This is a non-peer reviewed preprint submitted to EarthArXiv.

The Dry Sky: Futures for Humanity's Modification of the Atmospheric Water Cycle

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Author Contributions: PWK led this work, including conceptualization, data curation, formal analysis, investigation, methodology, project administration, visualization, and writing. LWE contributed to conceptualization, investigation, and writing. MLM, AP, FS, OV, RW, and RBW all contributed to investigation and writing. CF and PD all contributed to the investigation.

Funding: LWE and AP are funded by FORMAS, project number 2019–01220.

Acknowledgements: The authors acknowledge the facilitation provided by the Stockholm Resilience Centre during the "Water resilience workshop" held in February 2022.

Keywords: atmosphere; water; economic good; moisture recycling; weather; modification; scenarios

ABSTRACT

Humanity is modifying the atmospheric water cycle, via land use, climate change, air pollution, and weather modification. Given the implications of this, we present a theoretical framing of atmospheric water as an economic good. Historically, atmospheric water was tacitly considered a ‘public good’ since it was neither actively consumed (rival) nor controlled (exclusive). However, given anthropogenic changes, atmospheric water is becoming 'common-pool’ (rival, non-excludable) or 'club’ (non-rival, excludable). Moreover, advancements in weather modification presage water becoming a 'private’ good (i.e. rival, excludable). In this research, we explore the implications of different economic goods framings using story-based scenarios of human modifications of the atmospheric water cycle. We blend computational text analysis with expert perspectives to create science fiction prototypes of the future. The economic goods framing highlights that social choices play an enormous role in how the future will unfold with regard to human interaction with the atmospheric water cycle. The narrative scenarios serve two purposes. First, they provide creative artifacts for the investigation of future interactions with the atmospheric water cycle, that are rooted in a scientific evidence base. Second, they articulate trajectories of our coupled social-hydrological world that require deeper interrogation and anticipation in the present.

Introduction

Human societies are changing the atmospheric water cycle - evaporation, moisture transport, precipitation - primarily via land use change, climate change, and air pollution. Land use changes directly affect evaporation from land and include everything from replacing tropical forests with rangelands, to irrigating deserts, and converting grasslands to monocultures (Gasparri et al., 2016; Lambin et al., 2001; Lambin & Meyfroidt, 2011). Climate change influences precipitation patterns profoundly, and increasing air pollution, aerosols in particular, affect atmospheric physics including cloud formation and precipitation (Ramanathan et al., 2001; Rosenfeld et al., 2008). These modifications can have significant consequences for the timing, magnitude, and duration of evaporation delivery to the atmosphere, and the fate of precipitation elsewhere (Bagley et al., 2012; Keys et al., 2016; Mahmood et al., 2014; Staal et al., 2018; Swann et al., 2015; Tuinenburg et al., 2014; Wang-Erlandsson et al., 2018; Wei et al., 2012; Zemp et al., 2017). Given the actual, and potential, changes globally, we conceptualize these flows of atmospheric water — including the delivery of evaporation, the flow of water vapor, and eventual precipitation — as economic goods.

Historically, flows of atmospheric water were tacitly considered 'public goods' since evaporation flows and atmospheric water vapor are neither consumed (rival) nor controlled (exclusive) (Farley & Costanza, 2010). However, given that people can change this relationship, atmospheric water may transition into a 'common-pool' good (rival & non-excludable), and possibly to a controlled 'club' good (non-rival & excludable). Now, with the advent of scientifically verifiable cloud seeding, specifically via recent work on wintertime orographic cloud seeding (French et al., 2018; S. A. Tessendorf et al., 2015; Sarah A. Tessendorf et al., 2019), deliberate atmospheric water manipulation may accelerate in its deployment, in the near future. Along with scientific advancements in the understanding of fog harvesting (Qadir et al., 2018; Tu et al., 2018), it is now conceivable for atmospheric moisture to enter the domain of 'private good' (i.e. excludable and rival). Thus, there is a need to identify new research agendas and explore the implications for society (Keys et al., 2017; te Wierik et al., 2020).

Scenarios are a commonly used tool for exploring future trajectories of science, policy, and culture (Carpenter et al., 2006), yet such scenarios can vary widely in terms of approach, style, and depth of detail (Kishita et al., 2016). Importantly though, scenario narratives are often only descriptions - not stories - of a possible future world. While such descriptions can be creative, they often fail to foster student curiosity, engage the public, or interest policymakers (Milkoreit, 2017). Story-based scenarios have emerged as successful vehicles for impactful scenarios (Calvert, 2019; Johnson & Winkelman, 2017; Merrie et al., 2018; Nature, 2018). Story-based scenarios represent a deeper exploration of future worlds (Carbonell et al., 2017), and allow participants to explore how their daily lives, values, and habits can be mapped onto different projections of the future.

Very little policy or governance exists for managing changes to the atmospheric water cycle via land-use change (Keys & Wang-Erlandsson, 2018; Wierik et al., 2020), despite ongoing recognition of the various ways in which anthropogenic changes actively modify the atmospheric water cycle (Gordon et al., 2005; Keys et al., 2016; Kleidon, 2006; Schumacher et al., 2022; Wang-Erlandsson et al., 2018). There exist international policies guiding the use of precipitation enhancement for hostile intent. The Convention on the Prohibition of Military or Any Other Hostile Use of Environmental Modification Techniques, popularly known as ENMOD, was intended to ban weather modification for warfare (Bonnheim, 2010; Wunsch, 1980). However, weather modification, specifically precipitation enhancement is typically managed on a national basis. For example, in the United States any activities seeking to modify weather must submit a report of their activities to the National Oceanographic and Atmospheric Administration (Charak & DiGiulian, 1974; Simon, 2021). Nevertheless, there is no global policy for guiding human actions specifically regarding changes in atmospheric moisture. Chen (2016) explored the opportunity for updated property rights framings to be incorporated for atmospheric moisture in the United States, and the reality that legal interpretations of atmospheric moisture has led to communal, i.e. governmental, rights to management rather than individual or private rights. However, this discussion does not include anthropogenic modification of evaporation, and the associated delivery of moisture to the atmosphere. Thus, there is a gap in the scientific understanding of the potentially diverse sources of weather modification, and the associated policy discourse. This gap between scientific understanding and policy is, in part, due to the lack of framing terrestrial moisture recycling and atmospheric water manipulation in terms that are salient to policy (Keys et al., 2017).

Conceptual development: Rivalry and excludability for atmospheric water

In economics, the concept of 'goods' (e.g. timber, movie theater tickets, parking spaces) can be categorized into four quadrants based on how use and control of goods affects their status. First, if the use of a good reduces its available supply for others, it is called rival, while if use does not reduce availability it is considered non-rival (Kaul et al., 1999). Second, if a good can be intentionally or unintentionally controlled such that others can be prevented from access, it can be considered excludable, while if such control is not possible it is considered non-excludable. This classification produces a four quadrant space, including: 'public' goods (non-rival, non-excludable), 'common-pool' goods (rival, non-excludable), 'club' goods (non-rival, excludable), and 'private' goods (rival, excludable). Many natural resources are considered 'public' goods, especially spatially extensive phenomena like clouds, air, timber, or even ice caps. This classification is appropriate, absent human intervention. However, there are now few if any actual ‘public’ goods remaining, given the pervasive and widespread anthropogenic impacts on temperature, ocean heat budgets, and other planetary changes (Steffen et al., 2015) that drive and perpetuate unequal access to ecosystem services within societies and across generations (Hamann, et al., 2018, Thiery et al., 2021).

We classify atmospheric water into the four quadrants, based on how humans modify rivalry and excludability (Fig 1). For atmospheric water to be categorized as a ‘public’ good, anthropogenic activities that could modify atmospheric water would need to steward atmospheric water availability elsewhere in an undirected way. If anthropogenic activities change the quantity of moisture that is available elsewhere, then atmospheric water moves toward becoming a ‘common-pool’ resource. If anthropogenic activities exert control over the distribution of moisture but do not change the availability of moisture, then atmospheric water moves toward a ‘club’ good. Finally, if anthropogenic activities modify both the quantity and exert control over atmospheric water, then it moves toward a ‘private’ good.

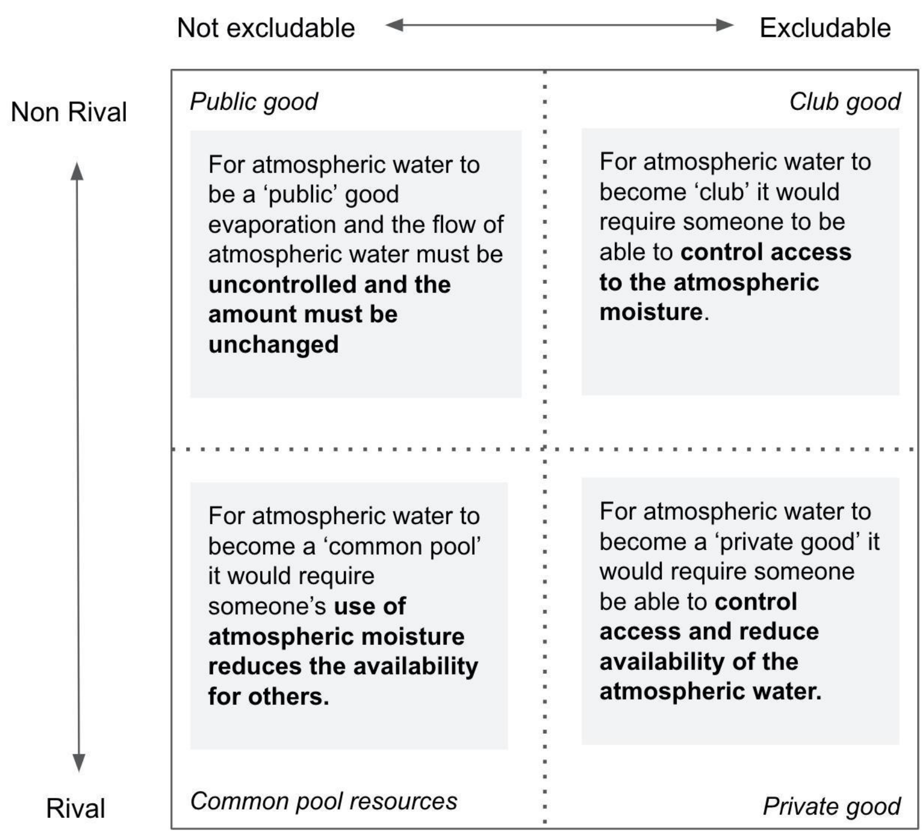

Figure 1. Conceptual overview of atmospheric water as an economic good. The horizontal axis indicates excludability of a resource. The vertical axis indicates whether the resource is rivalrous. Within each, there is a brief detail of the key requirement for atmospheric water to exist in that domain.

The core objective of this work is to advance the conceptual exploration of atmospheric water as an economic good, with story-based scenarios of how such human modifications of the atmospheric water cycle may unfold in the future. To do this we will blend multiple methods, incorporating text-based machine learning, expert participation, and creative storytelling. Our paper is organized as follows. First we will explain our methods, which blend a structured literature search, with computational text analysis, with expert training and collaboration, and storytelling. We then interpret these story-based scenarios in the context of improving our understanding of the future of human modification of the atmospheric water cycle. Further, we discuss a research agenda as well as policy frontiers that need to be explored given the findings of this scenario exercise.

Methods

There were five key steps in this research. First, we performed a structured literature search, and collected a corpus of scholarly abstracts on the topic of human modification of the atmospheric water cycle. Second, we employed a machine learning-based computational text analysis called latent Dirichlet allocation (LDA), which is a method for revealing the topics and keywords that exist across a corpus of documents. Third, we mapped the topics to the economic goods framework, based on a subjective interpretation of each topic's keywords. Fourth, we used the results of the LDA to inform a structured futuring exercise among a group of global water experts. This collaborative process involved guiding the experts through a set of creative exercises to develop imaginative visions of future worlds, where humans are (or are not) modifying the atmospheric water cycle. Fifth, a subset of the expert collaborators took these imaginative worlds, and were guided through a creative story-telling process. The results of this work are ten story-based scenarios. We provide a detailed explanation of each step below.

Structured literature search

The first step in our methods is to create a structured literature query to collect scholarly abstracts related to human modification of the atmospheric water cycle. After a preliminary exploration of various search terms, phrases, and exclusions, we identify the search query below, which is intended to maximize the literature that we collect while avoiding false returns. We used the Web of Science search function, which permits a sophisticated search query and automated download process for collecting scholarly abstracts. Throughout the query, we use asterisks (*), which allow a word could be completed by numerous suffixes, for example, "human*" indicates that it would include 'human', 'humanity', 'humans' or 'humanities'. Likewise metadata about the abstracts can be downloaded in a tabular format permitting easy cross referencing. The query is represented in Table 1, indicating that these words and phrases would need to be present in any of the searchable fields within Web of Science, including the article title, keywords, abstract, or other searchable text.

Table 1: Words and phrases that comprised the structured literature query in Web of Science.

Must include a **word** (or **phrase**, enclosed by quotes) from the following		Must include a **word** from the following
land atmosphere precipitation OR "moisture recycling" OR “precipitation recycling” OR “cloud seeding” OR “precipitation enhance*” OR “glaciogenic seed*” OR “weather modification” OR “climate manage*” OR “atmospheric water harvest*”	AND	human* OR anthropo* OR soci* OR people OR agricult*

We performed a manual quality control on the downloaded data, to ensure that the abstracts we collected actually included relevant text information, and were, for example, not erroneously blank.

Corpus preparation

The abstracts collected in the structured literature search above, were prepared for the computational text analysis by batch converting them into plain text format, so that they would be machine readable. Likewise additional information, such as author or other watermarks, were removed from the text so that only the abstract content was included in each document.

Latent Dirichlet allocation (LDA)

The computational text analysis was performed using python-based software including the natural language toolkit, the gensim package, and other common computational packages. The specific python software versions used for the analysis were Python v3.7.7, Natural Language Toolkit (i.e. NLTK), v3.4.4, and Gensim Python package v3.8.0. Following the methods of Keys and Meyer (2022), we performed the latent Dirichlet allocation (LDA) sequentially including: pre-processing the documents (including tokenization, stopword removal, and lemmatization), sensitivity testing to identify the most suitable number of topics for the LDA, and visualization of the final text analysis. First, tokenization is the process of converting each word across all documents in the corpus, into an individual unit of analysis. Second, we removed stopwords, which are words that appear in texts but convey little to no information (e.g. "I", "we", "and", "as", "the", etc). Third, words are lemmatized, which means similar words are collapsed into a common form. This process allows a greater number of unique tokens to be represented in the analysis.

The LDA is a process of iteratively identifying the underlying topic structure that exists across the entire corpus of documents. First, a target number of topics is assigned for the analysis, such as fifteen topics. Then, the LDA will be performed aiming to find the most representative set of fifteen topics (with corresponding keywords). Thus, by varying the number of topics, a different set of topics and keywords might be revealed. Several methods exist to find the most statistically robust set of topics. The idea of 'coherence' refers to a statistical representation of how each topic makes interpretable sense for a machine, such that the keywords included within each topic have some common meaning or connection. We used the coherence metric c_v (Röder et al., 2015), to perform a sensitivity analysis to identify the most statistically robust number of topics to use in our analysis. We do this by iteratively varying the number of topics in the LDA from 5 to 35. Then, we identified the top three topics with the highest coherence scores, to determine whether the resultant topics and keywords were interpretable for a person. To do this, we manually examined the keywords corresponding to each topic for each LDA analysis.

Finally, if the keywords for a topic represent <1% of total terms across the entire corpus, then that topic is removed from the analysis. While we do not want to miss topics that represent minority viewpoints across the texts, topics with low term representation may not be coherent enough for the story-based scenario process (Keys & Meyer, 2022)

Map themes onto economic goods framework

The topics produced from the text analysis were interpreted based on the semantic content of the keywords. This interpretation was then mapped onto the economic goods quadrants, as a way to connect the text analysis explicitly to the economic goods classification. This process was subjective and led by the lead author of this work. Multiple interpretations are possible of this mapping, and we do not claim that ours is the only interpretation. Likewise, given that there are potentially numerous interpretations, we discuss this at the end of the article, in the section on Future Work.

Expert participatory science fiction prototyping

The next step was to work with a set of global water experts to collaboratively interpret the thematic output of the computational text analysis and systematically develop science fiction prototypes. The water experts were recruited from a group of scientists, scholars, and practitioners with a broad expertise on global water topics (who attended a virtual water resilience symposium hosted by the Stockholm Resilience Centre, in Stockholm, Sweden) . A series of two workshops (22 February and 3 March, 2022) were convened to train the water experts in story-based scenario development, specifically a workshop on world-building, and a workshop on storytelling.

Workshop #1: Worldbuilding

Expert participants were led in individual, guided exercises that began with each participant reviewing a specific topic and its associated keywords. Each participant had their own pre-prepared, web-based worksheets. Participants were advised which economic good quadrant they were exploring, to provide some constraint to the world-building. From this they were prompted to visualize a future beyond 2050 that was inspired by the keywords and topic. After taking notes on these visualizations each participant was led in a structured Futures Wheels exercise (Pereira et al., 2018). Futures wheels permit an exploration of direct interactions and consequences, flowing from a focal event or item in the future (Hamann et al., 2020).

After the individual exercises, groups were formed for each economic good quadrant, with two participants each representing public good and private good and three participants each representing club good and common pool. Each group was provided with a new common set of pre-prepared web-based worksheets with guidance for three exercises including: 1) Three horizons framework; 2) Probe reality; and, 3) Make-it-weird. The three horizons framing is a structured exercise to systematically describe historical transitions from the present status quo, through a transition period toward a futuristic transformed third horizon (Sharpe et al., 2016). The first, second, and third horizons are often characterized as paradigms that shift in dominance over time. The three horizons exercise involves putting the visualized futures (e.g. from the Futures Wheels exercise) at the end of the third horizon and describing the first and second horizons.

After the three horizons exercise, participants were encouraged to 'Probe reality' and discuss what broader cultural forces might shape the broader future world. To do this, we employed the heuristic of the 'cultural iceberg' (Hall, 1989), which is used to reflect on deeper, less visible aspects of culture. Lastly, groups were encouraged to make it weird by pushing their ideas to ridiculous domains (Dator 1993). This included probing social norms, technological surprises and more.

Workshop #2: Storytelling

This second workshop was focused on guiding participants through the storytelling process, namely designing a character for a story and then systematically drafting a plot. For the character design section, participants were encouraged to imagine a character that would inhabit their world from the first workshop. Then, progressive activities focused on defining internal and external characteristics, motivations of what make the character act, obstacles that are relevant to their character, and thinking about the wants of a character versus what they might need for a satisfying story arc. In the second part of the workshop, participants designed a plot set in their world that their characters would navigate. The exercises here were built around identifying 'Story beats', specifically:

- *Act I.*
    - *Once upon a time…*
    - *Every day…*
    - *Until one day…*
- *Act II.*
    - *Because of this…*
    - *Because of that…*
- *Act III.*
    - *Until finally…*
    - *Ever since then…*

The story beats were nominally split into three acts, as a way to distribute action across a given story. This structure provided a basic scaffold on which a story could be built that would allow a character to navigate the created world, and work through obstacles to ultimately reveal something about the particular economic goods quadrant. Following the two workshops, participants were invited to contribute scenarios based on their workshop output. These scenarios were collaboratively edited by different members of the author team.

Results

Literature query

The structured web query returned 2,573 abstracts, and after our quality control (QC) checks we were left with 2,287 articles. These QC checks involved identifying whether a given document was associated with an abstract, searching for duplicate abstracts, and manually searching for abstracts that were not automatically retrieved with the Web of Science search. These abstracts (i.e. documents) were then used in our computational text analysis forming the corpus of analyzed literature.

Latent Dirichlet allocation (LDA)

Based on the coherence metric c_v, we identified LDA models with topics numbering 11, 15, and 17 as good candidates for our analysis (Supplemental Fig 1). Ultimately, while 11 topics yielded the highest coherence value, we selected 17 topics as the most suitable LDA model given it had the highest (subjective) interpretability for its words and topics. We also adjust the pyLDAvis 'relevance metric' slider to 0.6, which corresponds to the recommended value for maximum novelty and coherence in a given topic analysis (Sievert & Shirley, 2014).

The overall topic visualization is shown in Fig 2, and shows the distribution of the 17 topics, the terms (i.e. keywords) corresponding to the overall corpus, and the representativeness of these terms across the corpus. Moving forward, we exclude topics 13-17 because they each represent less than 1% of terms in the corpus, and have quite low interpretability. While this removal could lead to missing weak signals in the dataset, we consider this appropriate given that the remaining topics cover a substantial range of disciplines and ideas. A full set of visualizations for topics 1–12 are available in the Supplemental pyLDAvis figures.

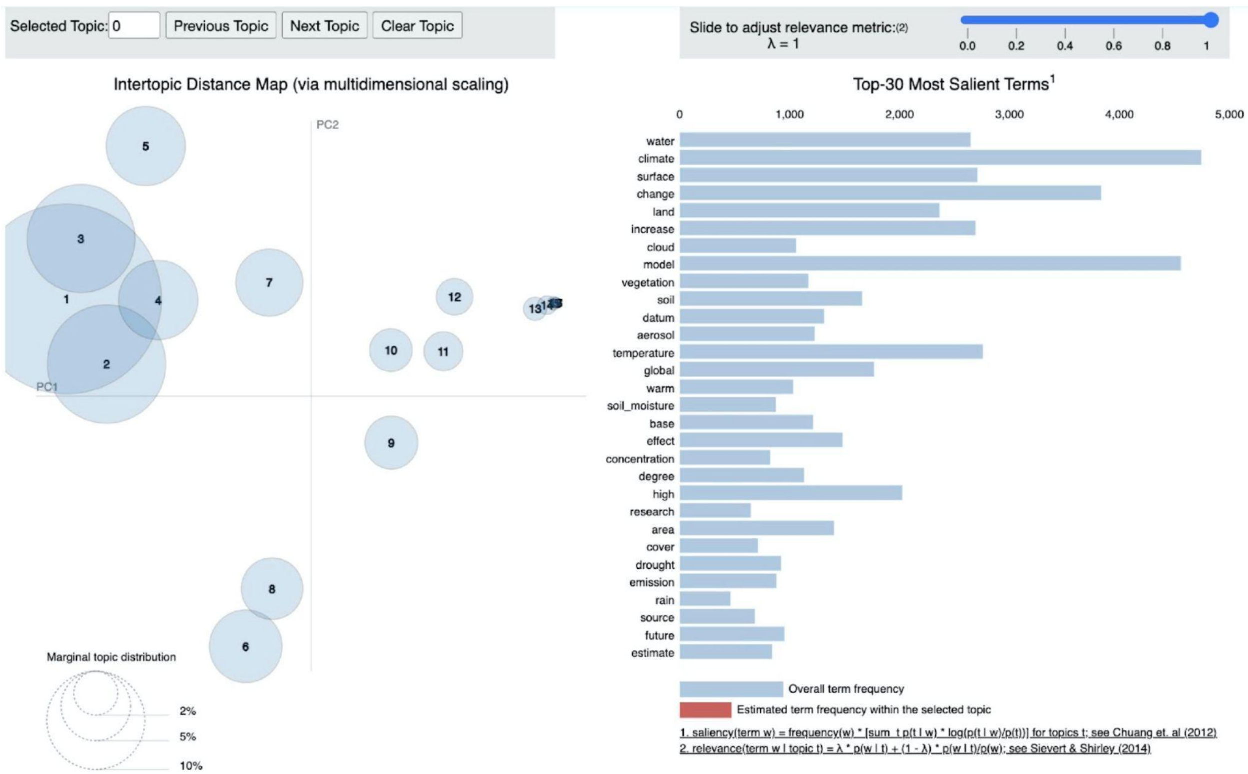

Figure 2. Visualization of topic distribution (left side of figure), and full list of keywords for the overall topic analysis (right side of figure). This visualization was created using the pyLDAvis python package. Note that visualizations for each individual topic are included in the Supplement.

We performed a preliminary filtering of topics 1-12, and their corresponding keywords, to consider whether they would be relevant in the analysis, or if they represented a topic that was erroneous for our study. We recognize that this subjective decision necessarily excludes some of the ideas collected during the structured web query and the subsequent LDA. Several topics were obviously focused on issues that were only tangentially connected to the topics we aimed to better understand in the scenario work. Ultimately, of the 12 topics we considered, we removed topic 2 (focused on carbon uptake, and nutrient loss) and topic 10 (focused on organic sediment and river discharge). Thus, we were left with ten total topics to be explored in the workshops and structured futuring (Table 2; the full table of all topics and keywords is available in the Supplement).

Table 2. Topics and keywords used in the scenario development.

TOPIC	KEYWORDS
1	precipitation, model, region, rainfall, study, observation, result, variability, observe, time, simulation, simulate, seasonal, scale, atmospheric, pattern, compare, air, high, associate, low, large, spatial, analysis, season, show, summer, difference, occur, event
2	climate, change, global, future, model, impact, management, scenario, land, project, regional, include, uncertainty, human, earth, country, current, strategy, landscape, projection, natural, terrestrial, expect, date, predict, tool, challenge, problem, population, assess
3	drought, temperature, increase, forest, area, trend, extreme, record, crop, annual, growth, yield, index, high, condition, degree, average, factor, agricultural, production, urban, year, significant, decrease, china, plant, stress, map, climatic
5	aerosol, warm, increase, response, effect, warming, decrease, induce, cool, ocean, reduction, anthropogenic, direct, temperature, surface, instrument, forcing, reduce, radiative, bc, force, degree, ozone, enhance, lead, east asia, heating, modus, ghg, maize
6	datum, method, base, approach, information, satellite, estimate, product, quality, performance, application, technique, provide, improve, pressure, measurement, develop, delta, propose, parameter, group, signal, objective, indicator, space, test, monitoring, new, obtain, achieve
7	vegetation, surface, soil moisture, land, cover, soil, energy, heat, exchange, water vapor, canopy, stage, flux, green, evaporation, australia, layer, leaf, atmosphere, content, moisture, cropland, subsurface, age, grass, condensation, dynamic, desert, heterogeneous, slight
8	research, design, technology, effort, scientific, community, policy, weather, science, program, system, development, paper, economic, knowledge, control, plan, use, gap, cost, review, address, benefit, solution, conclusion, weather modification, risk, issue, biotic, resource
9	water, irrigation, supply, series, demand, relevant, sector, requirement, availability, hydrologic, theory, deforestation, flow, efficiency, standard, platform, wetland, chamber, stream, amazon basin, operate, cycle, hold, amazon, capacity, energy, learn, connect, sky, evaporation
11	cloud, rain, ice, radar, snow, droplet, melt, aircraft, liquid, microphysical, snowpack, cell, altitude, artificial, suppress, storm, channel, mountain, boundary, reflectivity, hour, sequence, stratiform, pass, orographic, westward, scientist, radar reflectivity, formation, kilometer
12	match, island, april, middle, validate, drop, band, damage, image, bring, wrf, protection, wind, ccn, easterly, mm, bay, composite, air mass, size distribution, dry land, daytime, suppression, mature, salinity, ion, adequate, peninsula, night time, bulk

Map themes onto economic goods framework

Next, we took the remaining topics and mapped them directly onto the economic goods framing (Fig 3). This step allowed for a direct connection of certain topics and keywords to be explicitly explored in the context of particular economic goods framings. In other words, we considered the words associated with each topic and decided where it might exist in the spectrum of excludability and rivalry. We note here that our classification is but one of many potential classifications. There does exist an opportunity to classify the topics into different quadrants, which would eventually lead to different types of story-based scenarios. We discuss this aspect further in future work.

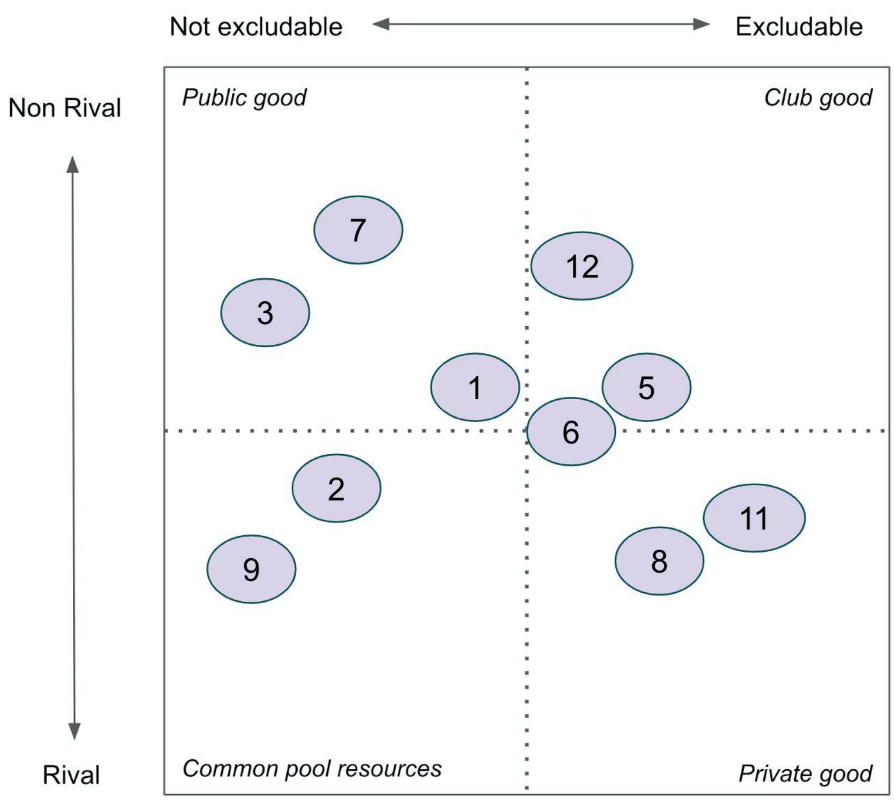

Figure 3. Classification of topics within the economic goods quadrant space, based on interpretation of keywords within each topic (see Table 2).

Expert workshops overview

The first workshop included ten participants, with specific activities for each workshop participant to complete individually, and then as a group. The disciplinary backgrounds included hydrometeorology, land use change, urban water infrastructure, comparative governance, water resources management, and ecology. Both the first and second workshops were conducted virtually, which enabled broad geographic collaboration. The second workshop included five participants, and was explicitly focused on story-based development.

Workshop #1: Worldbuilding

The expert collaborators developed scenario worlds in a two-phase process. First, they worked individually using exercises including a guided visualization and a Futures Wheels exercises (an example of a Futures Wheels diagram for the 'private good' category is shown in the Fig S2). Second, individuals were grouped together based on each of the four economic goods quadrants, and collaboratively participated in exercises using the three horizons framework (Fig S3), the cultural iceberg (Supplemental Fig S4), and the 'make-it-weird' framework (Fig S5).

Workshop #2: Storytelling

The second workshop was attended by five of the original ten participants, with the others accessing the recorded workshop afterward. The participants were led through a set of guided exercises, and produced the outline of character(s) and plot for their scenario world that they designed in Workshop #1.

Collaborative scenario writing

Ten story-based scenarios were generated that are representative of the original ten topics identified in the computational text analysis (available in Supplemental Story Scenarios). The final scenarios are short stories ranging in length from 1,000 to 2,000 words and include a range of forms including oratory, journal entries, internal reflections, third person narrative, conversations and dialogues, and a podcast transcript. Likewise the scenarios are set on all populated continents, in the countries of Myanmar, India, Australia, USA, Brazil, Nigeria, Germany, and China.

342 **Table 3. Summary of scenario story names, economic good quadrant, and corresponding descriptions of**
343 **worlds and story plots.**

Scenario name	Economic good	Scenario Description
We are as Gods	Public good	***World***: Scientific advancements in the manipulation of seasonal precipitation for agricultural production. ***Story***: Speech by Dr. Kay Rasmusdottir, recipient of the Inaugural AGU Tessendorf Lectureship on Weather Modification, speaks about the history of weather modification, and the dangers it may pose.
The Palash	Public good	***World:*** Profound 21st century weather modification led to global rejection because of problems, with transformation of precipitation toward a public good. ***Story***: Journal of 21st century farmer discovered by distant descendent, who is herself journaling about the contrasting worlds.
The Fertilizer Incident	Common pool	***World***: Transpiration is curated as a public good, and collaboratively stewarded to help mitigate downwind drought and precipitation deficits. ***Story***: Grandmother tells story to grandkids of how her daughter and son-in-law met in the transpiration fields of Australia's outback.
Pride of Burma	Common pool	***World***: International treaties exist to manage inter-national moisture flows, to ensure that no adverse consequences arise from uncoordinated land-use change. ***Story***: A activist and scientist in Myanmar discovers that moisture flows are being manipulated in Southeast Asia, and investigates the origin of this scheme.
T-Trading	Common pool	***World:*** Weather modification has been banned, but transpiration is managed to maximize downwind moisture, leading to surprising forest conservation. ***Story:*** An employee of SkyConnect LLC, a Transpiration Futures trading firm, reflects on her life and career.
Helping Heaven	Club good	***World***: Weather control is normal but conducted on a community basis, but finding a balance is often challenging among competing demands. ***Story***: Three travelers reflect on past management of droughts in their community, using a variety of integrated water management approaches.
Too Much Rain in Paradise	Club good	***World:*** Manipulation of cloud condensation nuclei (ccn) is regularly deployed to suppress destructive rainfall and flooding events. ***Story:*** A history podcast shares a story of how a CCN suppression effort in a future Lagos Bay led to a catastrophic outcome.
Igor's Diary	Club good	***World:*** Weather can be manipulated from satellite-based platforms, and the prohibitions on weather modification for hostile intent are ignored by some groups. ***Story:*** A leader struggling to cling to power aims to use weather control in an effort to lift his claim to historical legitimacy.
Any Weather	Private good	***World:*** Weather is privatized to the extent that rainfall and cloud cover can be requested, if a customer can pay the price. ***Story***: A farming household in Germany must see if they can outbid a neighbor to secure the precipitation that they need for their harvest.
Queen Bee	Private good	***World:*** Weather is modified for private customers in mountainous areas, so tourists can holiday at expensive ski resorts.

		Story: A group of ski resort cloud seeding employees try and one-up each other with stories about horrible customer experiences.

Discussion

Scenarios illustrate strange possibilities

These futures help illustrate important aspects of human modification of atmospheric water. First, geophysical features may confer some resistance of atmospheric moisture becoming anything other than a public good, given the constant replenishment via ocean sources. Second, technology change could lead to surprising social and legal problems related to liability and seniority in decision-making related to artificial weather. Third, climate changes will modulate every aspect of human society, including the interest in managing weather and precipitation. Fourth, radically different social norms from the present may become increasingly realistic as collapses caused by Anthropocene risks and climate change crises, lead to transformations (whether orderly or chaotic). We summarized key characteristics of these scenarios in Table 5.

Table 5. Comparison of scenario characteristics among Economic Goods quadrants.

PUBLIC GOOD ● Stewardship of moisture recycling processes ● Reaction to mis-use of weather modification technology leads to treaties protecting public good ● Transnational governance ● Civil society is in the lead	**CLUB GOOD** ● Community or Group management of atmospheric moisture in the absence of national and international coordination ● Technology related to suppression of unwanted rainfall as well as generating more rainfall are common ● The access to such technologies is in the hands of a low number of operators or governments
COMMON POOL ● Democratically coordinated management ● Treaties require that massive land use manipulations such as deforestation are tightly regulated ● Moisture recycling monitoring is highly regulated, openly available, and technologically advanced	**PRIVATE GOOD** ● Private management of atmospheric moisture tends to privilege the people with the most power and/or money ● Economies are built around the manipulation of weather, including tourism and agriculture ● Technology companies exist to exploit the desire for ‘on-demand’ weather ● Trade-offs between recipients of increased rainfall and those that possibly receive less become apparent

The scenarios allowed us to explore relationships among water-related sectors, as well as draw connections with many disciplines and topics typically unconnected to water science. Table 6 includes excerpts from four of the ten scenarios that were developed in this work. The public good quadrant is represented by an excerpt from 'The Palash.' The excerpt references how historical weather modification led to Earth system consequences (e.g. transformation of South Asian monsoon dynamics) and was later banned as a result. The story explicitly mentions human rights consequences that could arise resulting from human modification of the atmospheric water cycle. This "assault" led to atmospheric water being recognized and protected as a public good.

Table 6. Brief excerpts from the story scenarios that discuss aspects relevant to the economic goods framing.

PUBLIC GOOD - Excerpt from 'The Palash' *"Weather modification, particularly cloud-seeding came to be viewed as an assault on a basic human right. While the collapse of the AMOC ensured that the southwest monsoon winds never quite returned to their normal state, eastern monsoon winds, now freed from the cloud seeding efforts of several eastern nations, became the dominant harbinger of rain in drought-stricken areas such as Palashpaari."*	**CLUB GOOD - Excerpt from 'Too much rain in paradise'** *"The suppression of precipitation relies on careful and complete monitoring of air quality via the EkoCloud, a 3D network of sensors that continuously monitor and balance the right distribution of particles in the atmosphere. Many people who visit Lagos apparently comment on the strange haze over the bay. This haze is not by accident, but by design."*
COMMON POOL - Excerpt from 'T-Trading' *"At the NGO they were tireless proponents of additional ecological protections for the entire Amazon basin. With the tailwind of the Manaus Protocol, decades of mismanagement were being re-written. But the advent of T-trading saw Defenda being subsumed by an EcoFinance startup, SkyConnect LLC. Her job flipped inside out from advancing ecologically-based financial safeguards for her home, to working as a cog to maximize transpiration flows."*	**PRIVATE GOOD - Excerpt from 'AnyWeather'** *"AnyWeather regrets to inform you that your request for our 'Spring Rains service' conflicts with an earlier request by *Mueller, Tom* that supersedes your own. We apologize for any inconvenience. Note that your account has been credited a full refund. For any further questions, please click here for more information."*

The common-pool quadrant includes an excerpt from the scenario 'T-Trading.' The excerpt mentions how a comprehensive conservation and preservation effort for the Amazon led to a different perspective on how to profit from the intact forest cover. This story explores unexpected implications of successful conservation efforts, such as the financialization of the Amazonian atmospheric water cycle. While financialization is already discussed in the contexts of deforestation and commodities in the Amazon (Galaz et al., 2018), financialization of the atmospheric water cycle is a new topic.

The club good quadrant is represented by 'Too much rain in paradise', and the excerpt highlights the role of weather modification in community-scale efforts to avoid flooding or unwanted rain. This story could be viewed as a technologically advanced descendent of existing weather modification efforts that seek clear skies, particularly efforts throughout China (Bluemling et al., 2020). The story connects new topics, particularly advances in drone-based, three-dimensional monitoring of atmospheric conditions as well as the manipulation of conditions with the continuous management (and curation) of desired atmospheric aerosol conditions.

The private good quadrant is represented by 'AnyWeather', and the excerpt highlights how weather services are now 'on demand', similar to other delivery services. While this requires nonexistent technological advancements in microscale weather modification, the story is especially about the implications of pay-to-play services in the context of competing user interests. In this case, the story explores how a for-profit company might create different types of solutions for managing competing requests, including letting those with more money have greater levels of priority for their desired weather.

Improved anticipatory capacity

The scenarios depict a range of social, technological, and physical changes - many of which seem implausible or even impossible in the present. Yet, climate change, together with technological progress, is rapidly rendering the impossible, possible; and the unimaginable, a current event (Pettit et al., 2021; Samenow & Patel, 2022). Thus, prudence dictates that we take seriously the highly consequential ideas depicted in these scenarios. In this vein we recommend several relevant anticipatory practices:

1. Anticipate changes in regulatory regimes that will be oriented toward atmospheric water modification.
2. Anticipate substantial improvements in the diagnostic and monitoring capability of atmospheric moisture, precipitation, and cloud microphysics.
3. Anticipate overlapping crises, that relate to atmospheric water flows in surprising ways, and that will motivate unexpected social, economic, and geopolitical surprises.

4. Anticipate technological surprises that are disruptive, transformative, and seemingly impossible in the present, which will change what we deem is plausible regarding modification of atmospheric water flows.
5. Anticipate changes in power dynamics (e.g. geopolitical, social, cultural), that could lead to new configurations of who is able to exert control of atmospheric water flows.

Intentionally adopting these and perhaps other anticipatory approaches, will improve the responsiveness of both science and policy towards addressing a rapidly changing human relationship with the atmospheric water cycle.

Limitations

This is an initial exploration of atmospheric water as an economic good, specifically focusing on how humans are modifying this water globally. Given this we have aimed to be brief in the introduction regarding the conceptual framing, there is a substantial discourse that should yet be had regarding the economic goods classification. This discourse, however, is likely to be most fruitful when examined from multiple disciplinary perspectives, as well as inter- and trans-disciplinary perspectives. In this work, we have aimed to introduce the concept, and highlight how a specific approach — hybrid futures methods blending computational text analysis and expert creativity — can advance our perception of key issues. In this way, our work should be viewed as a horizon scanning exercise that can begin to enumerate the ideas, pitfalls, and potential challenges associated with thinking about human modification of the atmospheric water cycle.

The mapping of topics and keywords from the latent Dirichlet allocation (LDA) onto the economic goods quadrants was conducted prior to the expert workshops, and we emphasize that different subjective interpretations of this mapping could lead to different creative outcomes. Future work could aim to develop an objective procedure for interpretation of the LDA results into an economic goods framework. However, given that part of the point of this entire research effort is to embrace creativity, it may be more worthwhile to lean into the opportunity for numerous creative interpretations of the empirical LDA results.

Also, while the group of experts collaborating in this work are highly interdisciplinary (with expertise spanning resource economics, engineering, urban water systems, environmental humanities, biodiversity conservation, ecohydrology, and more), there are yet more disciplines that could be engaged. In particular, it could be worthwhile to engage weather modification personnel and practitioners to think about the future of their industry to better understand the perspective of 'insiders' in this topic.

Research frontiers

Given that this is among the first efforts to discuss human modification of atmospheric water using an economic goods framing (Keys, 2021), there is much yet to do to understand its dimensions, critique the framing, and deploy empirical tools to test hypotheses. First, there is already considerable scholarship surrounding water as an economic good more broadly (Rogers et al., 2002; Savenije, 2001; Savenije & van der Zaag, 2002), and these ideas could be brought to bear more fully to think about atmospheric water specifically. This could include reflection from similar types of 'source-sink' relationships such as watersheds that incorporate upstream and downstream ideas into their study (Jansson et al., 1999), as well as the payment for ecosystem services literature (Jack et al., 2008). Second, the notion of water as an economic good presupposes that concepts like 'valuation' and other ideas that permit management and control are tenable in the discourse of atmospheric water (Jenerette et al., 2006; Schaubroeck et al., 2016). Future work ought to more deeply engage other topics that have managed to examine valuation of diffuse economic goods, such as air quality (Levinson, 2012), or more broadly through cultural ecosystem services (Sukhdev, 2009).

Third, a tremendous amount of opportunity exists to use these scenarios as springboards for empirical analysis. This could take many forms (spanning numerous disciplines, such as mechanical engineering, ecohydrological modeling, theoretical economics, and weather modeling):

- *What are the theoretical limits of land-based weather modification?* What is the theoretical maximum evaporative contribution of the terrestrial biosphere? How does this vary around the planet? Are there biological restrictions to evapotranspiration that could be lifted with genetic modification? What are the barriers to this type of change?
- *What are the technological limits of drone technology and its use in weather modification?* How small could drones theoretically be constructed, while carrying a payload? What types of payloads could drones carry that are relevant to the weather modification conversation, including aerosols, cloud condensation nuclei, etc.?
- *What are the smallest scales of weather modification?* What are the smallest spatial- and time-scales at which weather could be modified? What prevailing regional and large-scale weather conditions would be more or less permissible for this type of micro manipulation?
- *What types of financial instruments could emerge to manage the flow of atmospheric water flows?* Are there existing financial mechanisms (e.g. trade rules, stock exchange listing agreements) which indirectly manage atmospheric moisture? Could there ever be a 'futures' or 'options' market to modify atmospheric water flows?

Another important dimension of thinking about this work is how existing governance and management of atmospheric water fit into this futures oriented discussion. Existing work has discussed the broad outlines of atmospheric water governance (Keys et al., 2017; te Wierik et al., 2020) and others have discussed manipulation of the weather more broadly (Bonnheim, 2010; Chien et al., 2017). Depending on the types of technologies that are deployed and the spatial scales over which atmospheric water changes operate, the administrative responsibility could shift. For small-scale situations, as depicted in the scenarios "AnyWeather" and "Helping Heaven" (where weather conditions are manipulated on a local basis), it could be that regulations remain a national issue, and governance need not interact with transboundary discussions. However, scenarios that involve large-scale transpiration modification, such as "T-Trading" and "The Fertilizer Incident" (which depict large-scale modifications of land-use and corresponding large changes to evaporation and transpiration) would necessarily involve transboundary negotiations. The scenario "T-Trading" specifically lists several international treaties and agreements which create the operational guardrails for financial instruments to emerge that manage transpiration. While fictional, this is analogous to other traded commodities that are regulated (to varying extents) at national and international levels (e.g. staple food crops, housing) (Clapp & Helleiner, 2012; Smith, 2010). Future work could advance the understanding of both practical examples of analogous governance structures that would be relevant for different quadrants of the economic goods framing, as well as to describe theoretical governance structures that could meet an as-yet nonexistent activity (e.g. what types of regulatory schemes would be necessary to govern Transpiration Futures trading?).

Conclusions

Humanity is transforming the atmospheric water cycle not least through climate change and large scale land use change. The advent of scientifically verifiable cloud seeding, may accelerate the uptake of atmospheric water manipulation in the near future. Moreover, scientific policies, legal frameworks, and governance strategies will need to anticipate this expanded manipulation. Thus, in this work we have introduced an economic goods framework for classifying the types of human modification of the atmospheric water cycle including atmospheric water as a public good, a club good, a common pool resource, and a private good. Moreover, we combine computational text analysis and collaborative expert visioning, to create ten story-based scenarios of the future. Specifically, this blending of objective and subjective approaches provided a rapid method for efficiently summarizing a large amount of information for a creative scenario workshop.

Our scenarios depict both familiar and strange futures. These include detailed worlds with characters that explore issues such as an Amazon basin dominated not by deforestation, but by

Transpiration Futures trading; privatized on demand weather that can be called up via an app; transformed drylands to provide continental moisture bridges; and, international efforts coordinating the management of the atmospheric water commons. Our approach effectively blended a broad literature survey into a rapid, expert-driven scenario development process that resulted in ten creative visions of the future. To be very clear, these scenarios are not meant to be prognostic. They are, instead, intended to provide a clearer perspective on present day scientific and social changes that require outside-the-box thinking. As the world changes around us these scenarios can help ignite new policy questions and lead to novel scientific inquiry to better understand the future of humanity's modification of the atmospheric water cycle.

Supplement

The full stories, along with all supplemental figures and tables are available in the Supplement.

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