Don’t discipline us for transdisciplinarily assessing global challenges

Prof.dr Rik Leemans

Farewell address upon retiring as Professor of Environmental Systems Analysis at Wageningen University & Research on 11 April 2024

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Esteemed Rector Magnificus, respected colleagues, beloved family, and friends,

As a teen, I secretly listened to the Hitchhikers-Guide-to-the-Galaxy radio play by Douglas Adams on Sunday evening. His quote "*I may not have gone where I intended to go, but I think I have ended up where I needed to be*" very much describes my emotions when I look back at my career. It stresses the difficulty to plan and execute a valid path. Many opportunities emerged and, hinging on interests and possibilities, I changed paths. In 2003 Wageningen needed me but I continued my interdisciplinary scientific journey with inspiring activities all over the world[1].

Rita Gelman[1] paraphrased why I enjoyed this journey so much: "*Risk-taking, trust and serendipity are key ingredients of joy. Without risk, nothing new ever happens. Without trust, fear creeps in. Without serendipity, there are no surprises.*" Gelman's three ingredients explain why I enjoyed my journey. My path implied risky and serendipitous endeavours but also involving trustworthy colleagues. My career tipping points were trading Uppsala for Laxenburg, and Charlottesville for Bilthoven. Wageningen was a minor but crucial step. Here, contributing to crossing the science-policy divide delivered transdisciplinarity.

Introduction

Science is one of the main drivers of human development and technology[2]. It helps to understand the world around us. However, technological and scientific developments resulted in the problems that we face today. Innovations to solve one problem, often created new problems that result from their unintended consequences[3][4]. When research

1 https://www.ritagoldengelman.com/ or https://www.youtube.com/watch?v=q2tijFrHJ9g

solved a problem, this can create problems elsewhere or for later generations. For example, anthropogenic (i.e. human-caused) climate change is triggered in the nineteenth century by technological and industrial developments and rapidly led to a successful fossil-fuel-dominated economy.

We now recognise the inherent complexity of such global challenges[5][6]. These challenges include climate change, biodiversity loss, food, water and energy security, health, and poverty and inequity. The complexity emerges not only from systemic nonlinear interactions, synergies, and trade-offs, but also from behaviours at specific dimensions and scales[7]. These global challenges, including the Sustainable Development Goals (SDGs), are essentially 'wicked problems'[8].

Environmental Systems Analysis (ESA) studies such wicked problems and educates students to deal with them. We explore, model, and integrate causes, mechanisms, effects, and possible solutions by combining qualitative and quantitative approaches, and integrating insights from relevant scientific disciplines. Our systemic understanding helps to promote and implement solutions but this is actually done by decision makers (i.e. in governments, companies, financial institutions, and non-governmental organisations). Our research is thus policy relevant, but never policy prescriptive[9]. In this lecture I will focus on my major contributions to 'Science for Impact' in my career and illustrate that by mentioning diverse doctorate topics of my students.

Definitions for integrative science

I follow the conceptualisation of academic disciplines and cross-disciplinary collaboration by Lawrence[10]. '*Disciplinarity*' refers to the specialisation and fragmentation of scientific disciplines; a process that progressed since the nineteenth century. Each discipline has specific concepts, definitions, and methodological procedures to study its precisely defined domain. This distinguishes its domain from other disciplines.

'*Multidisciplinary*' research involves an additive research agenda in which each scholar remains within his or her discipline. Disciplinary boundaries are not crossed. Integrating results from multidisciplinary projects is rarely possible as the applied concepts, definitions, and approaches are incompatible. Multidisciplinary projects are only suitable for simple problems. Therefore, I do not use and discuss them further.

'*Interdisciplinary*' research converges across disciplinary boundaries. Researchers collaborate to conceptualise the problem, to achieve a shared goal, and to develop compatible approaches. They acknowledge the disciplinary differences. Boundaries are recognised but not challenged. Such research involves a creative collaboration whose results are integrated.

For example, the Millennium Ecosystem Assessment appraised the consequences of biodiversity decline for human well-being to manage our home. Ecologists, geographers, political scientists, and economists contributed to this endeavour. I was responsible for the 'Drivers' chapter of its conceptual framework[11]. In accordance with ecologists' and geographers' traditions, we started with distinguishing drivers (i.e. factors that influence a system). Alex McCalla, an economist who chaired the World Bank's Rural Sector Board, criticised this concept: "**People are not driven, people make choices!**" We discussed who controls each driver, which enriched the final framework. More importantly, also economists accepted it and this contributed to the assessment's success.

'*Transdisciplinary*' research differs from curiosity-driven and applied scientific research. Transdisciplinary projects explicitly include non-scientific knowledge and expertise from the private sector, public administrations, and indigenous people or other minorities. Such knowledge is generally ignored (but sometimes studied) by scientists. Its inclusion allows for more societal-relevant research questions and results in widened perspectives and more comprehensive understandings[12]. Transdisciplinarity promotes creative thinking beyond conventional disciplinary boundaries. It achieves societal relevant goals, inspires mutual learning, enriches understanding, and creates dialogues on wicked problems[13].

A summary of my career

My research is nicely summarised in a 'word cloud' (Figure 1).

My graduate studies in Nijmegen and Uppsala

My graduate study at the Radboud University consisted of three research projects. The first was aquatic ecology. My supervisors, Hannie Geelen en Theo Brock, asked me to explore the diatom-flora under the floating leaves of fringed water lilies. I pictured them with a scanning electron microscope. In hindsight, this topic showed me ecosystem dynamics. The diatom flora moved within weeks from a homogeneous pioneer-succession phase into a complex climax phase. Recently, WUR's DIES called such flora a microbiome, which is now a new emerging research field.

My second topic focussed on comparing biodiversity patterns in European Beech Forests, guided by Eddy van den Maarel. He introduced me to quantitative multi-variate approaches. This study taught me not only that systematic and comparable measurements are essential but also that measurements have their limitations and need to be better integrated.

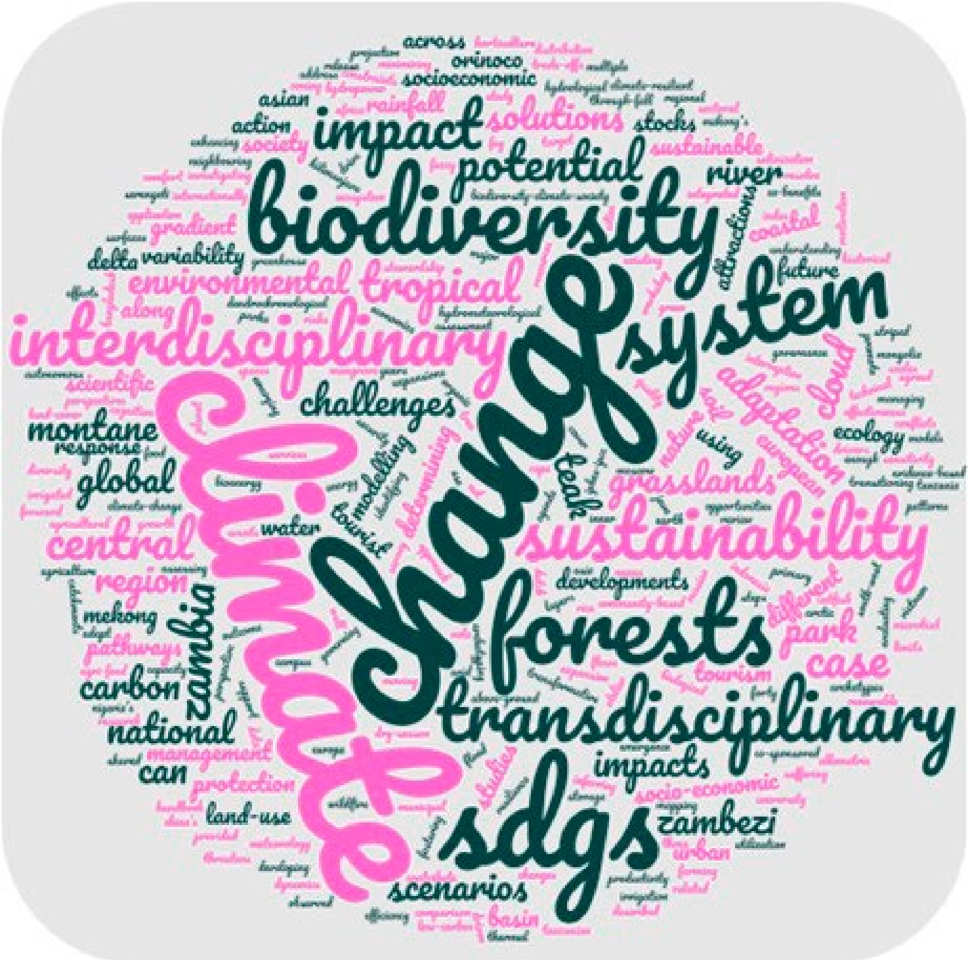

Figure 1. A 'word cloud' of the titles of my scientific papers of the last five years. The frequency of occurrence determines the size of a word. All words are converted to lowercase letters.

My last topic focused on developing an inter-faculty environmental-science course for biologists, geographers, and planners. It focussed on acid-rain pollution. This was my first contact with multi- and interdisciplinarity.

At my graduation in 1983, Eddy invited me to do a doctorate study at Uppsala University, where he was appointed as professor in ecological botany. Eddy and Marijke created an inspiring atmosphere, where doctorate students cooperated and thrived. I accepted and wanted to map and understand the forests of Fiby Urskog (the primeval forest of Fiby).

Unfortunately, deriving forests dynamics from my static maps[14] was hard. But Colin Prentice recognised my map's value and asked me to test and validate his new forest model, FORSKA[15]. He taught me the value of models and it became the main focus of my doctorate thesis.

The rationale for a model is the scientific desire to capture the essence and to remove the redundant aspects of a system. Essential for long-term forest dynamics is regeneration: Are seedlings capable of establishing and growing under a tree canopy? Light attenuation through the canopy towards the forest floor is thus important. Earlier forest models simulated trees as a stem with a disk of leaves at the top. FORSKA distributed them along the stem. The lowest leaf level was determined by a species' shade tolerance. For example, pines are shade intolerant and have high canopies, while spruces survive in deep shade and have canopies up to the forest floor. In late successional stages, only spruce regenerates, until a large canopy gap appears. FORSKA simulated the forest dynamics and the evolving forest structure on basis of such principles[16].

Modelling climate-change impacts on vegetation

My life took an unexpected turn after three years. Colin asked me to guide an American who wanted to collect tree rings from old pine stands in Lapland. I accepted and did field work with Al and Jean Solomon. We collected all the data, while surviving on reindeer pizza. Regrettably, the data were never analysed as Al was, immediately after this trip, invited to direct the Biosphere project at the International Institute of Applied Systems Analysis (IIASA). He offered me a post-doc position. His project included only few scholars throughout the year but in the summer, many guest scholars and students joined. Together we developed a System Analysis of the Circumpolar Boral Forest[17], in which all tree species, environmental conditions, and dynamics of these forests were discussed. Editing this book was a great new experience.

To assess the boreal environments, we needed gridded topography and climate data. NASA created a topography data base on a 0.5° by 0.5° grid, but climate data was missing. Wolfgang Cramer and I started to collect climate normals[2] from weather-station data. To better represent topography, all stations' temperatures were adjusted to sea level from their local altitude, interpolated to each grid cell and adjusted for topography. The resulting global data set, CLIMATE[3], was distributed widely, and many scholars who used

2 A climate normal is the mean weather data, averaged over a period of 30 years. We focussed on the period 1931 to 1960 as a baseline climate.

3 **C**ramer-**L**eemans **I**nterpolated **M**eteorology for **A**pplications in **T**errestrial **E**cology

the data, also supported us with more data. After a decade CLIMATE was replaced with annual data sets instead of climatic normals but our approach was replicated[18].

We used CLIMATE to evaluate global vegetation patterns, as described by early explorers, such as Köppen[19], Budyko[20][21], Holdridge[22] and Walter[23]. We learned that their models ignored crucial factors like seasonality and evapotranspiration. We developed a more advanced model, BIOME, that more realistically described global biome patterns (e.g. tundra, forests, grasslands, and deserts). We innovatively used plant-functional types (PFTs). The distribution of each type was determined by distinct ranges of climatic factors. Locally we then combined these types into biomes. The BIOME paper[24] was the only paper in my career where three reviewers had no comments and just stated "Publish this asap!" The BIOME model triggered several other global species and vegetation models, such as the Dynamic Global Vegetation Models that are currently incorporated in global climate models[25].

In the late 19-eighties, the threats of climate change were becoming apparent in the scientific community[26]. Only few quantitative climate-impact studies were available then[27][28]. We decided to overlay the coarse projected climate change of global climate models with CLIMATE. This approach is still common to create realistic and high resolution climate scenarios[29][30]. BIOME was used to explore vegetation shifts under climate change.

My vegetation-shift maps[31] were reprinted in the first report of the Intergovernmental Panel on Climate Change (IPCC; https://www.ipcc.ch/)[32]. I was then also asked to review the climate-change impact chapter of UNEP's[4] first climate-change report[33]. The chapter was disappointing and my extensive review addressed this. Pier Vellinga, who organised the meeting, recognised my impacts expertise and asked me if I wanted to realise impacts in the IMAGE model at the Institute for Public Health and the Environment (RIVM). Although I had just accepted a position at the University of Virginia, I accepted this offer. I married Carien and moved into her Utrecht apartment and forgot Charlottesville.

The Integrated Model to Assess the Global Environment (IMAGE)

The first IMAGE[5] model[34] innovatively simulated global greenhouse-gas emissions, concentrations, and sea-level rise. IMAGE, however, was unsuited to include spatially

4 UNEP is the United Nations' Environment Programme (https://www.unep.org/)

5 **I**ntegrated **M**odel to **A**ssess the **G**lobal **E**nvironment (IMAGE). IMAGE-1 was developed by Jan Rotmans and IMAGE-2 was developed by the IMAGE team, led by Joe Alcamo and me (1993 – 2001).

explicit impact modules. My first two years at RIVM therefore focused on actualizing my approaches and linking them to the research agendas of the international global change programmes[6], especially the International Geosphere-Biosphere programme (IGBP).

The IMAGE project strongly changed course when Joe Alcamo took over the helm. Joe wanted to combine all approaches into a single model. I strongly advocated my spatially-explicit approach to model land-use emissions, carbon sequestration, and impacts. IMAGE-2 uses data for past and current land-use change[35] and scenarios for future energy and food demands. We combined BIOME with the FAO crop-suitability approach[36]. Crops grew in their current (i.e. 1990) areas. If demand was more than production, agricultural land expanded and this led to deforestation and carbon emissions. If demand was less than production, agricultural land was abandoned and this land shifted to its natural vegetation, often resulting in afforestation with more carbon storage. The resulting land-use model simulated unique land-use patterns on all continents and included climate-change impacts[37][38]. We also perfected IMAGE-2's carbon-cycle model, which Jelle van Minnen later documented in his doctorate thesis[39].

When IMAGE-2 was validated and documented, we applied it, for example, to assess the consequences of the IPCC scenarios[40][41], to estimate biomass-energy potential[42], and biodiversity decline[43]. IMAGE-2 also contributed to the scenarios of UNEP's Environmental outlook[44], the IPCC scenarios, and the Millennium Ecosystem Assessment [43].

A timely application of IMAGE-2 were the Delft-dialogues[45]. These workshops were organised by the IMAGE team and facilitated by Wil Thissen of Delft University. The participants were climate negotiators from European and developing countries, who were supported in their quest for the Kyoto protocol. The first meeting presented all plausible scenarios up to 2100[46] to familiarise participants with IMAGE-2. The scenarios' focus on 2100 caused a stalemate, but one of the negotiators posed a brilliant idea: "Would it be possible to determine long-term (i.e. 2100) climate-protection goals and link them to short-term (i.e. 2010) emission-reduction targets?" This inspired the IMAGE team to develop the safe-landing approach. It showed that early action creates flexibility but also that all countries should eventually reduce their greenhouse-gas emissions[47][48]. As global emissions have not peaked, this finding is still timely.

6 The World Climate Research Program (WRCP), the International Geosphere-Biosphere programme (IGBP), the International Human Dimension Programme (IHDP) and DIVERSITAS were programmes that were hosted by the International Council for Science. WCRP was co-hosted by the World Meteorological Organisation (WMO) and IHDP by the international Social Science Council (ISSC).

Such a transdisciplinary process is now advocated by many, but few reflect on success and fail factors. We did then by carefully evaluating the dialogue process[45]. We recommended to model in enough detail, to map impacts and to connect impacts to climate-protection policies. Our paper inspired Eefje Cuppen[49] for her doctorate thesis. She developed more objective approaches to better select and group stakeholders.

The international global-change research programmes

In 1993, I participated in a vegetation-modelling workshop[50]. I presented IMAGE's first land-use-change scenario, which was created only a week earlier. The audience was flabbergasted. IGBP Chair, Brian Walker, invited me to represent IGBP in the Science Committee of the new international Land-Use-and-Cover-Change (LUCC) project. Up till then, I applied and expanded my ecological expertise, but suddenly I was discussing a highly interdisciplinary land-use-change agenda[51] with geographers, remote sensing experts, economists, agronomists, and political scientists. A new, steep but rewarding learning curve was sparked by the best teachers.

Louise Fresco also joined the LUCC Science Committee and this eventually led to my special professorship in WUR's Plant Production Systems Group in 1999, where I held my inaugural address. In 2003, I was appointed chair holder of the Environmental System Analysis group.

These global change programmes initiated new projects, defined research agendas and convinced funding agencies to fund them. In 2007, I was asked to chair the new Earth System Science Partnership (ESSP) with its global carbon, water, food, and health projects[52]. We founded the journal 'Current Opinion in Environmental Sustainability[7],' which is still among the most influential journals that publishes on global-change challenges[53]. The partnership organised major global-change symposia in Copenhagen[54] and London[55]. The latter, Planet under Pressure, concluded that a stronger sustainability focus is needed and that research should better connect to decision-maker's needs. This led a workshop on transdisciplinarity[12] to explore how scientists can better interact with stakeholders (Figure 2). Slowly the platform for sustainability research *Future Earth*[56] emerged, emphasising that sustainability science strongly relies on transdisciplinarity[57].

7 When I stepped down as editor-in-chief from COSUST in 2017, the editors and publishers published a 'legacy' paper [1] to honour my achievements.

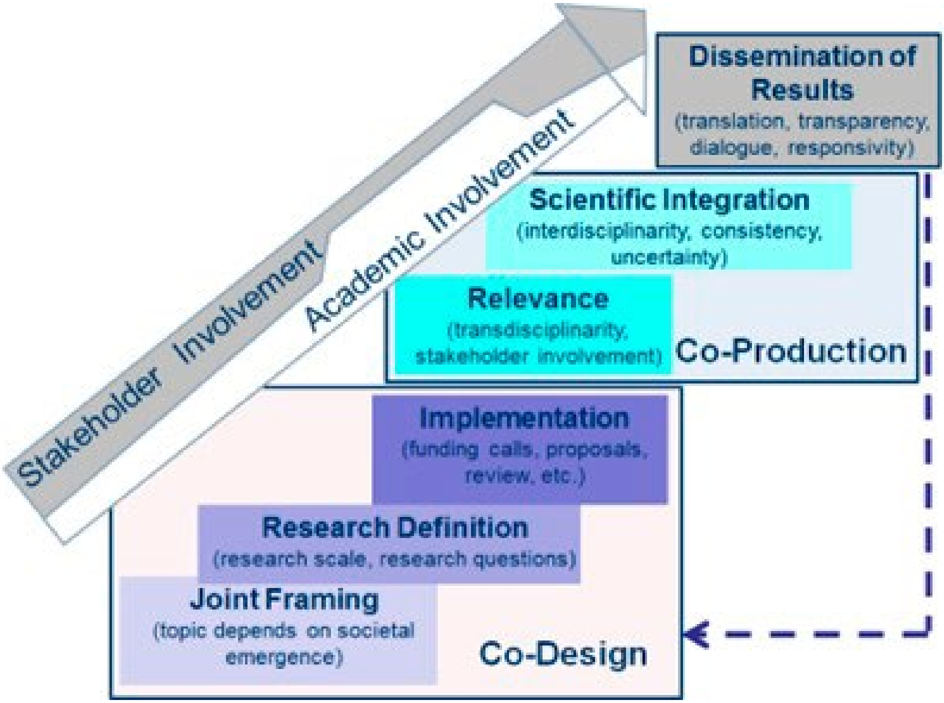

Figure 2. The roles of scientists and stakeholders in transdisciplinary projects. Co-design and co-production of knowledge requires the involvement of researchers and stakeholders during the entire research process.

The assessments by the Intergovernmental Panel on Climate Change

Because of my expertise with integrated assessment models, scenarios and impacts, I was again invited to contribute to the IPCC assessments. I contributed to the first five assessments on the carbon cycle[58], forests[59][60], biodiversity, and land use [29,30], and ecosystems[61]. I was also review editor of a chapter on attributing observed climate-change impacts[62]. The young chapter scientist, Gerrit Hansen, developed attribution approaches and analysed them in her doctorate thesis[63].

Interestingly, the early IPCC analyses already indicated that moving away from fossil fuels would necessarily emphasise a strong electrification that could absorb renewable energy. IPCC made clear that technologies, like solar and wind, and smart grid systems, were available. Recently, IPCC showed that electricity based on renewables is now cheaper than from fossil fuels. If energy ministries and grid companies would have responded to these scientific insights that emerged over the last thirty years, the current congestion of the electricity grid would have never occurred.

I was especially excited to contribute to Working Groups II's synthesis chapter in 2001[64]. We were asked to determine when climate change is dangerous[8]. Dangerous is not a scientific concept: It has political and individual pedigrees. Addressing it required an interdisciplinary approach and thus a common conceptualisation. We quickly focussed on global mean-temperature increase to indicate dangerous interferences' levels. Such increase is available from observations and various climate models.

We hypothesised that dangerous interference levels would start between 1°C and 3°C but we quickly learned that impact assessments then ignored increases below 3°C. Some studies, luckily, explored observed climate-change impacts. These occurred at temperature increases that reached almost 1°C. These few studies[65][66][67][68] already hinted at dangerous interference levels. We asked the lead authors from the system and sector chapters to discuss observed impacts. They were hesitant as they were trained to use models and scenarios, and rarely looked for evidence. Fortunately, we convinced some to support us. This led to several seminal papers[69][70] and a separate chapter on observed impacts in IPCC's fourth assessment[71].

Our approach settled on five different 'Reasons for Concern':

- Unique and threatened systems include not only vulnerable species and ecosystems, such as coral reefs and polar bears, but also sensitive crops such as arabica coffee and regional wines;
- Risks to extreme events, which now occur more frequently and cause unexpected damages. They include floods, droughts, and heat waves;
- Distribution of impacts focus on vulnerable regions. Climate-change impacts are felt more in countries that have contributed least to the emissions;
- Aggregated impacts include global impacts on trade and systemic impacts from, for example, sea level rise; and
- Risks to large-scale discontinuities include tipping points, such as the accelerated melting of the west Antarctic-Ice sheet and slowdown of global ocean currents.

In the diagram, colours ranged from white (minor risk), through yellow and orange to red (high risks) and they were linked to the global mean temperature-increase scale. Initially a traffic light was mimicked but green was interpreted as 'safe' and not 'minor risks'. Green was thus changed into white and the boundaries between colours gradually blended into each other. Each 'Reason for Concern' offered unique levels of dangerous interference. For

8 UNFCCC's objective includes: "… stabilisation of atmospheric greenhouse-gas concentrations at a level that would prevent dangerous anthropogenic interference with the climate system …" (i.e. UNFCCC's Article 2).

example, expressing aggregate impacts in monetary terms showed that a slight temperature increase benefits most economies[72], while most people in climate-sensitive countries already suffer then. The diagram's red bars imply vulnerability, which means that adaptation is impossible and/or too expensive. In IPCC's synthesis report[73] the diagram was linked to the temperature increases of the SRES scenarios, which all had substantial risks. Only below 2°C dangerous interference was somewhat limited. This diagram provided early scientific evidence for the 2°C Paris Targets.

The 'Reasons for Concern' diagram (or the 'burning-ember' diagram as it was soon nicknamed) was updated in IPCC's later assessments[74] An additional colour (purple: extremely high risks; Figure 3) was added. More frequently observed and attributed impacts and better adaptation-costs estimates allowed for more credible dangerous-interference transitions. A more vulnerable world emerges from these later assessments. The last assessment also created specific 'burning embers' for other systems, sectors, and regions, and these convincingly show that preventing dangerous interference strongly advocates the stricter Paris Target of 1.5°C.

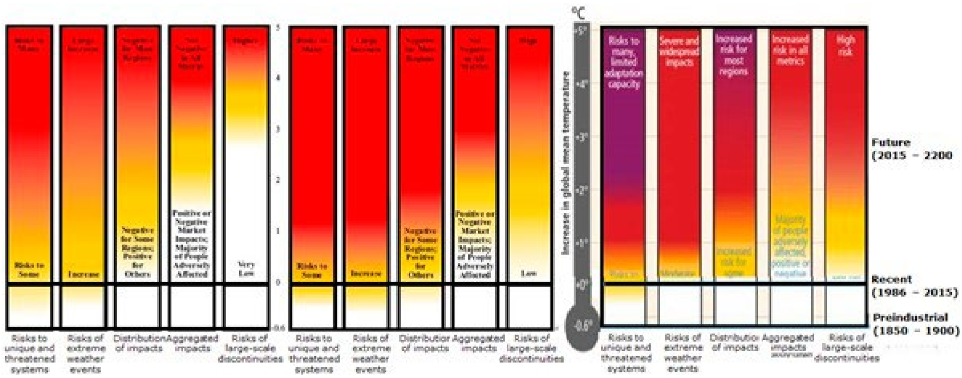

Figure 3. The reasons-for-concern diagrams by IPCC's third, fifth and sixth assessment reports linked to past present and future global mean-temperature increases.

Quantifying vulnerabilities through climate-change-impact assessments and scenario applications have always attracted graduate students. For example, Cheng Liu[75] assessed the climate-change impacts on microbial safety of leafy green vegetables. Here, management showed to be the major factor. Rumana Hossain[76] assessed the climate-change impacts and adaptation possibilities of the Sundarbans that are the world's largest mangrove forests, and Halima Hassan[77] determined how the possibilities of tourist attractions in Tanzania's national parks evolve under climate change.

The Millennium Ecosystem Assessment
In 2000, I got a new task. Kanchan Chopra (an economist from India) and I co-chaired the policy working group of the Millennium Ecosystem Assessment[78][79]. This assessment assessed the consequences of ecosystem change for human well-being and established the scientific basis for policies to enhance conservation and sustainable use of ecosystems. It appraised the current condition of, and threats to, the world's ecosystems; it developed scenarios for future trends; it discussed effective responses; and it inspired regional assessments.

To link ecosystems to human well-being, the concept of ecosystems services was applied. Although ecosystems services were already introduced by de Groot[80], Daily[81] and Costanza[82], the Millennium Assessment further developed them, characterised specific types and mainstreamed them. This helped to manage unprotected ecosystems.

Because our responses assessment targeted broad audiences, we started with a primer on successful policies that highlighted coordination across sectors and scales, transparency and participation, and assessing trade-offs and synergies. Then, past and current responses were assessed. Finally, lessons learned were presented from different perspectives (e.g. business, nature conservation or wetlands). In summary, key features of successful responses[79] are that:

- Today's technology and knowledge can already reduce ecosystem impacts. They are, however, unlikely to be applied when ecosystem services are perceived as free, and when their full values are ignored;
- Economic and financial interventions can regulate the use of ecosystem services. However, people should be paid for providing or managing services or penalised for degrading them;
- Measures to conserve ecosystems likely succeed if communities get ownership, share the benefits and participate in decision making; and
- Better protection of an ecosystems requires coordinated and integrated efforts across governments, businesses and international institutions.

The Millennium Assessment was successful and influential. It's conclusions were covered, for example, by Toles' cartoon in the Washington Post. Nowadays, many research groups, consultants, and governments use ecosystem services to manage natural resources. Although Dolf de Groot already advocated this in the late 19-nineties, Ecosystem services became a central research theme in the ESA group and we contributed to the Economics of Ecosystems and Biodiversity (TEEB;[83]) reports and later the assessments by the Intergovernmental Platform for Biodiversity and Ecosystem

Services (IPBES; https://www.ipbes.net/). Dolf also established the international journal Ecosystem Services, associated with his Ecosystem Services Partnership.

This theme certainly contributed to the excellent-on-all-accounts appraisal in my first international research evaluation in 2009. Five years ago, we appointed three new assistant professors, Solen, Jannik and Koen. They combine land-use change, biodiversity and ecosystems services with transdisciplinary approaches.

I also inspired Lars Hein to write an ERC proposal to map and account for regional ecosystem services. He was the first successful WUR ERC-grant holder, wrote a textbook on economics and ecosystem services[84], and is now personal professor in ecosystem accounting[9]. Many doctorate students[85][86][87][88][89][90][91][92][93][94][95][96] applied ecosystem-service approaches in their research. Mariska Weijerman added a next step and created an integrated assessment model to manage coral-reefs[97].

The Advanced Terrestrial Ecosystem Analysis and Modelling project
In 2000, the EU funded the **A**dvanced **T**errestrial **E**cosystem **A**nalysis and **M**odelling (ATEAM) project. **ATEAM** aimed to create comprehensive land-use and climate scenarios and apply them to different European regions and sectors to compare different impacts and vulnerabilities. To enhance ATEAM's utility, we invited stakeholders to propose adaptation measures. We developed detailed land-use and climate-change scenarios for Europe[98][99]. These scenarios showed that less agricultural land will be needed because productivity continued to increase. The resulting land abandonment scared especially Mediterranean stakeholders as this meant shrub encroaching and large forest-fire risks. My doctorate students Marc Metzger[100] and Pytrik Reidsma[101] respectively developed a vulnerability mapping tool and assessed farmers' adaptive capacity. ATEAM was successful and its conclusions were summarised in a Science paper[102].

Looking at ATEAM's results now, almost twenty years later, shows that its projected impacts are spot on! Larger forest fires, droughts and floods, shifts in plant and animal distributions, and snow-deprived ski resorts are happening now. However, our timing was very wrong. We projected these impacts to happen between 2070 and 2100, not now. These early impacts are likely caused by changes in extreme events. Our scenarios only depicted a gradual climate change that ignored extreme events. This 'mean-climate' focus thus makes impacts assessments very conservative!

9 This involves developing methods to measure natural capital that are consistent and comparable with national accounting.

UN's Sustainable Development Goals: Tackling multiple wicked problems

Over the last decade, I have assessed interactions (i.e. feedbacks, synergies, and trade-offs) between climate change, biodiversity loss, and other wicked problems. These problems strongly differ. For example, climate change is a globally systemic problem as greenhouse gases rapidly mix in the atmosphere and the influence of their increasing concentrations is immediately felt everywhere. Biodiversity is heterogeneously distributed across the world and this results in unique patters. Its loss is initially a local problem but such losses are currently so widespread (though through different causes) that cumulatively they have become a global problem.

Three years ago, I participated in the IPCC-IPBES assessment of climate change and biodiversity[103]. This assessment clearly showed that climate-mitigation measures negatively affect biodiversity, while biodiversity measures slow climate change and allow for quicker adaptation. The possible paths are quickly reduced when combining climate and biodiversity protection[104]. Sarahi Nuñez Ramos[95] and Gabriela Iacobută[105] did excellent analyses for this assessment. Their analyses show that distinct policy strategies for individual environmental problems are too siloed and ignore trade-off and synergies between them. Such undesired autonomies will never result in fully effective policies.

Figure 4. Much research has a tunnel vision that emphasises climate actions (i.e. carbon emission reduction) when addressing the Sustainable development goals.

In 2015, the UN not only adopted the Paris Agreement but also the 17 Sustainable Development Goals (SDGs) on, for example, poverty, health, food security, climate action, biodiversity, and peace & justice. These SDGs require a very comprehensive and integrated strategy for sustainability. Currently most research focusses on a single SDG or sometimes two or three SDGs but rarely on all SDGs together. In fact, most SDG-relevant studies emphasise carbon emissions and ignore other issues (Figure 4). We did the same. For example, Lambert Schneider[106] analysed the potential of carbon markets and Leonardo Nascimento[107] determined policy gaps to reach the Paris Targets.

To understand the policy needs to satisfy all SDGs simultaneously requires NEXUS approaches that quantify interactions between biodiversity, climate and other SDGs. We tried to analyse the synergies and trade-offs between climate measures and other SDGs[108]. Like the IPCC-IPBES assessment[103], our analysis clearly shows that these interactions have major effects. A NEXUS approach should be expanded to all SDGs but this requires more integrated interdisciplinary and transdisciplinary approaches. Such advanced and timely research is a fantastic opportunity for the IMAGE team at PBL and its linked researchers at different universities, and IIASA. This quest could create an innovative research path for future generations of doctorate students and scholars.

Recently, Karen Fortuin and I contributed to the 'Handbook of transdisciplinarity'[109]. This book shows that transdisciplinary research has matured. It clearly defines its history, domain, and approaches. In our chapter, we reviewed and discussed the emergence of transdisciplinary in the global change programmes and science-policy assessments[110] and we concluded that a plerthora of transdisciplinary approaches exists now. Josephine Chambers et al.[13] have nicely classified them. In their classification my work confers with "Researching Solutions". I am very happy with this category as it is ESA's main objective.

Education in Environmental Systems Analysis

All this research affected our teaching. We developed, for example, *Regional Management*, which focussed on managing ecosystem services, and *Methods and Applications*, which taught tools for integrated assessments. With Pavel Kabat, we created *Introduction to Global Change* in which we communicated our experiences with the global change programmes and the science-policy assessments.

Our courses are popular with students from many disciplinary and cultural backgrounds. Satisfying and convincing them all is challenging. Karen Fortuin strongly reflected upon our intercultural and interdisciplinary teaching approaches, and wanted to analyse them in her doctorate thesis[111]. Publishing reflections on education is essential and Karen successfully did this. I hopes she continues to do so and inspires others.

Lessons learned and conclusions.

My research evolved from being mono-disciplinary (ecology, biogeography and biogeochemistry) towards interdisciplinarity (combining natural, behavioural, and social sciences) and transdisciplinarity (working with decision makers). My participation in the global change programmes and science-policy assessments inspired this evolution and helped to create approaches to better understand and integrate the results from different disciplines. These programmes and assessments also evolved from "Reducing uncertainties"[112] in the 19-nineties to transdisciplinarity and codesign and co-production in recent years. **Developing comprehensive conceptual frameworks** is an essential first step that caters for this trend.

Large-scale wicked environmental problems require effective integrated national and international policies. To function effectively, they need timely and reliable and well-integrated scientific information. This is provided by science-policy assessments. Most university scholars, who contribute to these assessments, contribute their expertise voluntary. This scares many (no project to write your time on) but contributions are extremely worthwhile. You review all relevant literature, become part of an international interdisciplinary network, identify controversies, and become familiar with different policy needs in the world. The controversies often lead to ground-breaking review papers that define the next assessments and advance inter- and transdisciplinary research agendas. **Contributors likely become international research leaders**.

The science-policy assessments synthesise the scientific understanding at the time of their publication. Successive reports show the advancing insights (c.f. Figure 5) and make clear that disciplinary uncertainties are reduced and that interdisciplinary consensus and confidence increases. These discuss possible policy actions (including doing nothing) but do not actively advocate their necessity and urgency. However, as assessments are generally conservative, **scientists should better communicate that their impacts assessments advocate for much stricter emission-reduction policies**. If decision makers do not act appropriately, suffering[113] will increase.

I advocated the use of interdisciplinary and transdisciplinary approaches and the creation of such research teams. Successful teams need:

- Charismatic leaders, that have excellent credentials and networks;
- A team of brilliant young thinkers, who eagerly want to create solutions and connect disciplinary approaches and interdisciplinary needs;

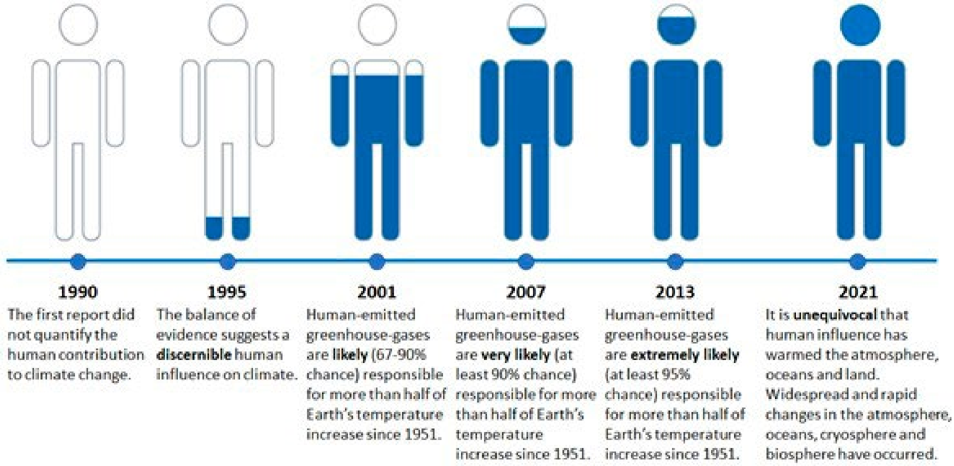

Figure 5. The IPCC summary conclusions of its subsequent assessment reports. Blue indicates confidence levels, which goes from 0% in 1990 to 100% in 2021. Climate-change science is now indisputably accepted[114].

- A sugar aunt (funding is essential but reputable agencies are unlikely to deliver);
- Problem and solution oriented research in executed in an active dialogue; and
- Persistence and courage.

Even when such a team is successful, many comment that publishing inter- and transdisciplinary results is difficult and that such papers are poorly cited. **This is a myth**. Many high impact journals nowadays publish such papers (e.g.[115]) and they often lead to media coverage. Interdisciplinary scientists in larger teams are also more productive[116]. Disciplinary papers quickly collect citations but their citations peak a few years later, and then return to zero. Interdisciplinary papers collect citations but their citations increase over longer periods (decades) before peaking[117]. Transdisciplinary papers are cited and their results are simultaneously applied by decision makers. Such papers often have immediate societal impact[118]. These differences are rarely recognised, as I have experienced as chair of the appointment and advancement committees (BACs) at WUR's Environmental Science Department. They should appreciate these differences and **not discipline interdisciplinary and transdisciplinary tenure-track scholars, but cherish them**. They deliver on WUR's motto "Science for Impact."

Measures to limit or adapt to climate change, and reduce or reverse biodiversity decline are manyfold but not very effective. Fortunately, more integrated strategies are emerging. For example, the 8th Environment Action Programme is the EU's common agenda for environmental policy until 2030. It builds on the Green Deal. It aims to decrease EU's material footprint to safeguard precious natural resources and reduce biodiversity and climate impacts. Although some groups (with tractors or yellow jackets) oppose these environmental strategies, **hope is on the horizon!**

To all my dear colleagues, your research and teaching should thus not only be interesting and innovative but also policy and societal relevant! We must be disciplined to address these wicked problems.

Acknowledgements

I have now reached the end of my farewell lecture. Many people have inspired me, have taught me new skills and insights, and have encouraged new experiences. I appreciate that many have contributed to my career. I will thank a few groups specifically.

I am grateful for all who trusted me to work in their organisations. I hope that our accomplishments fulfilled your expectations.

I thank all my colleagues in these organisations. Together we discussed and implemented novel approaches and applications, lectured and instructed students. We clearly showed that when everybody says something is impossible, this does not mean that it actually is impossible.

Not all colleagues were scientists. My secretaries, Ria and Mathilde, administrators, Matsen, Egbert, and Gerbert, and personnel advisors, like Patty, have been indispensable to achieve what we did. I very much appreciate your dedication.

My WIMEK directorship within SENSE was also rewarding. It focussed on the well-being and success of doctorate students. Johan, Ad, and Marjolijn impressively facilitated doctorate and honours students.

I am proud to have graduated fifty-three doctorate students. You build upon my expertise and ideas, and uncovered new insights. I hope that I inspired your work and contributed to your academic development. Most of you have obtained great positions and you will certainly inspire new generations of transdisciplinary academics.

I could never have succeeded without my friends and family. Sometimes they were sceptical on my future scenarios or bored by my gloomy disclosures. Still, they alerted me that the world is more than climate change and biodiversity loss.

My parents and my wife Carien passed away but they have stimulated me to follow my intuition to meet my ambitions. They would have enjoyed this day and celebrated that I will travel less.

I would like to thank my children Eva and Joris for their support and patience. I have been a father, who saves the world (as seven-year-old Joris said to his teacher) but was not always present to support you. I am so happy that you both now have great partners, worthy professional lives and nice places to live. I hope that my grandchildren, Nora and Tijn, will tell me, when they are adults, which scenario has become reality.

Last year, many witnessed that I married again. Josine, you have been interested in what I did and what I do. We have moved to a nice, energy-slurping home with a great forested garden. We can now bring all my sustainability experience in practice: stop biodiversity loss in our garden and use wind and sun to power our home and future journeys.

Ik heb gezegd.

Bio-sketch

Prof. dr Rik Leemans is the former chair holder of the Environmental Systems Analysis group of Wageningen University and Research and is now emeritus professor. He executed international research projects on climate-change impacts, ecosystem services, biodiversity, and sustainability. He has proven skills to stimulate and manage individual researchers, research groups, and (inter)national programmes and assessments towards excellence.

During the 19-nineties, he was a senior scientist of the National Institute of Public Health and the Environment (RIVM) in Bilthoven. Here, he directed the development of integrated assessment modelling approaches (i.e. the IMAGE-2 model), contributed to the different international science assessments of the Intergovernmental Panel on Climate Change (IPCC) and UNEP's Global Environmental Outlook, and co-chaired the Responses Working Group of the Millennium Ecosystem Assessment. From 2006 through 2012, he successfully chaired the Earth System Science Partnership of ICSU's international global change programmes and on their behalf presented an annual scientific update to plenary of the UNFCCC. He also helped shaping the international sustainability program 'Future Earth'.

His early studies at Uppsala University (Sweden) emphasised the dynamics and structure of boreal forests. His subsequent research position at the Biosphere Project of the

International Institute of Applied System Analyses (IIASA, Austria) focused on continental databases and boreal forest models. Since then, his research has excelled into modelling global land-cover patterns and land-use change and using these models in integrated assessments. His main research interests concern biodiversity, climate-change impacts, land-use and cover change, biogeochemical cycles, ecosystem services, human well-being, and sustainability. He is one of the world leaders in integrating innovative natural and social science knowledge to tackle major policy-relevant Earth System questions with inter- and transdisciplinary approaches.

Prof. Leemans published many papers on a wide range of topics based on specific cases from developed and developing countries as well as the world as a whole. His studies focussed on forest dynamics, vegetation and crop distribution, environmental databases, terrestrial C cycle dynamics, incorporating land-use change into Earth system models, climate-change impacts, biodiversity, interdisciplinarity and transdisciplinarity, potential mitigation and adaptation strategies, and, more recently, the Sustainable Development Goals (SDGs) and sustainability science. He participated in several editorial boards and is founding editor-in-chief of Current Opinion in Environmental Sustainability.

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Prof.dr Rik Leemans

Prof. Leemans is emeritus professor in Environmental Systems Analysis. His transdisciplinary research combines climate change with biodiversity, ecosystem services, and sustainability, and this resulted in seminal policy-relevant publications. He developed, for example, IPCC's burning-ember diagram that motivated the Paris climate-protection targets. His teaching focussed on integrated assessment tools, such as conceptual models and scenarios, and the essential interactions between climate, biodiversity, and sustainability policies. He also founded the interdisciplinary scientific journal Current Opinion in Environmental Sustainability. This farewell lecture summarized his career and lessons learned.