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ORIGINAL ARTICLE

Changing local climate patterns through hail suppression systems: conflict and inequalities between farmers and wine producers in the Burgundy Region (France)

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Abstract

Meteorological hazards can lead farmers to resort to strategies such as weather modifications. In this paper, we study how the use of such strategies, in this case silver iodide ground generators aimed at protecting vineyards from hail, caused a conflict between farmers (wine producers and cattle breeders) in Burgundy, France. The conflict emerged as the installation of these generators coincided with 3 years of severe droughts (2018, 2019 and 2020), which incurred additional expenses and organisational difficulties for local cattle breeders and led them to suspect a potential link between the generators and the droughts. We followed a transdisciplinary research approach, based on local stakeholder input and their need to mitigate the negative impacts of the conflict. Based on this approach, we studied the links between generator use and precipitation, and carried out in-depth interviews to study farmers' experiences of climate, generators and conflicts in the region. Whilst the climatic analysis shows no local or regional effects of the generators on precipitation volumes, the sociological study highlights the vulnerability of farmers to successive droughts, found to be part of a wider pattern of climate change based on water balance variables (temperature, precipitation, evapotranspiration potential, soil wetness index) over a long period (1959–2020). Our results suggest that the use of technical solutions to mitigate meteorological hazards, within a broader context of climate engineering, can lead to conflicts at the regional level, and that the climate change challenge in the context of agriculture requires a focus on wider social issues including vulnerability.

Keywords Cattle breeding · Climate change · Climate engineering · Drought · Vulnerability · Weather modification

Introduction

Meteorological hazards, such as hail, lead to billions of dollars in damage every year to crops and property (Changnon and Burroughs 2003; Púčik et al. 2019). France is an area of high hail risk (Prein and Holland 2018), especially in the area that extends from the southwest (Garonne valley) to the northeast (Alsace), through the central-eastern part (Rhône valley) and the southern Alps (see Vinet 2002 for more information, including hail distribution maps). Hail is a highly localised meteorological phenomenon: A hailstorm generally takes the form of corridors measuring a few kilometres in width and a few dozen kilometres in length (Latrach 2013). The energy concentrated in the storm is also not distributed homogeneously, with the greatest damage recorded in the "hail cores" (Dessens et al. 2016; Changnon and Burroughs 2003). Due to its localised nature, the study of hail is complex, with varying data availability within Europe and information on hail frequency and intensity difficult to obtain (Punge and Kunz 2016). However, in France, hail intensity increased by 70% in 1989–2009 (Berthet et al. 2011) leading farmers to explore the potential of technologies to deal with this hazard (Dessens et al. 2016).

One attempt to minimise the impacts of hail on crops is weather modification technology such as cloud seeding.

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Scientific efforts to control hail storms have existed since the late nineteenth century through the understanding of cloud physics (Changnon and Ivens 1981). At that time, cannons or mortars were used. In the 1950s, silver iodide (AgI) cloud seeding was developed. The process involves adding artificial ice-forming nuclei (IFN) to natural ones by using AgI particles, thereby disrupting the hailstone growth process, and preventing the development of large hailstones (Dessens et al. 2016; Hirschy et al. 2020). There are three main seeding agent delivery methods: rockets that transport the active substance inside the hailstorm core (rocket seeding); and Agl smoke generators, operated either from planes (aircraft seeding) or from the ground (ground seeding) that aim to increase the IFN concentration in the convective clouds or boundary layer (Dessens et al. 2016). In terms of the effectiveness of these technologies on hail suppression, or indeed other climatic effects, the literature is scarce (Palencia et al. 2009). Existing studies neither validate nor invalidate the effectiveness of these technologies against hail (Boutin 1972; Hirschy et al. 2020; Mezeix and Caillot 1983), and the possible impact of generators on other climatic aspects (Brodu 2000) or environment contamination by Agl has been questioned (Causapé et al. 2021).

Burgundy is one of the French wine regions particularly affected by hailstorms, with a high number of severe storms found on the leeward side of the Massif Central low mountain ranges (Fluck et al. 2021). Hail impacts on vineyards can be important, with hail storms potentially destroying vineyards in a few minutes with up to 92% losses in the hail cores (Vinet 1994) and measurable effects on plant physiology and growth, yield and quality as hail bruises stems and reduces total leaf area and phenolics of the fruits (Petoumenou et al. 2019). The South of Burgundy is located in the red zone of high hail risk (see Figs. 5 and 6 in Vinet 2001). Agl ground generators (henceforth referred to as generators) were installed by wine producers in the Saône-et-Loire area of the Burgundy region in 2017. The installation of the generators coincided, however, with spring and summer droughts in 2018, 2019 and 2020. This situation led to an open conflict during the summer of 2020 between cattle (Charolais) breeders concerned that the generators where diverting storms and reducing rainfall, and wine producers defending the effectiveness of the generators against hail and the lack of impact of generators on droughts. Whilst weather modification can be a source of conflict, particularly between farmers and their neighbours on issues of pollution (Hirschy et al. 2020), the conflict reported in this paper is novel, in part because the stakeholders, wine producers and breeders, belong to the same socio-economic world (Melé 2013). In addition, we know of only a couple of other examples of such conflicts around cloud seeding being used as a technology to mitigate a meteorological hazard (see Brodu 2000; Tuftedal et al. 2022).

Our paper explores two key questions in the context of climate change at a regional scale. The first question addresses the impacts of weather modifications, in this case the impact of anti-hail generators on droughts. Questions may emerge about the wider impacts of such technologies at the regional scale, just as debates remain over the impacts of climate geoengineering at the national scale (Bluemling et al. 2020) and in relation to mitigating global climate change (Tilmes et al. 2016). The second key question is to understand the potential social issues that can emerge from the use of weather modifications, such as power and vulnerability disparities between regional actors in the face of environmental change, and possible emerging conflicts.

We considered the situation between cattle breeders and wine producers in this regional context as a conflict with controversial interpretations of the role of generators on clouds and rain. To fully understand the situation and learn from this conflict more broadly, the integration of local actors both in the framing and implementation of the research, together with social sciences and climate sciences, was needed to encompass the diversity of stakeholders' arguments and the complexity of the situation. We integrated social sciences through interviews, and natural sciences through climatic data and data associated with the use of generators in the Burgundy region. We then presented the results of both approaches to key actors at a participatory workshop. We start with a presentation of the region, the data and the methodology, before outlining the results of the climatic analyses on meteorological and soil droughts. We then present the results of our interviews exploring farmer perceptions of meteorological hazards, the implementation and effects of generators and the conflict as well as the results of the participatory workshop bringing the conflict actors together. We conclude with a wider discussion of the links between climate hazards, climate change, geo-engineering and conflicts in a context of environmental change.

Methods and materials

A transdisciplinary approach

This research was transdisciplinary, addressing a complex social issue through diverse disciplinary approaches that integrated multiple perspectives towards a common-good-oriented descriptive knowledge to address the issue (Pohl 2011). Figure 1 presents the timeline of the conflict and our transdisciplinary research intervention. In keeping informed about regional issues related to climate change, the authors first came across the conflict through a newspaper article in the local press, which reported a meeting of 150 local farmers (equivalent to 67% of the farms of the local area)

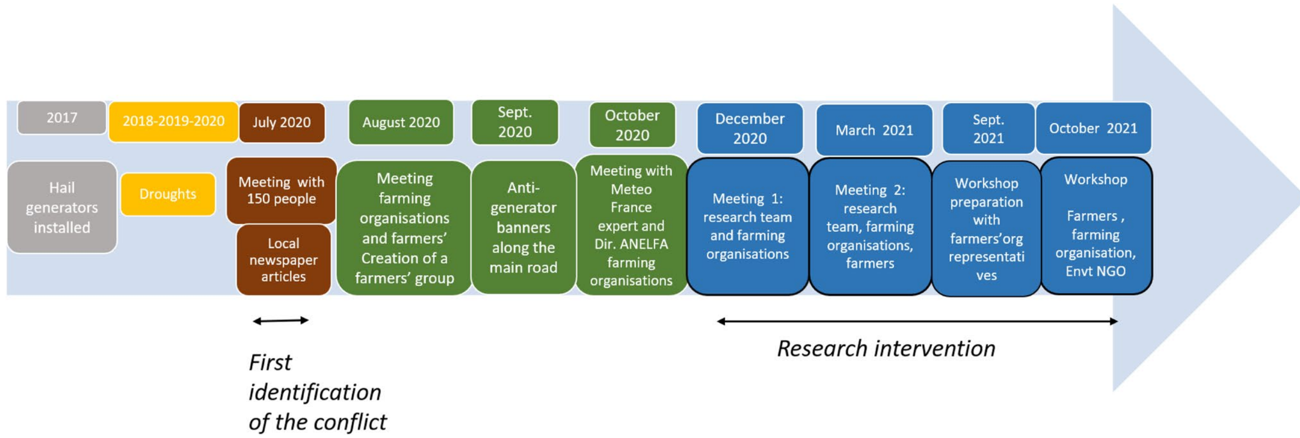

Fig. 1 Timeline of the conflict and transdisciplinary research intervention

in July 2020 concerned about years of drought in the area and blaming these on the installation of generators (Fig. 1).

This exceptionally large gathering, in a context where farmers are less and less involved in collective organisations and meetings, intrigued us. Representatives from the wine profession attended, aiming to provide information on the generators. The press reported a difficult atmosphere, with a sense of emergency from the breeders and a refusal to negotiate from the wine producers. The research team, which had worked together in a previous transdisciplinary research integrating climate and social sciences (Petit et al. 2020), gathered and agreed that the conflict deserved to be studied because it could be emblematic of tensions becoming more frequent due to the increasing effects of climate change. The team expanded further adding two Master students (in geography and climatology), a researcher in conflict management and a professional mediator to the group. The team then got in touch with the relevant agricultural organisations, thanks to the existing strong relationship with agricultural networks of one of the team members. The research team organised a series of small meetings with representatives of agricultural organisations (the Chamber of Agriculture, the farmers' union (FDSEA 71), the young farmers' Union (Jeunes Agriculteurs 71) of Saône-et-Loire, the association of wine "appellations contrôlées" and wine producers of Burgundy (CAVB) and the Burgundy regional association to prevent atmospheric hazards (ARELFA, with a national level ANELFA). The aim of these meetings was to understand the issue from their perspectives, identify the key question to be addressed ("do generators have an impact on rainfall and storms and cause droughts?") and design a common research approach. A final workshop, organised in October 2021, combined presentations of results, the start of a dialogue process between the wine producers and cattle breeders, and the development of guidelines for conflict management (Fig. 1).

As part of our transdisciplinary approach, we considered farmers as knowledge holders regarding climate hazards and therefore legitimate actors in framing the research question and its design jointly with the research team (Hoffmann et al. 2017). As observers of changes in their environment, farmers use an array of indicators to identify developments of observed impacts that may be related to climate change (Petit et al. 2020). Local knowledge can therefore provide a complementary input to scientific climate models often at a global scale and overcome apparent discrepancies (Reyes-García et al. 2016; Soubry et al. 2020). Based on our dialogue with stakeholders and experience in interdisciplinary practices (Petit et al. 2020), we developed a combined social sciences and climatology research design with stakeholders' concerns at the centre (see "Climate data and analysis approach" and "Interviews with livestock farmers and wine producers" sections).

Study system

The study area is located in the Burgundy wine region, with a local case study area in Saône-et-Loire (Fig. 2) where agricultural activities, although representing only 5% of local employment (Brion and Detroit 2011), shape the landscape's identity. On the one hand, bovine (charolais) breeding is extensive, representing 2/3 of the agricultural area (Le Hy 2008). The area of pasture and number of livestock are decreasing slightly, as is the workforce, not only due to ageing and low renewal rates, but also due to low meat prices (Froissart 2021). Viticulture, on the other hand, whilst covering only 2% of the area, took over from the meat sector in Saône-et-Loire in 2018 as the primary agricultural sector in terms of economic value (Froissart 2021). In 2019, the average annual income for a cattle breeder was 9600 euros (compared to 16,800€ until 2006) whilst for a wine producer it was 65,000€ (32,600€ in 2011) (Chambre d'Agriculture BFC and CER France, 2020).

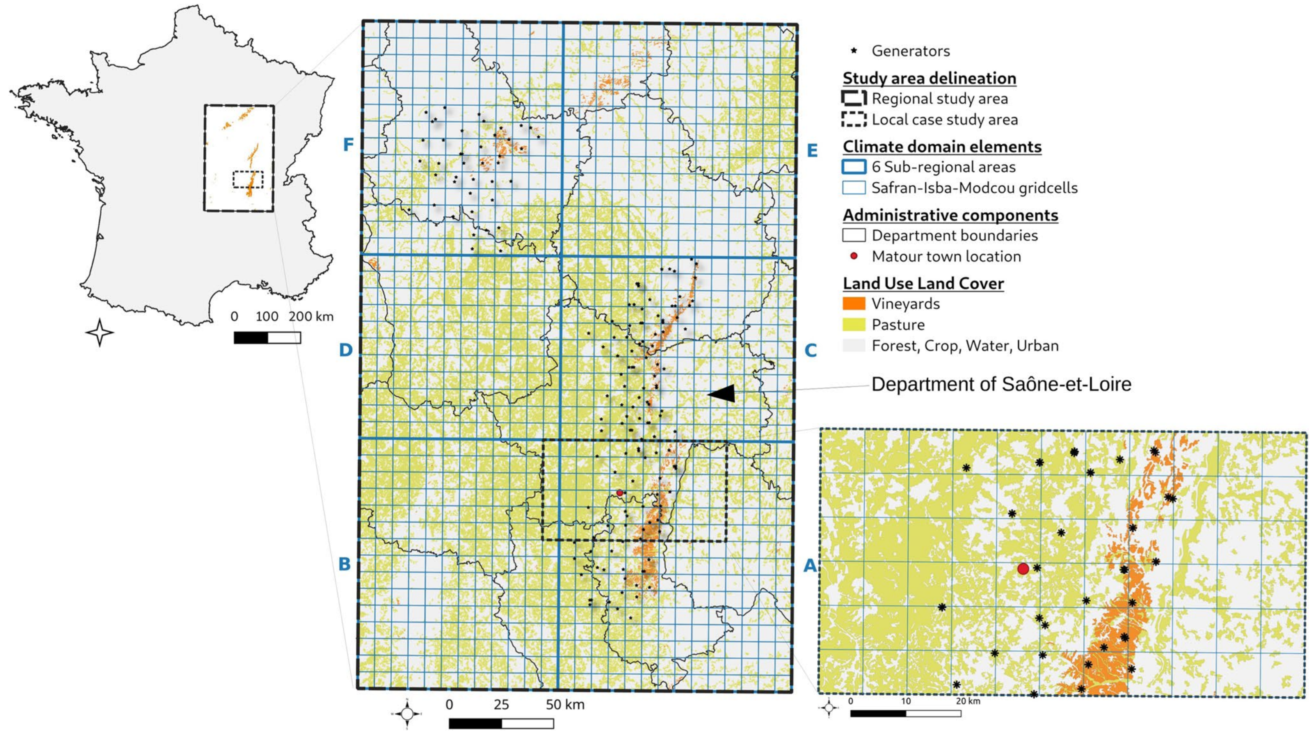

Fig. 2 Left pane: Map of France (data source: National Institute of Geographic and Forest Information) with the location of the regional study area (dashed line boundary box), the location of the local case study area (dotted line) and the vineyards areas (in orange—data source: Corine Land Cover). Middle pane: Regional study area and delineation of the 6 contiguous sub-regional areas located at the same latitude (A/B, C/D and E/F) used for precipitation comparison. Black stars indicate the location of the generators defined by ARELFA Bourgogne. The map shows the "department" boundaries (continuous black lines), and the Saône-et-Loire department and the Matour town (red dot) where the local case study takes place. The blue squares correspond to the daily climate grid cells at a resolution of 8km (source: Safran-Isba-Modcou SIM processing chain of Météo France; Habets et al. 2008). Vineyards, pasture and other land-uses are also mapped. Right pane: Local case study area with SIM grid cells used to analyse the evolution of climate and soil moisture drought evolution. Vineyards, pasture and other land-uses are also mapped.

The local case study area is also contrasted from a landscape perspective (Fig. 2): to the west, a large pastoral area dominated by permanent meadows and cattle breeding; to the East, a North-South strip of vineyards, the so-called "Mâconnais", along the Saône river. At the border of each are mixed systems combining cattle or sheep breeding and wine production.

The recent droughts led to acute crises recognised by the National Committee for Risk Management in Agriculture in Saône-et-Loire as an "agricultural disaster". In 2020, 40% of meadow harvests were lost. A few years before, in 2016, severe hail damages occurred in this part of Burgundy: 1500 hectares (or 48% of the wine area) of "Mâconnais" were impacted (Dausse et al. 2016). Following this event, local wine producers installed generators in 2017, one every 10 km to cover a 100 km^2 surface each (Fig. 2). No permission was required to instal generators and no communication was made locally about these installations. In relation to the prevailing south-west winds associated with thunderstorm trajectories (Vinet 2002), the generators were placed upstream of the wine-producing area, corresponding to the breeding sector located to the west of the wine-producing area (see Fig. 2). In theory, all generators in a subnetwork are triggered simultaneously in response to a hail alert. In practice, some generators are used without an alert and not all generators in a subnetwork are systematically used during alerts. This heterogeneity of use is explained by the fact that the activation of generators is based on volunteers.

Climate data and analysis approach

Based on our transdisciplinary partnership with key actors, the organisation that manages the network of generators (ARELFA) in Burgundy, composed of three sub-networks (Fig. 2—centre pane), provided the dataset linked to the generators (location, stack temperature and dates of hail alerts). The hail alerts come from the Keraunos consultancy firm (https://www.keraunos.org/) which transmits the information to the volunteers who then activate the generators. This firm's "Observatoire français des tornades et des orages violents" (French observatory of tornadoes and violent storms") publishes national maps. We mobilised hybrid meteorological data (observations/models) produced by the SAFRAN-ISBA-MODCOU (SIM) chain and validated by Météo France (Habets et al. 2008; Quintana-Segui et al. 2008; Soubeyroux et al. 2012). These daily data, with a spatial resolution of 8 km, cover the whole of metropolitan France. We delimited the study area (Centre-France) and analysed data over the period 1959–2020. This allowed us to look back at the evolution and geography of the climate beyond the period in which the generators were set up and the area in which they were located. We used liquid and solid precipitation data which are summed to obtain actual precipitation (PR), mean surface temperature (T), potential evapotranspiration (PET) and the soil moisture index (SWI).

These data were analysed according to two temporalities:

- Only on days with precipitation, defined as having a value greater than 1 mm from the spatial average. For these days, the relationship between PR and the uses of generators was tested. Three pairs of samples were analysed: each pair includes an area with and without generators. Based on these samples, the differences in precipitation between the areas with and without generators were calculated. The independence (Chi-squared) and Wilcoxon tests were then applied;
- To understand the evolution of climate and droughts from 1959 to 2020 (PR, T, PET, SWI), the analysis focused on the calculation of an annual Centre-France index (regional study area in Fig. 2). We first tested the presence of a climatic break with the Pettitt test (Paturel et al. 1996) as already shown on French weather stations (Brulebois et al. 2015). Trend analysis based on both the Mann-Kendall (Hipel and McLeod 1994) and the Cox-Stuart (Fatichi and Caporali 2009) tests was also applied to complement the break point detection method. We then studied the extreme "Summer" water droughts based on the Soil Moisture Index (SWI) from April to September, a key period for farmers (grazing, fodder, etc.).

Interviews with livestock farmers and wine producers

To understand farmers' perceptions of climate and regional change, we adopted a qualitative approach based on in-depth face-to-face interviews, lasting 2 hours on average. The interview guide was based on three narratives to facilitate the expression of perceptions, views and emotions: the experience linked to droughts and climatic hazards; the conflict between wine producers and breeders; and the perspectives for the future (see interview guide in Supplementary Material). We also asked questions regarding the main characteristics of the farm in terms of production, surface used and working conditions. We initially contacted the farmers who participated in the meeting located in the municipality of Matour in March 2021 (Fig. 1), followed by a snowball sampling approach that resulted in a total of 16 farmers, including eight cattle breeders, four wine producers and four mixed wine producers and breeders, referred to as hybrid farmers.

The interviews complied with the General Data Protection Regulation, including signed consents from respondents. To maintain anonymity, direct quotations from study participants are included in this paper using the following codes: breeder (BR1-BR8); wine producer (VI1-VI4); hybrid farmers (HY1-HY4). Interviews were recorded, transcribed verbatim and transcripts coded manually. We coded the transcripts according to a coding protocol using seven main themes:

1. Perception of climate change;
2. Narrative of the conflict and of the Matour meeting;
3. Knowledge and opinions related to generators;
4. Role of actors and organisations in the conflict process;
5. Links and gaps between wine producers and cattle breeders;
6. Sources of knowledge and expertise regarding climate change;
7. Capacity to plan for the future.

Workshop

The workshop took place in October 2021 with 35 participants including breeders, wine producers, elected representatives of municipalities, NGO representatives, farmers' and wine producers' union representatives, members of the chamber of agriculture, and the research team. The focus of the workshop was to share the results of the jointly designed scientific study, to understand the different viewpoints and allow the groups to "hear" each other, and to move towards conflict management (see supplementary material for the outline of the workshop and methodologies used). The workshop was led by a professional mediator. Given the existing tensions between stakeholders, we considered that it was crucial to use mediation skills. The mediator could fully listen to the participants and reformulate the points of view. Her presence also allowed the research team not to mix the roles of facilitator and knowledge provider.

Results

Climate analysis: sensitivity to generators and/or change?

The link between precipitation and generators in the study area

If generators inhibited precipitation, as farmers believed, the differences in precipitation between zones with (Fig. 2A, C and F) and without generators (B, D and E) during their use would be expected to be mostly negative, all other conditions being equal, i.e. analysed on days when generators are not used. Our results do not show significant differences between the precipitation in zones A (case study area) and B (Fig. 3). The results obtained for the C/D and F/E zones are similar (see supplementary material). During the use of the generators (blue dots), the differences between the precipitation in zones with (A) and without (B) are of varying degrees. When generators are not used (red dots), the same is true. This highlights a similar variability and level of daily precipitation between the zones. The result of the Chi-squared and Wilcoxon tests between the areas with and without generators shows that there are no significant differences (p-value respectively = 0.14 and 0.64). In answer to the farmers' suspicions of links between generator use and drought, the analysis shows no effect of generators on rainfalls in the three areas (A/B, C/D and F/E) studied.

The differences in precipitation observed between the areas with and without generators are due to the spatial variability in the distribution of precipitation. These differences are identical on days with and without the use of generators.

Soil moisture drought from 1959 to 2020 (PR, T, PET, SWI)

The conflict emerged after three consecutive years of droughts concomitant with the installation and use of generators, leading to difficulty in feeding animals on pasture and to a decrease in forage stocks. The research team raised the question of on-going climate change and its characteristics and impacts. In relation to droughts and grasslands management, we focused on the evolution of soil moisture. Over the 1959–2020 period, we first confirmed the results of previous studies (Brulebois et al. 2015; Reid et al. 2016; Tissot et al. 2016) with the presence of a break around 1987/1988 on the T, PET and SWI series. This is supported by a statistically significant trend of +0.37°C and of +31mm by decades for respectively T and PET. Note that if no significant trend is observed for SWI, there is on both sides of 1987/1988 break a significant difference (−4.5%, $p<0.04$) on the mean of the SWI. This break usually makes sense for farmers, who remember it as being a warm year and advanced harvesting (Petit et al. 2020). For precipitation, no significant climatic break or trend is detected, i.e. the mean annual precipitation accumulation varies around a quasi-stationary annual average over the entire period. 1976, a very dry year, stands out as an exceptional event.

Figure 4 compares the annual averages calculated before and after 1987/1988. The average annual precipitation (top left) increases (+27 mm), but not significantly. Before and after 1987/1988, the three other variables (T, PET and SWI) change significantly. Temperatures (top right) and PET (bottom left) increase by 1.1 °C and 98 mm respectively. At the same time, SWI (bottom right) decreased by 4%.

The current soil moisture droughts are part of a broader climatic context. If farmers are used to follow the evolution of rainfalls, each having a rain gauge in the corner of the garden, the evaporation due to high temperatures and

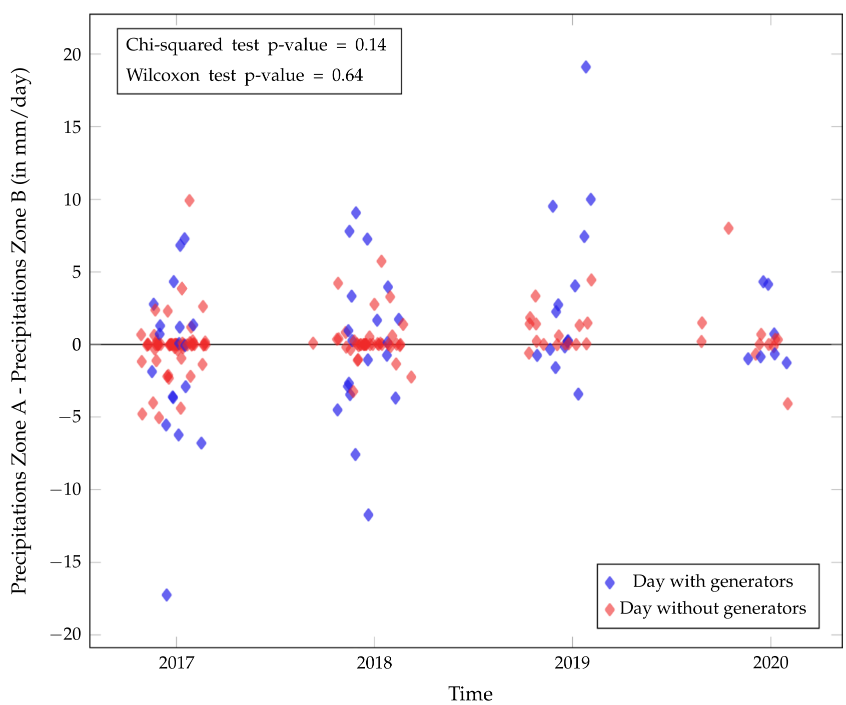

Fig. 3 Differences in standardised daily precipitation ($P \geq 1$mm) between the two sub-areas (see Fig. 2) A (with generators—blue diamonds) and B (without generators—red diamonds), April–September 2017–2020. Both Chi-squared and Wilcoxon tests show that differences of each group are not independent and there is no group for which the median is significantly greater or lesser to that of the other group. Results for the two others sub-areas (C–D and E–F see figure 1) are depicted in the supplementary materials

soil dryness with impacts on soil life are parameters much more difficult to grasp for them and for which they generally have no information. By analysing the post-breakup trends (1988–2020), two sub-periods can be distinguished (results not shown). A sub-period with stationary annual mean temperatures (1988–2014) including a global warming hiatus (roughly 2000–2010—Meehl et al. 2011) takes place followed by a new warming phase from 2015 onwards. Since 2014/2015, a new warming phase seems to be emerging, matching to recurrent droughts. The short time period does not allow us at this stage to conclude on the characteristics of this new warming phase. Nevertheless, it has been accompanied by a further increase in evaporative demand in recent years, with expected consequences for soil water content (SWI). During the workshop, a staircase curve with two thresholds was presented.

The analysis of the summer SWI (i.e. April to September) shows that 2019 and 2020 rank among the seven driest years between 1959 and 2020 (Fig. 5). With the exception of 1976 still in the memory of the older farmers as an emblematic drought, the six driest summers occur after 1987/1988. This indicates an expected effect of global warming on the acceleration of the water cycle and the availability of the resource (Milly 2008). The succession of two very dry summers has undoubtedly contributed to worsening the situation of farmers in terms of grass growth.

Farmers' perceptions of climate, generators and the conflict

Wine producers' perceptions

For the wine producers interviewed, climate change was a growing reality "*there is a real change in weather, this is sure, since about 10 years*" (VI2). Although climate change was seen by some as helping in terms of the ripening of grapes and enhanced wine quality, the yields were following a saw-tooth pattern. This was typified by "*warmer winters*

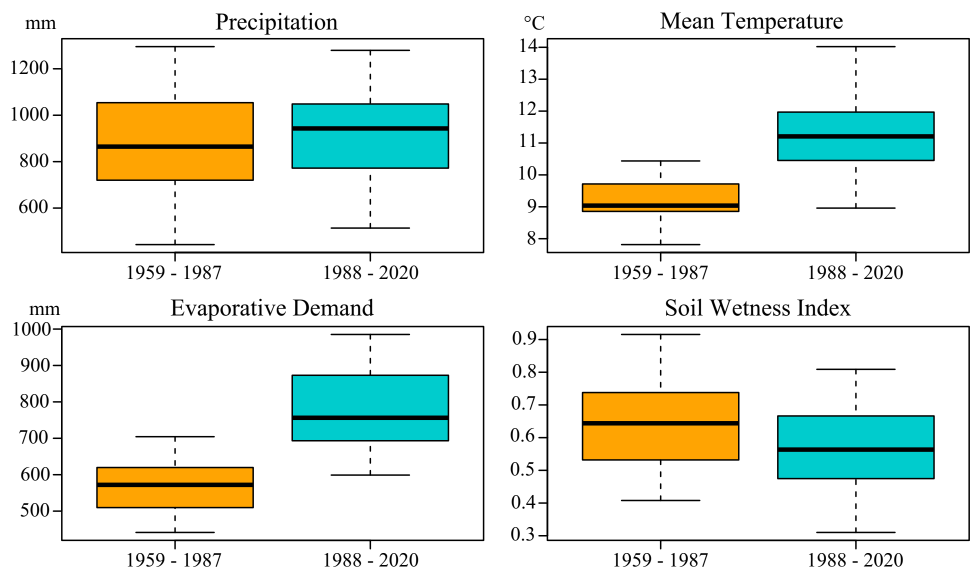

Fig. 4 Pre- and post-1987/1988 whisker boxes of mean annual precipitation (top left) and evaporative demand (PET—bottom left), mean annual temperatures (top right) and soil moisture drought index (Soil Wetness Index—bottom right). Statistics are calculated for the local case study area (see Fig. 2)

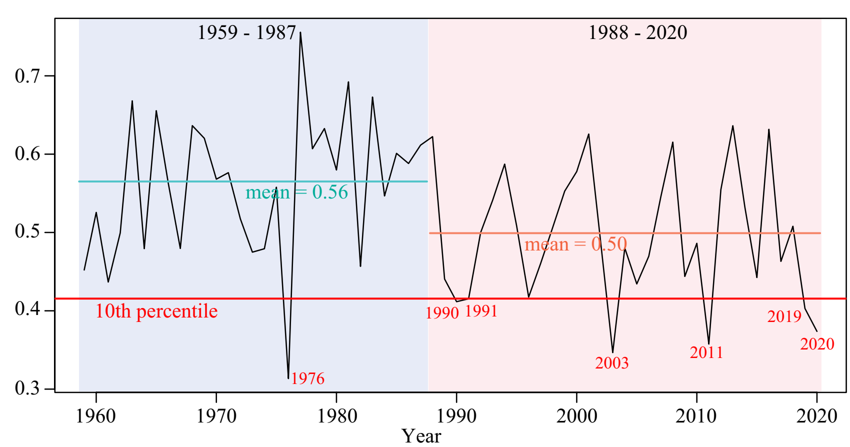

Fig. 5 Inter-annual evolution of the mean soil moisture drought index computed over the April to September period. The 10th percentile (horizontal red line) of soil moisture was used to identify the years when the highest dry periods occurred. Blue (1959–1987) and red (1988–2020) for periods and mean values of April–September SWI calculated on the local case study area

and springs" (VI3) as well as temperature swings: "*we can have 35-40°C, and 8 days later we can have 10°C and then shift again to 35°C*" (HY3). These statements converge with studies conducted on French vineyards (Touzard and Ollat 2021) showing that the developmental stages of the vine happen earlier, increasing the risk from spring frost. Drought was also becoming an important issue with high summer temperatures associated with irregular rains: "*today it can rain for two weeks and the next six weeks we don't have a drop of water*" (HY3). Faced with climate change, wine producers increasingly felt helpless: "*one can think that animals and plants will adapt. Well, that's not true. There comes a time when no: the plant suffers*" (HY3).

Wine producers tended to focus more on climatic hazards than climate change, and therefore reasoned more in terms of risk management rather than long-term climate change effects. This is partly due to the possibility for winegrowers to insure themselves by taking out multi-risk weather insurance that reimburses damage caused by hazards. With regard to the climatic hazards, hail and frost were the hazards most mentioned by wine producers. Hail was considered the "enemy" due to the heavy losses it could lead to. Interviewees described the unpredictability of hail, which can occur from April to October, and affect the plant at different phenological stages, piercing leaves, breaking branches, damaging wood and destroying young buds or young fruit. Whilst interviewees noted the spatial disparity of hail corridors, and the highly localised nature of hail "*big hail storms are always very localised. It can take more or less time, in general it follows corridors* (...) *so there is little chance that everything will be ravaged by the same hailstorm*" (VI4), interviewees conveyed the apprehension, fear and stress that hail generated: "*every time we tremble*" (HY2). Hail was considered by wine producers as a hazard that was impossible to anticipate, whose impacts can be long-term, and therefore difficult to manage and accept. As one wine producer highlighted: "*with a hailstorm he can lose two years (...) A vine can be in green bush and then a hailstorm happens. And then you lose 100% that year, and you lose a proportion of the following year*" (VI.1).

Faced with this hazard, wine producers installed generators to protect the Mâconnais vineyards. The decision was pragmatic "*we pay to be protected*" (VI1, VI4) leading to a situation in which wine producers have taken ownership, referring to them as "*our generators*" (VI3; VI2). With hindsight, some suggested the implementation process could have been managed differently: "w*hat can be criticised is that there was not much information about the installation* [...] *because nobody imagined that it would become a problem*" (HY2). In terms of the effectiveness of generators against hail, views were mixed. According to one wine producer, a meteorologist at one of their meetings told them that "*the generators could not have any effect on rainfall, but neither could they have any effect on hailstorms! Since we have had the generators, we still have hail in some places*" (VI4), leading another to highlight that "*it's hard to prove to us that it works, and it's hard to prove that it doesn't work*" (HY3). There were indications however that hail had decreased in the area (although whether this was due or not to generators is inconclusive): "*The only objective element we have is* [insurance company] *which says that since there are these generators* [...] *there are fewer compensations linked to hail*" (HY2). Generators were seen as a shield, alleviating the feeling of powerlessness in the face of hail: "*it eases the mind*" (VI1), especially considering their limited cost (8€/ha).

The conflict, as perceived by the wine producers, was centred around their reluctance to remove these inexpensive generators, whatever small effect they might have on hail, simply based on perceptions from breeders that the generators incurred droughts. The generators represent reassurance and therefore questioning their use was considered an attack. At the Matour meeting, wine producers were not ready to hear the distress of the breeders. The clear message from the wine profession at that time was "*'we're not going to stop the generators anyway.' And I think that was the wrong thing to say*." (HY3). All the wine producers interviewed regretted the language used at Matour, and some expressed their understanding of the breeders' situation. One wine producer highlighted that "*if the meteorologist said "yes, yes, it moves the rain", I would have been the first to say "let's stop it"*" (VI4).

Cattle breeders' perceptions

Since 1990, breeders have noticed changes in the climate and impacts on farming: "*the dry season arrives earlier and earlier in the spring. So we escape the storms more and more and we end up with such long periods of drought that animals have to be fed 10 months out of 12*" (BR6). Many referred to their land becoming a desert: "*There is no more water in the soil and our meadows become a desert (...) Seeing cows in the meadows, hungry, eating dirt*" (BR4). The physical desert was also used as a social metaphor referring to a farming dead end: "*If it goes on like this, in any case the farm, like all farms, will be doomed, we won't be able to produce anything. If it ends up as a desert... or else we'll have to start riding camels! If there is nothing more than sand*" (BR6). In addition to the concrete environmental changes, breeders highlighted many other impacts of droughts on their cattle production (see Fig. 6), including a decrease in forage production, with repercussions on the health and condition of the animals (reproductive capacities of the cows), an impact on income with farmers spending 5000–20,000 euros more in 2020 on feed and fodder or water tanks and water from the public network, or the sale of animals: "*Last week I sold 5 cows again. I have to cut back. (...) it's heart-breaking*" (BR4). These impacts regarding the sustainability of the farm placed a very heavy physical and psychological burden on breeders, with no respite. Whilst summer was usually a quiet period, the drought disrupted this: "*We spend all day doing this, giving food and water*" (BR1). For many interviewees, livestock farming was so difficult that they mentioned early retirement, a change of career, and even suicide: "*I'm fed up* […] *It has to stop* […] *at some point we're at the end of our rope*" (BR3).

The extent of the impacts of droughts on farmers may explain the acute crisis around generators. A number of breeders described a similar phenomenon since the implementation of generators, summarised here: "*We have noticed differences over the last four-five years. This coincides with the installation of the generators. I don't know if it's that or not, but we're seeing phenomena that we didn't see before. Last year, there were big black clouds coming in, and you thought: "Oh, that's good, it's coming in on the left of Mount Saint-Cyr, we think we're going to be in a storm. Then it cuts in two and disperses*" (BR2).

The conflict from the perspective of breeders was centred not only around the potential impact of generators on droughts (as described above), but also the hidden nature of their installation and a lack of communication about what the generators aimed to do, how and with which consequences. According to the breeders interviewed, the explanations expected at the Matour meeting lacked clarity and were often contradictory. Wine producers were perceived as being contemptuous of the breeders, resulting in tensions and a breakdown in dialogue. What emerged most during the Matour meeting, according to the breeders interviewed, were the differences between themselves and wine producers: "*We have such different productions that…we are almost two different professions* [...] *the constraints are not at all the same*" (B5). These differences led breeders to feeling ignored, belittled and insulted by the wine producers and the associations representing them during the Matour meeting: "*We are so despised, no one cares, we can die in our corner, nobody cares*" (BR6). There were, however, some indications of common ground, especially in terms of shared difficulties in a changing climate: "*we are also dependent on the climate, that's for sure*" (BR5); and "*What is certain is that we should not start a war between livestock farmers and wine producers (…) we don't need to wage war on each other, it's complicated enough as it is*" (BR5). In this regard, hybrid farmers often had a more moderate view and empathy towards breeders: "*I understand the distress, I understand that a scapegoat is needed. I understand it completely*" (HY2).

Workshop

The results of the climatological study on the effects of generators on droughts were eagerly awaited by cattle breeders and winegrowers. We assumed that the contribution of recognised scientists would be decisive in resolving the conflict.

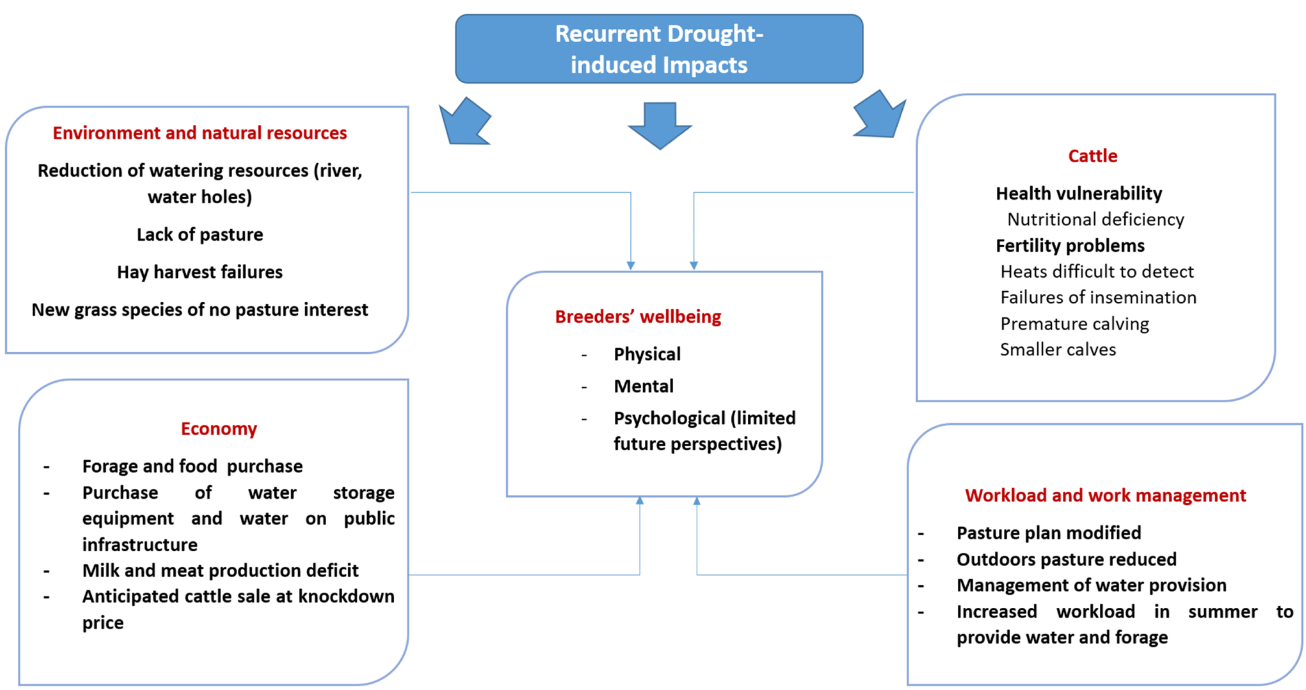

Fig. 6 Recurrent drought-induced impacts based on the results of interviews

Following the presentation of the climatological study on the effects of generators on drought, most of participants accepted the results, although a few breeders disagreed with them, highlighting again their experience of seeing storms appearing, splitting in two and disappearing. They also suggested local land planning and works (roads, high-speed train, forest management) as potential causes of local climate change. Scientific data competed with the experiential knowledge of the farmers based on repeated observations over time. New information provided on climate change was not sufficient to move the dialogue forward to the challenge of farming systems adaptation. It was at first necessary to acknowledge the distress of the farmers that the sociological analysis had revealed.

Regarding social aspects, a shared accepted view of the breeders' distress dominated. However, wine producers were able in the workshop to communicate their own risks and difficulties, including environmental and societal demands. This emerged in the session where participants were asked to illustrate their situation through drawings. In the breeders 'group, the gap between breeders and wine producers was often represented, underlining a better economic position for wine producers. However, conviviality between the groups (represented by a table with food and wine) also emerged as a past feature and desired future. Wine producers acknowledged a lack of communication, without harmful intent, and a need to develop a common farmers' identity. For this group, all highlighted the insecurity of their jobs and the common key challenge of adapting to climate change.

The workshop was a key moment of articulation of the two research questions. The analysis of the effect of generators on rainfall is a question that came from local stakeholders, addressed by scientists in order to provide "tailor-made" knowledge to be shared with the protagonists of the conflict. The social sciences sought to understand what triggered and maintained the conflict. They shed light on the conflict by understanding people's experiences and the inequalities between socio-professional groups. During the workshop, they also observed the elements (knowledge, social recognition, etc.) that influenced the evolution of the conflict, towards its appeasement. By extending the problem of drought to climate change, the research group, from an action-research perspective, set the stage for stakeholders to consider the situation more fully and to prepare for recurring difficulties.

The workshop also produced suggestions to prevent new tensions and for better preparedness for future droughts, including the dissemination of the scientific study's results through a communication campaign in technical or local newspapers; the restricted use of generators for clear high-risk situations; and a compromise to postpone the first use of generators to June to increase the perceived livelihood of storms and grass growth.

Discussion

Our paper explored two key questions in the context of climate change at a regional scale. The first question addressed the impacts of weather modification aimed at reducing meteorological hazards. Following a jointly developed research question and design, our results show no correlation between generators and precipitation in the area. Furthermore, the analysis of the evolution of the climate over the 1959–2020 period confirms a clear climatic break in 1987–1988 in terms of temperatures, which was accompanied by a significant increase in evaporative demand (+98 mm average per year) and a Soil Wetness Index showing a significant drop of 6% during the vegetative period. These parameters explain the consequences of an acceleration of the water cycle (Milly 2008) through the expected increased frequency of soil droughts. Soil droughts are one of the primary determinants of the degradation of grassland growth and the drying up of rivers (Brulebois et al. 2015). This corroborates a significant drift towards drier climates by the end of the century (Graux et al. 2013).

The second key question our study aimed at was understanding the potential social issues that can emerge from the use of weather modification approaches. Based on our interviews, the different experiences of meteorological hazards and their management coalesced into an acute conflict between two agricultural professions that were not exposed to climate change in the same way, and had different levels of vulnerability: wine producers and cattle breeders did not experience the same climate change. For the wine producers, who seem to have more resources to cope with hazards (weather modification systems, an insurance system, better economic resilience), the generators were an economical means of countering the risk of hail. The breeders, however, felt they had no technology to make rain, and that the various adaptations put in place to mitigate droughts (fodder crops more resistant to water stress, rearrangement of water points in the meadows, unloading of livestock in the summer, etc.) were insufficient. According to the breeders, the situation was uneven, with wine producers "controlling the weather", at a time when cattle breeders needed rain more than ever. Our study therefore highlights the need to integrate, within our understanding of climate engineering, the risk of emergence of environmental conflicts, and how to integrate different actors' vulnerabilities in any future adaptations to climate change (Marks et al. 2022; Ribot 2011).

In addition to the above questions, our study raises four major issues relevant to environmental change. Firstly, this conflict is not an isolated case. Similar tensions can be found in the past, such as in 1986 in the Dordogne (Brodu 2000) or, more recently, in 2017 in Dakota in the USA (Tuftedal et al. 2021). In 1986, in Dordogne (South-West of France) during a severe drought, a rumour was picked up by the media and 500 farmers signed a petition against “aircrafts chasing clouds away”. The farmers suspected that the large orchard owners and their insurance companies were protecting their orchards from hail by sending planes into the sky which released silver iodide and thus kept the rain clouds away. In western North Dakota, in 2017, a controversy over cloud seeding intensified as farmers and ranchers coped with extreme drought. Farmers suspected that the North Dakota’s state-managed program aimed at suppressing hail exacerbated the drought. Farmers fought to “return to natural weather again”. In both cases, as in our study, commonalities are drought, the concern of cattle breeders as victims of drought and the use of technologies (cloud seeding planes or generators) to modify the weather and protect against hail. In all three cases, farmers’ hypotheses and observations became certainties and swelled into rumours and mobilisation, which were echoed in the press. In all three cases, whilst other actors, such as orchard owners or wine growers, can protect themselves, the cattle breeders feel powerless.

Secondly, the study reveals the complex and dynamic nature of conflicts at a regional scale. Whilst already complex, the existing study did not address the concerns of an environmental association regarding the possible toxicity of AgI released into the environment (the amount of silver concentration in the ecosystem due to hail suppression systems was analysed in Aragón, Spain by Causapé et al. 2021). The conflict is also dynamic over time: the late spring and rainy summer of 2021 removed the threat of drought for the year. Conflict seems to have subsided, although long-term concerns remain for farmers. What will happen when the drought returns, and will the transdisciplinary approach used and common ground identified allow farmers to be more resilient to future impacts of drought?

Thirdly, the study helped highlight some positive impacts and limitations of transdisciplinary research. The research team remained united, very committed to the workshop, and was able to share research results directly with the stakeholders. The two Master students were trained in supportive conditions. The team identified a new research theme based on interviews with cattle breeders: the impact of climate change on the work and mental health of farmers, a subject under-developed, except in emerging research being carried out in Australia (Berry 2011). On the social impact of the research, we were able to generate mutual listening during the workshop, thanks to the key role of the mediator. The wine growers recognised that they had not adopted the right attitude towards the breeders during the initial meeting that gathered 150 farmers. We raised awareness about the effects of climate change and the need to think collectively about adaptation. A link was established with the environmental association of the territory which has since asked us to present results at its general assembly and then solicited climatologists for two presentations on climate change (one to the mayors of Saône-et-Loire and one for the science festival). In terms of challenges, our hypothesis that jointly devising a research question and designing it with all relevant stakeholders would lead to a greater acceptance of results was only partly confirmed as some stakeholders maintained their initial position regarding the effects on generators despite the scientific analysis highlighting that trends were instead linked to climate change. In addition, integrating scientific and local knowledge was difficult due to acute tensions. In addition, the list of suggestions that closed the workshop was not taken up. The results of the work have not been disseminated in the agricultural press and a communication on hail suppression systems in the local farming journal in 2022 made no mention of the study. Farmers’ organisations have not taken any action to assist farmers directly in line with the research results. We should also mention that the regional case study was embedded in wider processes: local actors were often focussed on local climate hazards, rather than wider global climate change process; equally, they were focussed on the economic impacts of drought or hail on the farm, rather than the wider socio-economic context responsible for their current distress. The project was able to address this situation by working with a very small budget, in a very flexible way and without being constrained by the themes of a research call. We were, however, not able to extend funding of the project further.

Last but not least, this study could be valuable in relation to larger scale weather modifications, based on scalability as defined by Tsing (2015) as changing the scale without changing the action model, of these technologies targeting climate modifications. This practice, called geo-engineering, is fast becoming a topical research topic (mentioned in the last IPCC report), with emerging private and public interests mitigating the climate. In China, for example weather modification is institutionalised and deployed at a national scale with a National Weather Modification Plan. It is implemented for a range of ecological, water and food security reasons, and to prevent rain during mega-events (Chien et al. 2017). Whilst the example of China might be quite extreme, Bluemling et al. (2020) caution that interventions at the local scale provide increased legitimacy for current research on geo-engineering and implementation at the global scale. Whilst our case study can be considered local and anecdotal, it may be informative in terms of the potential social impacts of geo-engineering in relation to legitimacy and equity. As cloud water becomes a resource appropriated and managed (Chien et al. 2017), the question of “who does the sky belong to?”, asked by a workshop participant, could become a key question at the global scale. In addition to issues of legitimacy, weather modifications aiming at preventing or mitigating meteorological hazards can become a source of conflict further reinforcing existing inequity, as demonstrated in this study. All this with a backdrop of a scientific literature that is uncertain on the effectiveness of these weather modifications that might in turn generate more hazards and more uncertainties. As such, engineering local, regional or global climate highlights a risk that actors may be changing the human-weather relationship from "adaptation to the weather" to "taming the weather" (Chien et al. 2017), despite the adverse effects of these manipulations being neither totally foreseen nor controlled, but most likely resulting in environmental and social risks. Our study is also in line with the finding at broader scale that "*making use of geo-engineering technologies will not 'solve' the basic problem of the climate drift that has begun, but will reconfigure it, scientifically and politically, with considerable political and cultural consequences*" (Briday 2014, p.130).

To conclude, despite uncertainties concerning the evolution of precipitation and the resilience of the environment, the challenges of adaptation are real and agriculture will be affected—although as highlighted above, different vulnerabilities will mean that actors will be impacted differently. With the break in stationarity on the water cycle, adjustments may be insufficient and a transformative and evolutionary adaptation (Bassett and Fogelman 2013) of agricultural systems and practices will be necessary. Such adaptation will require increased mutual understanding and dialogue to allow potential conflicts to become levers for transformative change (Skrimizea et al. 2020).

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