# 7

# Conclusions and Outlook

In this final chapter, I first turn to the larger picture and discuss the frequent shortcomings, as well as the rare strengths, of institutional responses to TNTs. After, I expand on several latent themes that lie beneath the wider problem field of environmental sustainability, technology, and international institutions: the dilemma of regulated use versus prohibition, the regulation of scientific research, the problem of path dependence, and the management of trade-offs. I conclude this chapter with some tentative thoughts on the applicability of the analysis developed in this book to areas beyond the environmental domain.

## 7.1 Islands of Effectiveness in a Sea of Dysfunctionality

In this book, I have assessed the institutional responses to the promises and perils associated with TNTs from the vantage point of scope and depth – that is, the coverage of institutional responses relative to the technological issue which they address, and the degree to which they provide binding and specific international rules, potentially combined with additional support mechanisms for enhancing implementation and compliance. As noted in Chapter 3, this conceptualization is based on the simplifying assumption of a linear relationship between scope and depth, on the one hand, and the degree to which institutional responses facilitate the realization of technological promises and the avoidance of perils, on the other. While this allows for a systematic stock take of institutional responses across issue area, I have also noted that 'deeper' and 'broader' will not in each and every instance imply 'better' in terms of the effectiveness of institutional responses, although there are good reasons to assume that this relationship holds as a general rule of thumb.

Seen from this angle, and subject to the caveat that many of them are 'moving targets', the institutions that I discussed in Chapters 4 to 6 have largely failed to respond to the promises and perils associated with TNTs in robust



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ways. Digital sequence information on genetic resources is an issue that remains unresolved under the FAO Seed Treaty as well as the CBD's Nagoya Protocol, which means that its promises remain largely unrealized and its perils unmitigated. Gene drive technology, with crucial implications for public health, food security, and biodiversity conservation, yet also with enormous and likely unprecedented risks, remains a matter of (so far) inconclusive discussions and technical consultations under the CBD and has received no more than cursory treatment through guidance issued by the WHO. Other major developments in biotechnology that are of note for environmental sustainability (for better or worse), such as de-extinction or Horizontal Environmental Genetic Alteration Agents, are not even part of the international discussion. The international regulation of climate engineering remains minimal for the most part: the CBD offered a response that, albeit broad in scope, provides no more than an ambiguous and non-binding recommendation at the highest possible level of generality. The Paris Climate Agreement encourages the large-scale deployment of NETs through its net-zero target yet relegates the operational details to its member states and their NDCs, with some international support mechanisms possibly beginning to emerge in the context of the Sustainable Development Mechanism of Article 6.4. The ozone regime under the Montreal Protocol and its Vienna Convention has so far failed to respond in a meaningful manner to the risk that some climate engineering technologies would pose for the ozone layer. In the United Nations Environment Assembly, politics and ill-conceived issue framing caused attempts at closer engagement with climate engineering to fail. On asteroids and other space resources, COPUOS has not yet managed to give operational clarity to the Outer Space Treaty in order to provide regulatory signal and direction to the emerging space industry. Under UNCLOS, the International Seabed Authority has made significant strides towards the development of an operational regime for deep-sea mining, yet critical issues remain unresolved and its most recent November 2022 Council session raised the spectre of a last-minute veto from France and others.

While it would certainly be too much to speak of governance failure, this overall picture is unsatisfying, both from a perspective of leveraging TNTs for environmental sustainability as well as from the vantage point of avoiding their potential negative impacts. For instance, we may reasonably disagree whether climate engineering technologies for the regulation of planetary albedo should be placed under a comprehensive moratorium (for avoiding their perils) or under a regulatory framework that would facilitate responsible innovation and, possibly, allow for controlled deployment.[1] Yet, as it stands, neither side is getting their way. The story is similar for gene drives. Given their risks, there is a strong case for an international moratorium. Given their potential benefits, however, a strong case also exists for

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proceeding with scientific research and for carefully evaluating potential deployment scenarios. As international institutions do not give clear direction one way or the other, the future availability of gene drives as an instrument of public health, food security, and biodiversity conservation remains unclear while scientists and funding agencies continue to pour resources into a technology that might end up being prohibited. Regulatory uncertainty adds to this picture. Depending on how policy preferences and bargaining coalitions evolve, scientific research with digital sequence information might continue as before or suddenly encounter formidable regulatory obstacles. Deep-sea mining might go ahead subject to international rules and oversight or it might suddenly face categorical prohibition, as was the case with CRAMRA under the Antarctic Treaty System. The very nature of TNTs, as something that is exceedingly promising and perilous at the same time, creates these situations where regulation is either indeterminate or bound to profoundly shift on a whim. This is a stark reminder of their specificity vis-à-vis other, regular technologies. There might be disagreement or even political conflict on the modalities of regulating, say, electric vehicles, civilian drones, or satellites – but any scenario in which these technologies are in regulatory limbo between prohibition and controlled use, or in which controlled use might turn into prohibition at a moment's notice (or vice versa), would seem extraordinarily far-fetched. The overwhelming failure of international institutions to provide adequate solutions for the emergence of TNTs is thus not just a matter of their general effectiveness deficit that can be observed across a wide range of issue areas, but is a consequence of the specific problem which they are confronted with.

While success stories exist, they are rare. In fact, there are only a few unambiguous instances where international institutions have responded to the promises and perils of TNTs through the formation of robust regulatory frameworks. One is the regime under the LC/LP for the regulation of marine climate engineering. Presently limited to ocean fertilization, this framework can be extended via majority decision to arguably a wide range of climate engineering techniques, such as marine cloud brightening or ship-wake brightening. A 2022 decision by the LC/LP's correspondence group on marine geoengineering to assess these and two other schemes for potential regulation further highlights the flexibility of this regime, simultaneously indicating the feasibility and rationale of addressing techniques from the NETs portfolio (such as ocean iron fertilization) within the same framework as techniques from SG (such as marine cloud brightening). At the same time, there is perhaps some irony in the fact that, at the time of writing, the formal treaty amendment has still not entered into force due to an insufficient number of ratifications. The same applies to the LP's amendment on subsoil CCS and the associated assessment guidelines and the framework for risk assessment and management: While the LP devised a robust response to the emergence of subsoil CCS as a political issue, the

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failure to secure sufficient ratifications for the Article 6 amendment to enter into force highlights the fragility of international institutional responses in the context of shifting domestic politics.

The other instance of what we might call a success story is the regulation of mining under the Antarctic Treaty System. Despite their fundamental difference in purpose, both the defunct CRAMRA as well as the Madrid Protocol provide comprehensive responses to the problem of resource extraction in Antarctica. Their differences in purpose and, accordingly, institutional design of course have different implications for the promises and perils associated with Antarctic mining. Yet both are clearly (and, in the case of CRAMRA, hypothetically) superior to the status quo ante, which is something that cannot usually be said for other institutional responses. CRAMRA and the Madrid Protocol thus represent a situation where the operational details of a regulatory choice might be less important than the fact such a choice is being made in the first place.

The three theoretical perspectives that I draw on differ in the extent to which they can shed light on the variation in outcomes. The interest-centred perspective which focuses on distributional implications and possibilities of joint gains from international cooperation can explain a good deal about institutional responses. Yet the structural and intentionally coarse conceptualization of interests that I have adopted here only goes so far. While it holds great explanatory sway for the field of biotechnology, the invariance in the international constellation of interests that likely characterizes the cases of climate engineering and mining beyond national jurisdiction appears inconsistent with the variation that characterizes the institutional responses. Looking purely at interests, it is not entirely clear why states would create a robust international regime for the regulation of ocean iron fertilization but not for SG, considering that both technologies are, to some extent, prone to potential misuse by rogue actors with possibly significant adverse impacts on the global environment.[2] Similarly, the international constellation of interests would be appear to be extremely similar for Antarctic mining and for deep-sea mining, including from a perspective of environmental impacts, yet there is substantial variation in the scope, and particularly the depth, of institutional responses under the Antarctic Treaty System and UNCLOS, respectively, not to mention the diametrically opposed purposes of those responses. (At the same time, the distinct recent possibility of a French veto during the final stages of concluding the Mining Code under the International Seabed Authority shows how the history of CRAMRA in Antarctica might ultimately repeat itself for the deep seas.) Finally, the almost complete absence of international institutional responses to NETs is difficult to reconcile from the vantage point of interest constellations, considering the centrality of this class of technology for

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the long-term climate policies of a majority of countries as well as for the prospects of limiting global warming in line with international temperature targets.

The knowledge-centred perspective also offers robust, though not all-encompassing, explanatory power. In biotechnology, pervasive difficulties in conceptualizing gene drives, Horizontal Environmental Genetic Alteration Agents, or de-extinction can help explain the lacklustre institutional responses. This is primarily an issue of insufficient political problematization: these technologies may provide large leverage for interfering with the natural environment and some may carry unprecedented biosafety risks. By itself, though, this does not necessarily turn them into political problems. How exactly these technologies 'matter' within the conceptual matrix of policy frames and policy priorities remains unclear.[3] SG may well be another technology where weak governance object constitution explains the dearth of institutional responses. In other areas, the approach holds less explanatory power. Digital sequence information remains a governance object characterized by substantial conceptual ambiguity yet, in recent years, they have emerged as a distinct political problem, with robust and comprehensive institutional responses being absent nevertheless. The same applies to NETs, where strong governance object constitution appears inconsistent with the observable inertia at the level of international institutions: at the same time that the private sector shows rapidly increasing engagement with questions of research, development, financial support, and questions of governance, the response under the Paris Agreement, particularly in the context of Article 6, has been extraordinarily lacklustre. The observable stakeholder engagement and buy-in suggests that the drift observable at the level of international institutions must have reasons unrelated to the constitution of NETs as a salient and actionable governance object. For mining in the deep seas and Antarctica, finally, the knowledge-based perspective may face difficulties in explaining variations in specific institutional outcomes but, simultaneously, draws our attention to the contradictions and ambiguities in the governance object itself that make it conducive to vastly different regulatory approaches. Much more than the other two explanatory perspectives, a focus on knowledge and governance object constitution hints at the profound contingencies in the international regulation of TNTs.

The notion of normative fit possibly provides the best way – albeit still an imperfect one – for making sense of institutional responses to TNTs. Technological developments such as SG and the proposed high-leverage biotechnological interventions discussed in this book are largely incongruent with existing norms, rules, and procedures and are thus difficult to reconcile with pre-existing governance structures. Due to a lack of precedents or analogues, no clearly applicable and unambiguous regulatory frameworks exist. The question of how to

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regulate these TNTs thus tends to be disputed as states struggle to fit new problems into old solutions. With greater normative fit, the depth and scope of institutional responses tends to increase. Ocean iron fertilization, the only type of climate engineering for which a robust international regime has emerged, is the best example here. In the context of the LC/LP, ocean fertilization amounts to no more than an extravagant form of marine pollution, regardless of its specific purpose of carbon sequestration. As a consequence, ocean fertilization can be processed on an 'as if' basis – that is, analogous to ocean dumping and placement of matter – thus fitting seamlessly into the pre-existing structure of the LC/LP. The same applies to CRAMRA and the Madrid Protocol. Despite their different purposes – the former being geared towards management and the latter towards prohibition – both fit into the evolving environmental competences of the Antarctic Treaty System, as well as the general provisions of the Antarctic Treaty regarding peaceful use, avoidance of international discord, and the common interests of humanity. A theoretical explanation in terms of normative fit is particularly straightforward for deep-sea mining. Unlike with the Antarctic Treaty System, UNCLOS (particularly its part XI) was created for the purpose of providing overarching norms for a specific TNT, setting UNCLOS apart from most of the other institutions I have discussed here. The sole technological field where normative fit lacks explanatory power is digital sequence information where, despite an extraordinarily high degree of fit, tangible institutional responses are largely non-existent. Yet the problem of digital sequence information, similar to stratospheric aerosol injections under the Montreal Protocol or gene drives under the Cartagena Protocol, also shows how there may be important differences between normative fit at the level of abstract norms and at the level of operational rules. TNTs may have a strong fit with existing institutions at the level of abstract norms but simultaneously be inconsistent with their rules as they exist 'on-the-ground'. The regulation or prohibition of stratospheric aerosol injections might fit well with the commitment to 'protect human health and the environment against adverse effects resulting or likely to result from human activities which modify or are likely to modify the ozone layer' set out in the Vienna Convention and its Montreal Protocol.[4] In operational terms, though, a problem that revolves around emissions is difficult or impossible to reconcile with a regulatory framework centred on production, consumption, and trade. In the same manner, stringent regulation or even prohibition of gene drives aligns with the precautionary orientation of the Cartagena Protocol at an abstract level. At the operational level, the Protocol was designed for (primarily) the regulation of cross-border trade in living modified organisms in (primarily) an agricultural context, not for the potentially uncontrollable transboundary movements that may occur with different degrees of probability due to the environmental release of a gene drive.

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I noted in Chapter 3 that this explanatory framework is not intended as a contest between theoretical perspectives, but was rather meant to indicate the value of looking at the problem of institutional responses to TNTs from different angles, each with its own strengths and limitations. At the same time, and notwithstanding the issues pointed out in the preceding paragraph, the notion of normative fit appears to offer a particularly useful entry point to the problem of institutional responses. In the following section, I explore the implications for institutional design: to what extent can we devise institutions in such a manner that normative fit will be high and institutional responses will accordingly enable for a sizeable share of promises to be realized and of perils to be avoided?

## 7.2 Institutional Design and Normative Fit

The problem of institutional fit with a pre-existing institution applies both to technologies that have been anticipated in the original design of that institution and to technologies that have not. For instance, whereas UNCLOS was drafted with a view to regulating deep-sea mining further down the road, marine climate engineering did not exist as a regulatory issue when either the LC or the LP were created. The challenges associated with either type obviously differ in magnitude. UNCLOS has a strong normative fit with deep-sea mining because it was explicitly designed to this end. Conversely, the LC/LP has been designed to address marine pollution from the dumping of waste and other matter, which only much later turned out to also involve certain types of marine climate engineering. In more abstract terms, the problems of normative fit and of international technology regulation are mainly of concern with regard to technological challenges that were unpredicted, or unpredictable, at the point in time when an international institution was created and which only later turned out to unexpectedly have a bearing on the matter. Compared to technologies that have been anticipated during institutional design, unanticipated technologies typically showcase greater uncertainty regarding distributional impacts, divergence in risk perceptions, legal ambiguities, and other elements standing in the path of adequate institutional responses.

This raises the question of whether there are specific characteristics at the level of technologies themselves that shape the degree to which they fit into pre-existing regulatory frameworks. That is, are there technologies that intrinsically gravitate towards low, or high, degrees of normative fit? This problem is commonly discussed under the label of ‘problem structure’, a concept intended to capture the physical, social, or other attributes that define a specific governance object and shape the ways in which institutions operate on it. In other words, the idea of problem structure assumes that the ways in which institutions deal with specific issues depends not just on the institutions but also on the attributes of these issues in

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their interaction at the institutional level.[5] While there is no consensus about the precise elements that determine problem structure, one major factor influencing the degree of normative fit with pre-existing institutions may relate to the nature of transboundary effects. Even where a TNT is unambiguously within the scope of a given international institution, low degrees of normative fit can result from a mismatch between the nature of the transboundary effects associated with that technology and those for which the institution was designed. The Cartagena Protocol and the Montreal Protocol illustrate this kind of mismatch. Gene drive organisms generally amount to living modified organisms for the purposes of the Cartagena Protocol, and the potential harm that some types of SG may cause to the ozone layer makes them relevant for the purposes of the Montreal Protocol. Yet while gene drives will tend to propagate across international borders in a more or less uncontrollable manner, the Cartagena Protocol is primarily geared towards the regulation of the export, transit, and import of living modified organisms. Similarly, the injection of certain ozone-depleting substances into the stratosphere for purposes of solar radiation management would amount to vessel- or ground-based emissions, thus being incongruent with the regulatory focus of the Montreal Protocol on the production, consumption, and trade of such substances. This also harks back to the earlier discussion on the regulation of ocean fertilization as an analogue to ocean dumping under the LC/LP, where congruence in the nature of transboundary effects ensured a high degree of normative fit. Partially, such a problem of incongruence between the pathways through which a TNT acts and the pathways for which institutions are designed may also characterize digital sequence information. At an abstract level, these have a strong normative fit with international instruments regulating access to genetic resources and the sharing of resulting benefits. In operational terms, these instruments have been designed for the regulation of bilateral transfers of physical specimens between providers, intermediaries, and users. They have *not* been designed to deal with the decentralized and high-volume transfers that digital sequence information encompasses. The normative fit of digital sequence information is accordingly lower at the operational level than at the level of abstract norms. While transboundary impacts establish a rationale for international institutional responses as such, the specific patterns of those impacts could have an important effect on whether a given TNT does, or does not, fit with pre-existing regulatory frameworks. As there might well be a general bias in global governance towards problems that manifest themselves as distinct transboundary transactions between identifiable parties, and against problems that present diffuse transboundary impacts from diffuse sources, TNTs operating through the latter rather than the former mechanism may intrinsically gravitate towards low degrees of normative fit and, accordingly, comparatively unsatisfactory responses to their associated promises and perils.

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The Antarctic Treaty and the LC/LP are perhaps the best examples to highlight how to design international institutions in order to enable strong normative fit with unpredictable future challenges, technological and otherwise, by providing a high degree of flexibility for parties to evolve and develop an initial regulatory framework subject to overarching norms of common interests and responsibilities. At a deeper level, both of these cases also lack the normative ambiguity that characterizes many of the other institutions discussed in this book, such as the Outer Space Treaty (with its unclear allusions to the common heritage principle) or the CBD (with its tension between the diffuse benefits generated from access to genetic resources and the direct benefits that are to be channelled back to providers). Such ambiguity is certainly a result of the conflicting interests and visions that states frequently have on complex matters of international politics. At the same, ambiguity also feeds back onto states by reproducing and stabilizing certain ways of seeing the world – and there is certainly a difference in whether states look at the problem of mining in ABNJ through the metaphorical eyes of the Antarctic Treaty System or those of UNCLOS. That is to say, the degree to which state interests and perceptions diverge or converge is partially also a result of the institutions which they have created in the past. The Nagoya Protocol, for instance, has been hailed as a 'masterpiece in creative ambiguity'.[6] Only this, so the argument goes, unlocked the possibility of a negotiated outcome between groups of states with strongly diverging regulatory preferences. But questions of diplomatic expedience aside, there is a distinct possibility that such compromise solutions end up reinforcing the very problems that gave rise to them in the first place. Ambiguity at the level of institutions, while understandable and to some extent unavoidable, limits the degree of normative fit with the TNTs that may emerge at one point or another: where the institutions themselves are ambiguous, their normative pull will be weak and lack directionality, while actors will have wide latitude for interpreting institutional rules in terms of their respective parochial interests. While this problem likely goes far beyond the issue of TNTs, we might note that international institutions that have been designed for ambiguity due to reasons of political expedience are predestined to exhibit low normative fit and thus to deliver responses of limited relevance for the realization of technological promises and avoidance of technological perils.

### 7.3 Regulated Use, Prohibition, and Precaution

In this and the following three subsections, I step away from these and other larger, abstract questions of institutional responses to TNTs, instead exploring several salient conceptual issues at a lower level of abstraction. One crucial element which the discussion in this book has highlighted is that the diverse political controversies

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over TNTs commonly revolve around whether they should be *prohibited*, at least until there is satisfactory evidence that they are unproblematic or comparatively benign, or whether we should allow their *regulated use* based on case-by-case assessment and subject to some form of international oversight. The difference between the two is at the core of political disputes, in different contexts, about the operational implications of the precautionary principle. This principle is, of course, of utmost importance for the regulation of TNTs. Its most common definition is provided in the 1992 Rio Declaration and holds that '[w]here there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation'.[7] At its core, the precautionary principle reverses the burden of proof, in the sense that the proposers of a potentially harmful activity are responsible for demonstrating its lack of harmfulness, instead of its detractors being charged with providing definite evidence of its harm.[8] This approach informs technology regulation in many parts of the globe and is a normative centrepiece of international environmental law, despite persistent disputes on its interpretation, implications, and legal status. In the context of TNTs and the question of their prohibition or regulated use, two specific aspects stand out.

The first is that a reversed burden of proof may create a standard that is difficult, or sometimes even impossible, to meet for the purposes of TNTs. This particularly applies to SG and biotechnological interventions such as gene drives or Horizontal Environmental Genetic Alteration Agents. Such technologies are not amenable to standard risk assessment procedures because the distinction between field trials and full-scale releases is either uninformative or non-existent. The full impacts of technologies such as SG are likely impossible to gauge from field trials and, for self-propagating artificial genetic elements, field trials may cascade to the level of full-blown releases. Other TNTs may have indirect, systemic impacts that can be impossible to assess in advance, one example being the global environmental impacts that gigaton-scale NETs create through land system changes or at the level of supply chains and material flows. Requiring conclusive evidence of a lack of harmfulness prior to deployment will, in practice, amount to a ban due to the categorical impossibility of fashioning such evidence.

A second aspect is that the existence of risk–risk trade-offs complicates the use of the precautionary principle as a decision tool. The FCCC, for instance, calls for precautionary measures not in the context of technological deployment choices but in the context of climate change itself. That is, parties to the Convention 'should take precautionary measures to anticipate, prevent or minimize the causes of climate change and mitigate its adverse effects' and, '[w]here there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures'.[9] In principle, such a framing of

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precaution is aligned with the large-scale deployment of climate engineering techniques, including both NETs and SG, even though those may come with significant uncertainties. Thus, there is a question of how to assess precaution at the level of TNTs in relation to the assessment of precaution at the level of the environmental challenges which these technologies are intended to address. Does uncertainty mean that we should deploy a broad response portfolio, including novel gene technologies, in order to deal with the problem of global biodiversity loss because the uncertainties that exist regarding its causes, consequences, extent, and implications should not be used to justify the postponement of potential countermeasures? Or should we refrain from deploying novel gene technologies against the problem of global biodiversity loss until they have conclusively been proven to be harmless?

This problem drastically reduces the utility of the precautionary principle as a decision-making rule. Whereas the principle may be 'defensible, if not appropriate, in cases where the risks are public, widespread, or nonexcludable and any benefits of the risky activity are private, local, or excludable', it ultimately ' offers less guidance . . . when both the risks and the activity's benefits (including reducing other risks) are public, widespread, or nonexcludable'.[10] The point is simply that the regulatory choice between prohibition and regulated use presents a dilemma that cannot be resolved by recurring to the precautionary principle. This applies well beyond technologies that are problematic due to associated uncertainties and risks. Some technologies are simply harmful as such, and that categorically includes all types of mineral extraction. But whether deep-sea mining should be prohibited or whether it should be allowed based on case-by-case assessment and international regulatory oversight is matter of balancing different and incompatible goals and values. To what extent do we accept irreversible harm to the marine environment as the price of a zero-carbon transition or as a substitute for conventional, terrestrial mining operations with environmental consequences that may well be similarly catastrophic? There is simply no good answer to such questions, and this book has shown that international institutional responses tend to come down on either side of the divide. Under a forward-looking perspective, a partial and imperfect response to the problem could be the design of regulatory exit ramps, meaning the periodic reverification of existing regulatory approaches subject to criteria that have been specified ex ante. This could mean instituting a categorical ban on the deployment of problematic technologies while committing to regular reassessments of whether the reasoning that justifies this ban continues to hold. In reverse, it can also mean allowing for limited, regulated use subject to international oversight while periodically checking whether there are sufficient indications for shifting towards prohibition. Self-reinforcement is likely to be the main limitation in the use of regulatory exit ramps: TNTs cannot easily be switched on or off

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without incurring harm of foregoing benefits. Mining projects take years to set up before they may yield resources at a meaningful scale. Gigaton-scale NETs cannot be deployed overnight, just as SG technologies cannot be abruptly terminated without catastrophic consequences, instead requiring a gradual phase-out.[11] These are major limitations, yet the dilemma of having to choose between prohibition and regulated use without knowing in advance the future costs and benefits that can result from either choice implies that regular review and an open-ended orientation in international regulation may provide capacities for adjusting to changing circumstances and novel information.

## 7.4 The Regulation of Scientific Research

The problem of prohibition versus regulated use goes beyond questions of the *deployment* of potentially problematic technologies and extends to questions of research and development. For some, though not all, of the technologies discussed in this text, various observers have raised concerns about possible 'slippery slope' effects, meaning that research and development for high-risk technologies creates momentum for their eventual deployment irrespective of whether this is ultimately considered desirable. Once SG technology is ready for deployment at the press of a button, so the argument goes, decision-makers are not going to abandon what may well be a highly effective tool for masking global warming. Once gene drives or other high-risk biotechnological interventions such as Horizontal Environmental Genetic Alteration Agents have been developed, stakeholders will want to see them deployed against vector-borne diseases or invasive species. Even with mining activities, the problem may partially apply: mere prospecting and exploration may create a dynamic towards the commercial exploitation of metals and other mineral resources even if clear evidence emerges that the benefits of resource extraction are far outweighed by its downsides, for instance in terms of expected environmental harm. At the core of this argument is the idea of emerging path dependence: over time, self-reinforcement increasingly drives research and development towards deployment. Sunk costs are one reason: as financial investments cannot be recuperated in the case that research and development projects are prematurely terminated, the pressure to deliver tangible results builds up over time. Similarly, the reputational stakes of abandoning research and development projects increase over time: giving up on projects for which developers have committed significant chunks of their careers incurs drastic hits to professional prestige and may similarly deter disengagement. Allowing potentially problematic research processes to move ahead, so the argument goes, increases the likelihood of detrimental consequences being realized regardless of whether we understand them to be detrimental. The exploration of certain potentially harmful courses of action

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would thus make it more likely that these courses of action end up being realized, rather than such exploration leading to their exclusion from the set of potential decision alternatives.

While this argument has its merits, there are two common responses. The first is that any assessment of the overall desirability of a novel technology requires a sufficient informational basis: whether the risks of gene drives outweigh their potential benefits, for instance, cannot be determined without developing the technology to a high level of readiness. Similarly, without prospecting and exploration, we may not be able to know whether the environmental harm from deep-sea mining would be so severe that its benefits would pale in comparison. The second response is that the diverse challenges of global environmental sustainability require a diversified portfolio of potential options. Solar geoengineering might end up not being needed but, in case a catastrophic collapse of the global climate system *should* take place, it would be at hand as a measure of last resort. Similarly, unexpected improvements in resource efficiency or recycling rates might make the material requirements of the zero-carbon transition less stringent than presently assumed, making deep-sea mining or asteroid mining unnecessary – but, ultimately, we do not know and things might turn out differently. Keeping our options open by refraining from restrictions on risky lines of research is thus a way of hedging against uncertainty: although we might disapprove of a given technological solution, we might disapprove even more strongly of the alternatives to its deployment. It is one thing to oppose research on stratospheric aerosol injections while a 1.5℃ global warming remains theoretically within reach via mitigation only. It is likely another thing entirely if the alternative consists of dangerous levels of global warming in excess of 2℃.

None of this is to downplay the problematic role that path dependence can play leading up to the deployment of technologies in spite of potential evidence of their malignancy. It is noteworthy, though, that there appears to be no automatism behind the slippery slope effect. Particularly in the life sciences, numerous examples exist of research and development projects being abandoned at advanced stages and in spite of the potential path dependence that may have accumulated. Human cloning is an obvious case. While the technical feasibility of human cloning is high, it is universally condemned as blatantly inconsistent with ethical norms, and the process of its technological development has apparently not resulted in path dependence building up to an extent sufficient to overcome this principled opposition.[12] Similarly, gain-of-function research, where pathogens are genetically enhanced in order to study their properties, has been placed under diverse moratoria across time and geographical regions. Offensive bioweapons programmes have purportedly been discontinued everywhere, notably through unilateral action in the United States prior to the development of a global disarmament regime in the

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1970s.[13] The implication is that there is empirical evidence that, in principle, conditions exist under which path dependence in the research and development of risky (or otherwise problematic) technologies does not create an automatism for their eventual deployment. While this raises the challenge of identifying these exact conditions, a more basic point is that, by itself, path dependence does not provide a sufficient rationale for prohibiting or otherwise restricting research and development on novel risk technologies.

Pre-defined minimum performance criteria might offer a way around the slippery slope problem. While the precise characteristics of TNTs are difficult to anticipate, international rules that specify the pre-conditions of their usage can mitigate the pressure for undesirable deployment that might result from path dependence. Certain types of harm could be designated in advance as exclusion criteria – for instance, with a requirement that any potential future uses of stratospheric aerosol injections would be categorically impermissible if non-trivial harm to the ozone layer were to be expected. Similarly, as discussed in Chapter 6, deep-sea mining activities could be considered as impermissible in advance unless the environmental harm which they are expected to cause to the marine environment is demonstrably lower than it would be the case for terrestrial mining operations of similar magnitude. In other words: if the problem is that the process of technological development creates pressure for technological deployment even where it ultimately turns out to be undesirable, the solution is to specify in advance the criteria which these technologies would be required to meet. In the long run, whether or not such criteria will persist, especially in the face of potential pressure for their revision or withdrawal, is another matter entirely – just as any contemporary moratorium on research and development might be lifted, broken, or circumvented in the future. In the end, the conditions that determine the stability of, and compliance with, institutional rules are largely extra-institutional in nature.

Another aspect to the question of regulating scientific research is that restrictive approaches, up to and including moratoria, can preclude leveraging TNTs for the creation of information commons. This is particularly obvious for the case of digital sequence information, where scientific stakeholders have repeatedly pointed out how heavy-handed international regulation on access and benefit-sharing can interfere with non-commercial research.[14] It is also, albeit less obviously, the case where commercial motives could contribute to the information commons as a spin-off effect, for instance when commercial operators are required to make freely available information collected in the context of resource extraction from asteroids or the deep seas. As information commons constitute a form of benefit-sharing, they are particularly attuned to legal contexts that emphasize collective rights through diverse variations on the theme of the common heritage of humanity. This aspect should be borne in

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mind when considering regulatory interventions that would impede scientific research in order to forestall path-dependent dynamics towards a possible undesirable use of a given TNT.

## 7.5 Path Dependence

The problem of path dependence raises further questions beyond the domain of scientific research. TNTs are prone to exhibit path dependence,[15] which is at the core of the slippery slope argument discussed in the previous section. The degree to which different TNTs tend towards path dependence likely varies: those with significant infrastructural components, such as DAC, would likely exhibit a stronger tendency than those with a lighter footprint, such as gene drives or some types of SG. As path dependence ramps up, we would expect TNTs to become more challenging to regulate effectively, with promises becoming harder to realize and perils more difficult to avert. This provides a strong rationale for early regulatory action while also raising concerns in the face of the widespread inaction that is observable at the international level and likely corresponds to a gradual loss of regulatory leverage. That is, at the same time that international institutions fail to provide robust responses, TNTs may consolidate across wider socio-technical systems, making meaningful regulatory intervention more and more demanding. On the flipside, there may often simply be no feasible alternative to adopting a 'wait and see' approach while, in the meantime, sorting out associated uncertainties and political divergences. The ambiguity and plasticity that characterizes TNTs during their emergence may thus stand in the way of early regulatory action, whereas later action will have to confront the challenge of path dependence.

A second, more subtle, aspect are the implications that TNTs have for path dependence in the socio-technical systems that create the sustainability challenges that make necessary a (technological) solution in the first place. In principle, TNTs might help overcome path dependence and shift socio-technical systems onto a more sustainable trajectory. But it is more likely that they provide mere band-aid solutions for temporarily masking the worst outgrowths of those systems without changing their fundamental nature: while their impacts are transformative at the level of the global environment and society–nature relations, they may tend to reinforce the status quo at the level of socio-economic order. By allowing for the mitigation of diverse types of harm that result from the unsustainability of that order, TNTs can alleviate pressure for systemic change. Advanced genetic biocontrol agents could mitigate the problem of evolved resistances in plant pests and thus stave off the need to consider alternatives to the unsustainable contemporary model of intensive agriculture. Mineral extraction in the deep seas or outer space would allow inefficient production and consumption patterns to persist longer than they

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would otherwise. NETs enable a smoother phase-down of the fossil-fuelled model of global economic development and accordingly channel economic benefits towards legacy industries organized around the emission of carbon dioxide. Thus, aside from the question of their own path dependence, TNTs likely stabilize unsustainable social structures that would otherwise have to confront greater pressure for change. Their transformative impacts at the level of the global environment and of nature–society relations would thus simultaneously provide an obstacle to deeper, more radical forms of socio-economic transformation. The scale of their potential impacts, with limited or no historical precedents, may thus obscure their essentially conservative nature.

## 7.6 Managing Trade-Offs

Trade-offs are at the core of contemporary discussions (and controversies) regarding the merits and downsides of TNTs. These can be trade-offs between different risks: for instance, the risks associated with global warming versus the risks associated with SG.[16] They can also be trade-offs between competing values: the contemporary deficits in the international regulation of digital sequence information is unjust from the perspective of the providers of the associated genetic resources, but the price of stricter regulation would be a reduction of the global benefits that derive from associated research, development, and innovation.[17] Trade-offs, in other words, can exist at two different levels: between TNTs and their political alternatives, but also between the different technology-specific promises and perils. This latter type is of greater theoretical interest for our purposes. The empirical discussion in Chapters 4 to 6 suggests that the simultaneous realization of promises and avoidance of perils can be challenging or even impossible: fuelling a global sustainability transition through deep-sea mining appears impossible without causing environmental harm, just as global temperature control via SG likely entails irreducible social and political risks. Such trade-offs raise a complex conceptual challenge: how do we evaluate the relative merits of different institutional response options when it is only possible to either realize promises or to avoid perils, but not to do both at the same time? In contexts where the realization of promises does not interfere with the avoidance of perils (or vice versa), we can relatively easily assess and compare the relative effectiveness of the various institutional responses and response options. Conversely, unavoidable trade-offs require value judgements for ranking and prioritizing promises and perils, making it significantly more difficult to determine the comparative effectiveness of different responses and response options.

Value conflicts regarding promises and perils are central to the politics of TNTs, notably regarding the question of precautionary regulation that I briefly discussed

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earlier in this chapter. Where differences in values imply differences in policy objectives, effectiveness is relative and a given institutional response could be perceived as effective by some and as ineffective by others. Such value conflicts can pose major challenges for the conceptualization of effectiveness. They are also arguably a major political stumbling block in the global governance of TNTs as well as technology more broadly. Yet there are two important qualifiers. The first is that value conflicts typically mask uncertainty. Those arguing for a moratorium on technologies such as SG or gene drives do so under the assumption that their aggregate environmental, social, and political risks outweigh their aggregate benefits. Those arguing for their assessment under the perspective of potential deployment do so under the assumption that, possibly, the technological promises in their sum total outweigh the perils. The value conflict, and thus the trade-off between promises and perils, chiefly results from the question of how to deal with the informational deficit: what are the appropriate governance choices when technological impacts are uncertain? The severity of value conflicts and of the associated (perceived) trade-offs is thus directly linked to the various types of uncertainty that, to different degrees, can characterize the diverse technical, economic, social, and other aspects of a given technology. Research and development for facilitating the robust assessment of TNTs may thus be crucial for the mitigation of value conflicts and, accordingly, for enabling the assessment of institutional responses and response options based on shared understandings of effectiveness as the primary decision criterion.

The second qualifier is that trade-offs between promises and perils can be exogenous to the technologies as such, originating instead from the governance structures into which they are embedded. Realizing the informational commons as a promise associated with the use of digital sequence information in bioinformatics only creates a peril of injustice towards the providers of the underpinning (physical) genetic resources because of the specific regulatory structure of the CBD, its Nagoya Protocol, and related instruments such as the FAO Seed Treaty. Where fair and equitable benefit-sharing requires the monitoring and enforcement of bilateral contractual obligations between providers, intermediaries, and users, any attempt to create just outcomes for providers will necessarily entail detrimental effects on users. Under an alternative tax- or fee-based model, greater justice for the providers of genetic resources in developing countries and elsewhere could likely be achieved without generating compliance costs for end users that would interfere with the use of digital sequence information as an information commons. Similarly, the risk of termination shock is frequently invoked as an argument against the global deployment of SG. As the abrupt termination of an SG programme would cause a catastrophic rebound effect as global temperatures rapidly return to the equilibrium level associated with a given atmospheric greenhouse gas concentration, the promise of using SG for the robust management of societal impacts on nature and of

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environmental impacts on human societies comes with the peril of potential devastating harm from termination shock. While this trade-off cannot be *eliminated* without major changes in the technical implementation of SG as currently conceived, its severity could likely be *reduced* by devising institutional solutions geared towards the prevention of abrupt termination and, potentially, a coordinated and gradual global phase-down.[18] What appear to be irreconcilable objectives originating from the very nature of a given technology can, instead, be the result of its surrounding regulatory framework. Where this is the case and trade-offs can be mitigated or even eliminated through adequate institutional design, the various responses and response options can be assessed from the vantage point of a shared understanding of effectiveness in terms of aggregate contributions towards the realization of promises and the avoidance of perils.

While potential and perceived trade-offs between promises and perils are a key challenge in the global politics of TNTs, it is thus worthwhile to inquire into their origins and conditions of existence. Ultimately, some trade-offs are unavoidable or require significant effort to mitigate, accordingly requiring collective choices regarding which of several competing values should take priority. At the same time, the careful consideration of the degrees to which trade-offs could be avoided or mitigated in an efficient manner might contribute to the elimination of bones of contention that are ultimately unnecessary and thus enhance the quality of the social and political debate on the overall utility and relevance of TNTs in the context of environmental sustainability.

## 7.7 Beyond Global Environmental Governance

Transformative technologies exist outside the immediate scope of global environmental governance, and an important question is how the arguments developed in this book might carry over. A field that easily comes to mind when thinking about high-impact technologies is artificial intelligence (AI). The future promises of AI leave hardly any sector of human activity untouched. In 2020, an artificial neural network solved the decades-old problem of predicting the structures (and thus the functions) of proteins from their respective amino acid sequences, with potentially revolutionary implications for medicine and drug discovery.[19] AI-controlled robots could reduce overall human workload and substitute for human labour in hazardous or extreme environments, including in potential asteroid mining operations. Autonomous vehicles might transform personal transportation, including by improvements to road safety or through the reduction of congestion. Tools such as predictive policing, where statistical pattern recognition enables pre-emptive law enforcement action, are certainly more ambiguous and difficult to reconcile with conventional ethical understandings of criminal justice.[20] A much-related issue, yet

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one that is already indisputably on the side of perils, is algorithmic discrimination. The machine learning algorithms that are nowadays used to predict everything from consumer preferences to personal credit scores are trained using historical data, thus making predictions based on historical data, and, accordingly, reproducing historical patterns of discrimination that are contained in these data.[21] The erosion of data privacy and civil rights, in the context of big data analytics and facial recognition software is another type of peril. Lethal autonomous weapons systems, colloquially known as killer robots, are sometimes touted as a way to reduce the humanitarian costs of warfare (due to both superior targeting and the absence of base human cruelty in robots), yet they raise complex questions about ethical responsibility and human control capacities. Undoubtedly the biggest threat of all, and the wildcard event par excellence, is the technological singularity, the development of artificial general intelligence capable of improving itself to a level far beyond the limits of human understanding and bound to pursue goals that are inconsistent with the continuation of self-determined human civilization.[22]

Examples of the promises and perils of AI are too numerous to list. Perhaps unsurprisingly, global governance has not responded in kind. In fact, institutional responses to AI are piecemeal and fragmented across forums such as the G7, the G20, and the Organization for Economic Co-operation and Development, amounting to little more than political declarations.[23] Under the United Nations Convention on Certain Conventional Weapons, in 2019 contracting parties adopted a sparse set of non-binding principles that provide no more than abstract guidance on technological developments in the area of lethal autonomous weapons systems.[24] Elsewhere in the UN system, engagement with AI is similarly timid.[25] And, despite the increasing criticality of cyberwarfare, states are shying away from negotiating an international arms control instrument.[26] The shallowness that characterizes the global governance landscape for AI is starkly at odds with the technology's stakes, and the lack of a robust international regulatory framework likely means that many perils are not being avoided and many promises remain unrealized. Taking into account how the difficulty of regulatory intervention will increase the more consolidated AI becomes in virtually all sectors of global societies, the total lack of ambitious and comprehensive international efforts at sorting out one of the key technologies of the twenty-first century while doing so is still possible runs counter to what appears, on the face of it, prime material for international cooperation.

The three explanatory frameworks that I have used in this text would lead to different interpretations. From an interest-based perspective, what is perhaps standing in the way of deeper and more comprehensive institutional responses is the global asymmetry in AI capacities. The few governments in the world with advanced capacities in cyber and robotic warfare have little interest in developing

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common solutions with the many governments that would perhaps prefer to see these capacities constrained. As a high-tech sector where vast commercial intellectual property is at stake, it is also unsurprising that high-innovation states do not have a strong wish to devise international arrangements for having low-innovation states participate in the associated economic and other benefits. As the international constellation of interest gives rise to distributive bargaining, institutional responses will be severely limited absent the possibility of larger package deals whereby high-capacity and low-capacity states can exchange concessions in a mutually beneficial manner. In terms of governance object constitution, the difficulties in conceptualizing AI as a political problem are comparable to synthetic biology. This starts from the question of whether AI is one problem or whether it is an inopportune umbrella term for several problems. When policymakers or academics speak of the politics of AI, they might be lumping together what is perhaps better considered as a suite of loosely related yet distinct issues – some of which, such as technological singularity, might even appear too outlandish to warrant serious political engagement.[27] From a perspective of normative fit, finally, many of the specific problems under the general heading of AI are quite challenging to accommodate within pre-existing regulatory frameworks. International humanitarian law is based on a notion of attributable responsibility for acts committed during armed conflict that is not well-suited for robotic warfare with algorithmic decision-making on the use of lethal force. Human rights are an area of international politics where contestation and value conflicts are already so pervasive that the lack of robust international action on the ethical implications of mass surveillance in the age of big data may not be surprising. While interest constellations can become more benign over time, and governance objects can gradually become easier to articulate as clearly defined political problems, a better fit between AI and existing global governance structures would likely require substantial normative evolution that is impossible to predict and difficult to plan.

Looking to the past, the history of nuclear technology highlights both the challenges in governing TNTs and the advantages of robust international institutional arrangements that are of sufficient scope and create rights and obligations that are binding and specific, as well as facilitated and enforced through additional support mechanisms. The precise promises and perils of nuclear technology are certainly a matter of debate – cheap energy was a major initial promise, yet in most places of the world, nuclear energy kept being outcompeted by other energy sources – with the commitment to nuclear energy thus likely having crowded out feasible alternatives, such as earlier and larger investment into renewables. Perhaps more important than its promises, the peril of harm, from waste, reactor accidents, or weaponization, has always been central to the politics of nuclear technology. Initially, however, international rules did not keep pace with technological change.

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Nuclear weapons started to proliferate from the 1940s and, by the 1960s, five (or possibly six) countries possessed operational warheads. Next-generation thermonuclear weapons quickly came to surpass the destructive power of the initial designs used by the United States against Japan in August 1945. In parallel, novel delivery systems quickly came into use, from submarine-launched ballistic missiles to intercontinental ballistic missiles that, since the late 1960s, could be outfitted to carry multiple warheads that could be targeted independently of each other on atmospheric re-entry. The US nuclear weapons stockpile increased from less than 400 devices in 1950 to approximately 20,000 a decade later.[28] Nuclear doctrine in East and West started to coalesce around the idea of a balance of terror, known as mutual assured destruction, from the 1960s.[29] In parallel, from the mid-1950s onwards, nuclear power stations started to come into use in the United States, the Soviet Union, the member states of the European Atomic Energy Community, and elsewhere. Among the second generation of nuclear reactors, the pressurized water reactor, which uses two separate coolant loops running on regular light water to transfer the heat generated during fission to a steam turbine, emerged as the dominant design in most of parts of the world. By 1980, more than 100 nuclear reactors worldwide produced roughly 600 terawatt hours, amounting to a small but sizeable share in the global electricity mix.

Nuclear technology has diverse transboundary implications that make it a prime candidate for international regulation. Unlike for the technologies discussed in this book, practically all of the international institutions that regulate different aspects of nuclear technology had to be created from scratch – and the emergence of an international nuclear regime lagged considerably behind the emergence of the technology itself. The 1950s and 1960s saw limited efforts to ban some types of nuclear weapons testing, including under the 1959 Antarctic Treaty and the 1963 Limited Test Ban Treaty, which prohibited tests below water, in the atmosphere. and in outer space. Since 1968, the Non-Proliferation Treaty obliges its nuclear-weapon state parties not to share nuclear weapon technology with others and commits all parties to the treaty to 'pursue negotiations in good faith on effective measures relating to cessation of the nuclear arms race at an early date and to nuclear disarmament'.[30] Efforts at nuclear arms control surged in the 1970s and 1980s, resulting in agreements such as the 1972 Anti-Ballistic Missile Treaty, the 1979 SALT II Treaty, and the 1987 Intermediate-Range Nuclear Forces Treaty. Agreements related to civil nuclear technology only emerged from the 1960s, starting with the Vienna Convention on Civil Liability for Nuclear Damage. The Convention on Early Notification of a Nuclear Accident was adopted mere months after the 1986 Chernobyl catastrophe, and further instruments on nuclear safety, the safety of spent fuel management, and the safety of radioactive waste management were only adopted in the 1990s.

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While the contemporary international nuclear regime possesses considerable scope and depth, institutional development has lagged technological development by decades. Going back to the issue of path dependence, the efficacy of international rules decreases as technologies consolidate themselves – raising the question of which international institutions, at some point in time, cease to exert autonomous causal effects of their own and merely codify behavioural patterns that have already been regularized across socio-technical systems. At the same time, the international nuclear regime is comprised of robust institutions with considerable regulatory depth and scope. The strong institutionalization of non-use as a central norm of the international nuclear regime has arguably contributed to the absence of any military deployment after August 1945.[31] The Non-Proliferation Treaty is significantly reducing proliferation risk.[32] International institutionalization has also facilitated the emergence of a nuclear safety culture at organizational and individual levels.[33] Outside of the immediate field of international nuclear agreements, the 1972 London Convention, discussed in Chapter 5, has contributed to curbing the dumping of nuclear waste at sea.[34] Robust institutional responses, in other words, have had tangible impacts on the evolution and utilization of nuclear technology. At the same time, the international nuclear regime also highlights several of the challenges discussed previously. One is the problem of prohibition versus regulated use. While international institutions have improved its safety, nuclear power is a technology prone to 'normal accidents' that are a largely inevitable product of non-linear and unpredictable interactions among the components of complex technical systems.[35] Under the current reactor fleet size, Fukushima-scale events have a 50 per cent likelihood of occurring every 60 to 150 years.[36] Any up-scaling of global nuclear power, as is often proposed as a supposed solution for the challenge of transitioning to zero-carbon energy systems, would lead to a corresponding increase. Finally, as the diffusion of civilian knowledge and technology inevitably increases proliferation risk,[37] the peaceful use of nuclear technology always carries with it the threat of weaponization. Gradually converging interests, improved scientific and technical understanding of the technological benefits and risks, as well as the emergence of strong international background norms on the regulation of ultrahazardous activities may all serve to explain, in different ways, the historical emergence of robust international institutions for nuclear technology.

Overall, this short overview shows that robust international institutions can contribute to the effective management of *some* aspects of TNTs – and we may well wager the thought experiment of how the nuclear age would have gone if, in their stead, global governance arrangements had been reduced to non-binding codes of conduct, vague political declarations, and multi-stakeholder partnerships. At the same time, some challenges and trade-offs are beyond the scope of international institutions and, in some ways, the regulations which they provide to make

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problematic technologies more amenable may well contribute to their lock-in. That is to say, a world in which the management of nuclear waste is rigorously regulated is clearly inferior to a world in which nuclear waste is not being produced in the first place.[38]

## 7.8 Concluding Remarks

In this book, I have attempted to develop a broad conceptual and empirical analysis of TNTs and their role in the politics of global environmental sustainability. There is pervasive ambiguity. Against the background of an intensifying and devastating global environmental crisis, we find technologies that might generate vast benefits or harms, although we might not know, or might disagree, on the precise extent to which they would do either. There are institutions which, more often than not, deliver imperfect solutions that are often subject to complex trade-offs that can differ in origin, severity, and resolvability. The international configuration of state interests goes a long way towards explaining the pervasiveness of inadequate institutional responses, as does a knowledge-based perspective that highlights the problem of turning diffuse and fluid technological developments into well-defined and actionable policy problems. A theoretical focus on the degree to which TNTs fit into pre-existing regulatory frameworks holds even greater – albeit not *much* greater – explanatory power for institutional outcomes. Besides all this, there are incompatible visions of what the future *might* look like, what it is *likely* to look like, what it *should* look like, and what role technology should play in the various possible, probable, or preferable futures, either as a (smaller or larger) part of the problem of the global environmental crisis or as a (smaller or larger) part of the response portfolio. Path dependence likely plays a crucial role for TNTs either by exposing them to lock-in through their reinforcement of the lock-in characteristic of unsustainable contemporary socio-technical systems, or via their facilitation of path-breaking, comprehensive, and foundational socio-economic transformations. And, while the need for adequate and robust political solutions becomes more urgent with every passing day, month, and year, any and all contemporary policy choices take place under a shadow of the future that vastly exceeds human capacities for planning, prediction, and effective anticipation.

In attempting to elaborate the 'big picture' of TNTs in the context of the present environmental crisis and potential transitions towards sustainability, I have sought to occupy a middle ground between the sceptics that are perhaps excessively dismissive of the necessity for integrating a strong technological component into the solution portfolio for the global environmental crisis, and the techno-optimists that perhaps buy into the notion of efficient, controllable, and safe technological innovation in need of minimal regulatory interference at best, with excessive

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confidence in the human capacity for innovation and control. Regardless of whether we believe in an inevitable and fundamental contradiction between the 'pro-tech' and 'anti-tech' sides of the debate, or whether we believe that many elements that feed into this contradiction are ultimately contingent and avoidable, the ways in which international institutions have responded to the emergence of TNTs in the context of the environmental crisis is, ultimately, disappointing. To a large extent, institutional responses fail to prohibit (or restrict) TNTs in order to avoid their associated perils, or to provide enabling regulatory frameworks that could contribute to responsible innovation and, possibly, fair and safe deployment subject to international regulation and oversight.

There is a need for greater scholarly engagement with the broader role of technology in the politics of global environmental sustainability across the 'pro-tech' versus 'anti-tech' divide. There is a need for better assessment of the role that different technological options might play in different policy portfolios. But there is also a need for more systematic, cross-case comparison of technological role assignments and of the background assumptions informing both narrow regulatory considerations and broader political framings. The contemporary debate on technology and environmental sustainability includes various elements that are potentially problematic and that are at risk of being mainstreamed as unreflected, commonsensical talking points. For instance, if considerations of global justice make zero-carbon development a moral imperative, how do we prevent social and environmental impacts from the required scale-up in the extraction of the required raw materials from constituting mere collateral damage – regrettable, yet ultimately justifiable, unintended consequences of the global transition towards climate neutrality? Given the need for rapid decarbonization of global transportation, why do we oppose deep-sea mining for scarce raw materials indispensable for electrification, especially where this might substitute for terrestrial mining operations in ways implying reductions in aggregate harmful impacts on the environment and nature–society relations? If the environmental risks and governance challenges associated with the deployment of a global SG programme are sufficiently grave to justify prohibition of deployment and interference with scientific research,[39] why do we largely accept as a fact of life that NETs, with all of the adverse effects that various technical implementations would cause for the land system, for marine biodiversity, or as a result of the social and environmental footprint from associated changes in global material flows, are an indispensable element in contemporary national climate policies as well as an object of significant commercial enthusiasm and hype due to their monetization potential? If the challenge of global biodiversity loss is existential in nature, and if conventional policy responses under the CBD and elsewhere are demonstrably inadequate and highly likely to remain so for the foreseeable future, why are genetic biocontrol agents an

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inconceivable option in need of an international moratorium? Why do observers sympathetic to the interests of the Global South tend to assume intuitively that developing countries will receive net benefits from international regulations that effectively redistribute assets from the users of genetic resources to their providers while impeding the provision of knowledge as a public good through the exposure of non-commercial research to excessive regulatory compliance costs? Conversely, why do observers more attuned to the concerns of research, development, and innovation as voiced in the Global North intuitively assume that the benefits that developing countries draw from the public good characteristics of biomedical and other research on digital sequence information exceeds the value they would receive from the robust implementation and enforcement of bilateral benefit-sharing? Observer positionality in respect of opposing 'pro-tech' versus 'anti-tech' framings appears to account for a sizeable share of the discursive variation observable here and elsewhere. The often controversial role of technology in the debate on environmental sustainability should accordingly be understood as an invitation for a critical reflection of the assumptions that inform considerations of governance and regulation in ways that are perhaps intuitive and commonsensical without necessarily being true.

At the same time, these and other examples highlight the contradictory nature of the contemporary debate on technology and environmental sustainability. Yet in one crucial way, the contentious nature of TNTs is not about the technologies themselves but something larger instead. Framing contemporary debates on, say, gene drives or climate engineering in terms of proponents versus sceptics misses the point. If we ask whether we should mine the deep seas, or whether we should deploy experimental and high-risk methods for tampering with the global climate system, the answer will always be 'no' in one way or another. But the question itself is misleading: a more appropriate way of framing the broader problem is to ask whether we should mine the deep seas, or tamper with the climate system at a global scale, *rather than pursuing other options*. By dismissing TNTs as potentially important elements in a response portfolio for dealing with the global environmental crisis, we implicitly assume that the conventional approach, meaning the negotiation of global targets and the facilitation of their domestic implementation through regulatory action within the parameters of the incumbent technological paradigm, holds comparatively greater prospects. Dismissing the capacity for TNTs to make meaningful contributions to the problem of environmental sustainability implies confidence in the problem-solving capacity of political processes that have persistently failed to live up to the challenge for decades. In parallel to the emergence of the sophisticated and increasingly dense system of international agreements that has characterized global environmental governance since (at least) the 1992 Rio Earth Summit, the negligence and often

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even counter-productive behaviour of governments has contributed to an escalation from problems that would have been largely manageable through marginal adjustments to system parameters to problems that, today, require transformative action, at a global scale, across all sectors of contemporary societies over time frames that are so short as to appear inconsistent with the human capacity to direct and control change in social organization. In other words, mistrust in technology should not instil overconfidence in the problem-solving capacity of the political structures that have overseen the emergence of the contemporary global crisis and failed to respond in adequate ways.

At the same time, it is important to acknowledge the continuous relevance of the intergovernmental organization of global politics. TNTs do not amount to 'techno-fixes' in the sense that they obviate the need for international rules. Instead, this book has hopefully shown how international rules are crucial for leveraging the potential benefits of TNTs while avoiding their various downsides. The deficiencies that have led to vastly inadequate political responses to the environmental crisis in past decades will persist regardless of whether or not TNTs become a crucial element in the global politics of environmental sustainability. The doubts that we can legitimately raise about diverse aspects of these technologies themselves thus add to the doubts which the track record of global environmental governance raises for the global politics of environmental sustainability in the future. On the face of it, the idea of outfitting a global polity that has demonstrated its inadequacies persistently over decades with novel tools that are difficult to wield in ways that leverage the substantial potential benefits while also mitigating a significant and partially unprecedented capacity to cause social, political, and environmental harm may not appear particularly attractive. Perhaps, though, the specific characteristics of TNTs, in the sense of the leverage that they provide for effectuating both beneficial and harmful impacts for the environment and the nature–society interface, might serve to compensate for the structural problems that plague global environmental governance, and global politics more broadly. By providing potential solutions to problems that are otherwise difficult or impossible to overcome, these technologies might improve the prospects of international cooperation in cases where cooperation failure results from insufficient capacities or other reasons that result in a lack of feasible policy options. Similarly, the perils which TNTs entail might eventually instigate greater cooperation due to the need to hedge against their diverse social, political, and environmental risks. The perils associated with TNTs, regardless of whether they are adopted as part of the response portfolio to the global environmental crisis or whether they merely exist as niche objects of interest at the margins of commercial or non-commercial research and development, might well be of a nature and magnitude that

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provides an incontrovertible rationale for international regulatory action due to their potential transboundary impacts and associated aspects such as jurisdiction shopping for purposes of regulatory arbitrage.

In an abstract sense, the most important promise that TNTs hold for the future politics of environmental sustainability might ultimately not reside in the extent to which they facilitate the achievement of one or the other specific policy problem. Instead, by possibly providing significant leverage for generating harms and benefits at a global scale, their greatest promise could be their role in overcoming persistent problems of international collective action that have so far precluded adequate global responses to the sustainability challenge in spite of the good-faith efforts of myriad activists, scientists, inventors, journalists, and others, even including many governments, over decades. It is thus perhaps the impact of TNTs on international politics in the abstract, rather than environmental sustainability as a concrete empirical domain, that could be of primary scholarly interest: as the scale of potential impacts expands, pressure for organizational change in global politics intensifies,[40] meaning that, in addition to looking at how international cooperation does (and does not) affect TNTs by means of international regulation, it may be worthwhile to consider how technological change influences key parameters of international cooperation as such.

An overwhelming amount of academic thinking about technology arguably incorporates predictions that are either inaccurate or flat-out wrong, as well as analyses that either over- or underestimate the consequences of technological change to degrees that range from moderate to spectacular. This book is unlikely to be an exception. Over time, some of the technologies here understood as transformative may turn out to be mere hype and fizzle out of the public consciousness. Technologies that might appear innocuous or that do not even exist at the time of writing might emerge as potential gamechangers over short time frames. Regardless of whether we deal with technologies that turn out to be genuinely disruptive, no more than hot air, or something in between, there is both a rationale and a need for stepping up international regulatory capacity: at the same time that TNTs could have beneficial implications for the prospects of international cooperation, greater buy-in from international institutions is indispensable for realizing the good while simultaneously avoiding the bad as well as the ugly. Most often, we will not know in advance whether something is a gamechanger or merely hot air. But, as the number of potential candidates for either category continues to increase in line with the extraordinary pace of contemporary technological innovation, the systematic consideration of the role played by international institutions should be a priority for scholars of global politics.

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## Notes

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