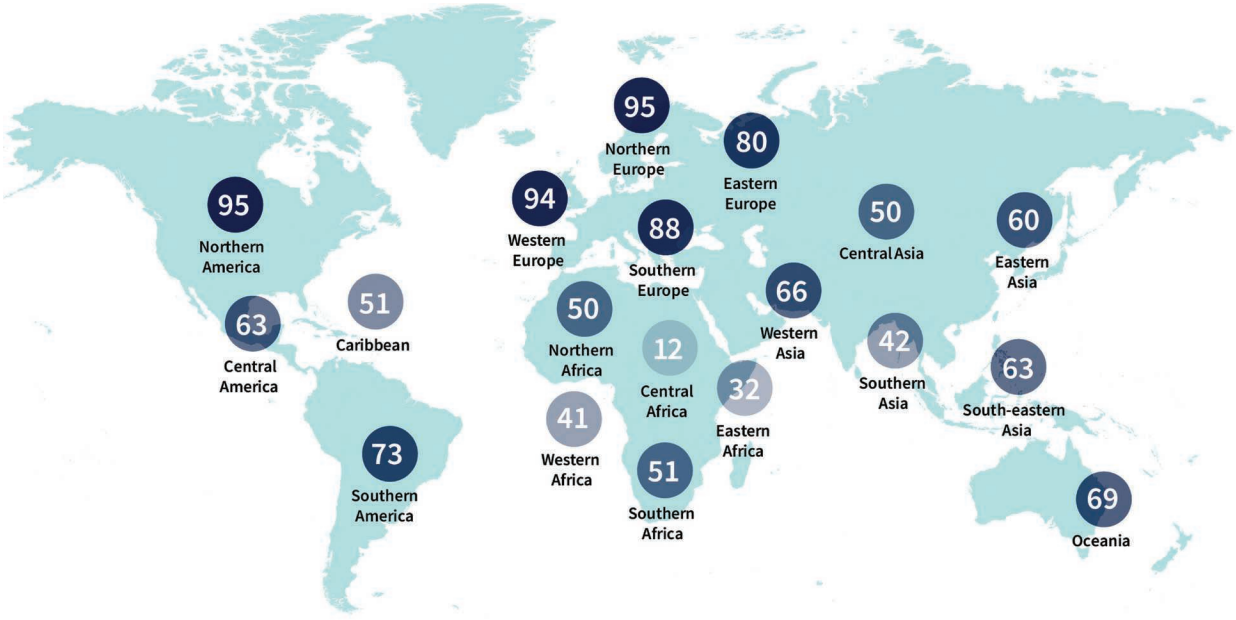


FIGURE 4. Percentage of population connected to the Internet by sub-region. Internet penetration rate ranges from 95% in parts of Europe and America to 12% in Central Africa. Darker circles indicate a higher rate of connection ([91], compiled from multiple sources).

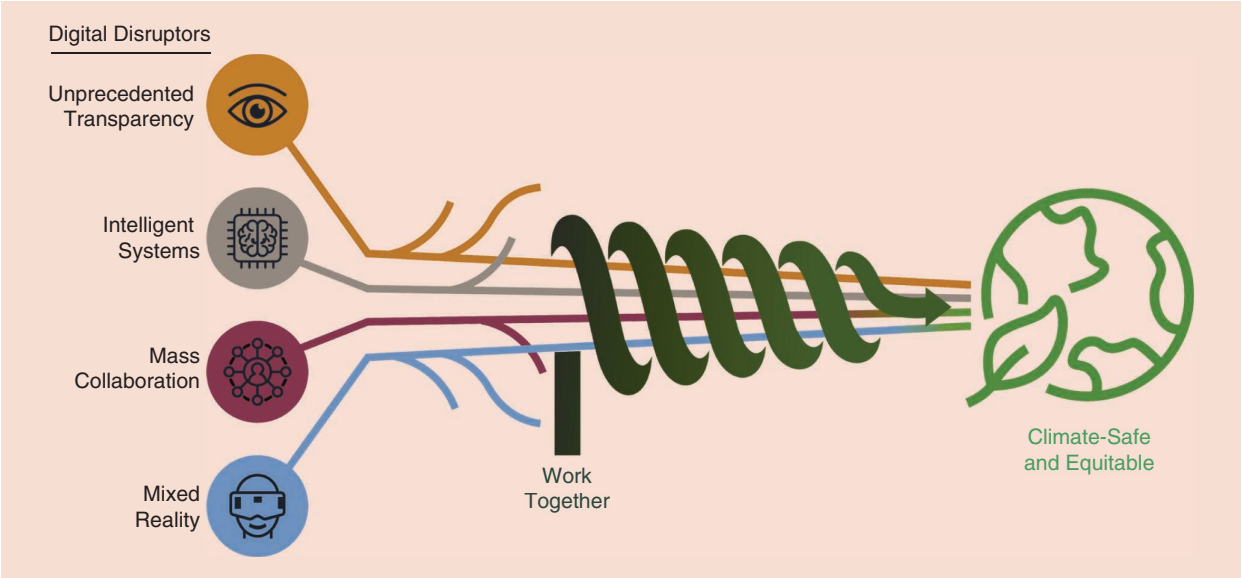


FIGURE 5. Working together to steer digital disruptions. There are systemic risks associated with these disruptors — issues related to privacy, human dignity, social justice, the future of democracy, and environmental sustainability. We do not know where digital disruptions will lead society, but with a concerted effort, we believe it is possible to work together to steer these digital disruptors towards unleashing the societal transformations necessary for a climate-safe and equitable future.

- Expand public-private partnerships to build our digital future.
- Reduce environmental impacts of the digital age.
- Foster cross-sectoral collaboration and innovation.
- Invest in targeted communication, engagement, and education

The Path Forward

The D^2S Agenda explores the opportunities and challenges of leveraging the digital age to tackle the climate crisis. Four key messages emerged from the D^2S analysis: 1) There are tremendous opportunities for leveraging the digital age to drive the transformative systems changes needed to address the climate crisis, but there are also major risks; 2) Tackling climate change and building a just and equitable digital world are one intertwined agenda, because humans are interconnected through and dependent on both the natural and digital worlds and our current trajectory poses global systemic risks that emerge from both worlds; 3) Seizing the opportunities of the digital age to drive transformative systems changes will require transdisciplinary research and innovation and collaborative actions; 4) Success will depend on overcoming the digital divide and developing inclusive strategies that consider differences among social and cultural contexts. The D^2S Agenda provides an initial framework for these ambitious tasks.

The D^2S Agenda initiated a global collaborative process, engaging over 250 individuals from different sectors around the world. We need to continue to expand the circle and deepen these collaborations. Steering digital disruptions will require concerted efforts through inclusive, interdisciplinary, intersectoral, and community-based collaborations (Figure 5), including efforts from both private and public sectors to build sustainable partnerships. Join us (sustainabilitydigitalage.org)!

Acknowledgment

This article provides an overview of the D^2S Agenda. The full D^2S Agenda is available online at http://www.sustainabilitydigitalage.org/ It contains direct excerpts from the Agenda, with permission from the Sustainability in the Digital Age project team who led the development of the report.

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