Adaptation and sustainability of water management for rice agriculture in temperate regions: The Italian case-study

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Abstract
We review, analyse, and discuss the recent evolution and the future sustainability of rice paddy fields in Italy—the largest European producer—using outcomes from available literature and new analysis of agricultural statistics from local authorities, land-use and surface temperature data from remote sensing, hydrological and climate data from observations, and numerical models. We show that Italy can be considered a good representative for rice cultivation in temperate regions that are not freshwater-limited. However, this situation is changing. We report strong evidence linking the largest European reduction of seasonal surface water that have gradually occurred since 2000 over the rice cultivation area of Northern Italy, to the change in paddy management from traditional continuous flooding to a less greenhouse-gases-emitting practice, that is, dry-seeding with postponed flooding. This change was accompanied by several improvements in agro-practices and crop varieties. Concurrently, regional climate rapidly shifted towards sunnier weather conditions that partly contributed to higher rice yields and stability, decoupling yields from inter-annual climate variability, but also reducing water availability. In Northern Italy, a complete shift of rice cultivation towards dry-seeding is not compatible with seasonal water availability, and a number of drawbacks, with respect to the traditional wet seeding, are also identified from literature review. Therefore, in the context of near-term climate change, sustainable rice cultivation in the middle latitudes seems achievable (without limiting production and/or increasing volatility) by balancing traditional and dry-seeding.

KEYWORDS
agroecosystems, climate change, climate change adaptation and mitigation, land-use change, rice paddy fields, sustainability, water management
INTRODUCTION

The Po Valley in Northern Italy is characterized by sunny summers typical of the Mediterranean climate and large water availability from spring precipitation and runoff from the surrounding mountain ranges (Zampieri, Giorgi, Lionello, & Nikulin, 2012; Zampieri, Scoccimarro, Gualdi, & Navarra, 2015). These unique conditions, as well as the highly developed irrigation infrastructures (see Figure 1), has promoted Italy as the top European rice supplier with a production of almost 1.6 million tons of paddy in 2016 (FAOSTAT, 2018).

Italian rice is sown between the end of April and the end of May; it flowers in July, and it is harvested in September/October. During the growing season, it needs between 1,500 and 3,000 mm of water for irrigation depending on the year (Miniotti et al., 2016). Rice represents the most profitable cultivation in Northern Italy, but it also has the largest impact in terms of fertilizer and pesticides’ use (Bechini & Castoldi, 2009). It is mostly grown in the upper Po Valley (see Figure 1), especially in Piedmont and Lombardy regions, under controlled field flooding (Cesari de Maria et al., 2017). These regions alone (with about 120,000 ha and 100,000 ha of harvested fields) contributed to the 52% and 41% of the total Italian production in 2016, respectively.

The Po basin hydrological cycle is subject to large inter-annual variability related to the meteorological conditions (Montanari, 2012; Zampieri et al., 2016) that strongly affects crop yields (Ceglar et al., 2018; Zampieri et al., 2019; Zampieri, Ceglar, Dentener, & Toreti, 2017). During sunny seasons that are favourable for rice, less rain feeds rivers and channels, the watertable is lower, and larger withdrawals are needed for rice paddy fields irrigation, especially in Lombardy fields where sandy soils drain faster than in Piedmont. During cold and wet seasons, cloudiness and intense precipitation affect crop yields by reducing photosynthetically active radiation and setting the conditions for diseases and grain sterility (Jena & Hardy, 2012; Khumairoh, Lantinga, Schulte, Suprayogo, & Groot, 2018; Miniotti et al., 2016). Higher precipitation also raises the watertable and generate larger runoff and river discharge (Nikolopoulos, Anagnostou, Borga, Vivoni, & Papadopoulos, 2011).

In the temperate regions of the middle latitudes, dry-seeding with postponed flooding can be implemented to save water, save seeds, reduce labour and machinery cost, and simplify the management. However, this practice can be used when night-time temperatures are not too low (Hill, Buyer, Bocchi, & Clampett, 1991; Sipaseuth et al., 2007). In Northern Italy, low temperatures during the establishment (Ranghetti et al., 2016; Russo & Callegarin, 1997) and especially during the flowering stages (Russo & Callegarin, 1997) can also be limiting factors for rice yields. Dry-seeding was tested in Italy already in the late 1980s in order to improve the establishment in sandy soils and reduce fermentation of organic matter and infestation by aquatic weeds (Moletti, Giudici, Nipoti, & Villa, 1990). However, heavy rain events were found to hamper field preparation for dry-seeding and increase diseases risk afterwards (Moletti et al., 1990). Over the last 20 years, dry-seeding has been continuously developed and...
increasingly adopted in Italy (Ente Nazionale Risi, 2014; Ranghetti et al., 2016; Ranghetti, Cardarelli, Boschetti, Busetto, & Fasola, 2018). Compared with the traditional water seeding practice, dry seeding in Northern Italy does not reduce yields (Minioiti et al., 2016), whereas it reduces the irrigation demand of about 20% (Cesari de Maria et al., 2017) and the global warming potential of 56% with respect to continuously flooded rice paddy fields (as the reduction of methane outbalances the increase of nitrogen oxide emissions, Peyron et al., 2016).

This paper synthesizes an extensive literature review, combined with results from field experience and original analyses relevant for rice cultivation sustainability in Northern Italy, considered a good representative for the typical conditions found in the rice growing areas of the middle latitudes.

First, we introduce the study region, and we show the changing distribution of flooded rice field in May through satellite data (Section 3.1).

Then we present a classification of the world's largest rice producers in terms of the hydro-climatological drivers of inter-annual yield variability (Section 3.2), using results from observations and from hydrological model simulation driven by observed data.

We investigate the past and current links between Italian rice yield anomalies and downstream river discharge inter-annual variability (Section 3.2) as well as the regional yield sensitivity to local climate variability (Section 3.3) using observed data in two different periods (1975–1994 and 1996–2016).

We estimate current and future climatic trends over rice paddy fields in Northern Italy by analysing observations and climate model simulations (Section 3.4). We also show preliminary results of customized regional climate model experiment and surface brightness temperature analysis estimating the effects of rice flooded fields on local climate.

We finally conclude synthesizing our results in concert with the available literature (Section 4.1) and discussing the possible issues for future sustainability of rice paddy fields in Northern Italy (Section 4.2).

2 DATA AND METHODS

2.1 Study region and changing distribution of dry and wet seeded rice paddy fields

The rice field spatial distribution map (Figure 1) has been produced with CORINE 2012–layer 213 (rice paddy fields) data. The spatial distribution of irrigation channels has been provided by regional administrations (Regione Piemonte http://www.geoportale.piemonte.it/geocatalogor/index.jsp, Regione Lombardia http://www.geoportale.regione.lombardia.it/, Consorzio di bonifica Delta del Po http://www.bonificadeltadelpo.it/02-header-menu/sistema-informativo-territoriale/cartografia/).

Data of harvested areas under dry and wet seeding at the subnational level have been provided by Ente Nazionale Risi (https://www.enterisi.it/).

Qualitative estimates of changes in surface areas across 2000 are provided by the EC-JRC Global Surface Waters dataset (GSW, https://global-surface-water.appspot.com/; Pekel, Cottam, Gorelick, & Belward, 2016). The reader is encouraged to navigate the web interface of this dataset for quick diagnostic and comparison of surface water spatial distribution from 1984 to 2015 and the change occurred across 2000 at the global scale, as well as the evaluation of the amount of valid satellite images included characterizing the database. The web interface also highlights the seasonality of surface waters and of the changes.

In order to quantify the surface water change over rice paddy fields in Northern Italy, we have produced a mosaic of two cloud-free atmospherically corrected LANDSAT images for 3 years: LANDSAT-5 TM data for 1987, LANDSAT-7 ETM+ images for year 2000, and LANDSAT-8 OLI for 2016. Data were downloaded from the Earth Resources Observation and Science (EROS) Center Science Processing Architecture (ESPA) On-demand interface (https://espa.cr.usgs.gov/).

The analysed Piedmont and Lombardy regions pixels are the ones classified as rice paddy fields in the CORINE land use maps. The ratio of noise (due to cloud contamination), over the analysed areas and for the analysed years, is less than 1%. Details on the exploited LANDSAT images are reported in Table 1.

With reference to the local rice crop calendar, we selected satellite acquisitions at the end of May. In this period, paddy fields are in different conditions according to farmers’ management: already flooded in the case of traditional sowing management or still dry in the case of dry sowing and delayed field submersion (locally called ‘dry sowing’ technique).

The identification of rice-flooded fields is performed exploiting a simple threshold method based on the Normalized Difference Flood Index (NDFI; Boschetti, Nutini, Manfron, Brivio, & Nelson, 2014). NDFI is derived from satellite spectral bands sensed along the red and short wave infra-red regions and is considered one of the most sensitive approach to identify standing water. Therefore, it is often exploited in remote sensing as a proxy of rice paddy fields flooding conditions (Boschetti et al. 2014). The detection of rice flood is performed by applying a threshold value of 0.32 to the index. Such a value was identified by Ranghetti et al. (2016) as optimal in discriminating flooded and non-flooded pixels and for the creation of high resolution reference flooding maps for the case-study of Northern Italy (overall accuracy of 92% in discriminating flooded and non-flooded LANDSAT pixels for the reference period of May 2014). To further improve detections, we consider as valid only flood detections occurring for the areas identified as rice cultivation by CORINE land cover maps (CORINE land cover 1990, 2000, 2012–layer 213 rice paddy fields, European Union, Copernicus Land Monitoring Service 2018).

2.2 Global analysis of hydro-climatic drivers of yield variability

The analysis of rice yield and climate variability is conducted at country level by using FAOSTAT data (FAOSTAT, 2018; www.fao.org/
faostat/en/) and non-parametric estimators of heat stress and soil moisture anomalies over rice paddy fields, following a recently proposed methodology applied in several other studies (Zampieri et al., 2018; Zampieri et al., 2019; Zampieri, Ceglar, et al., 2017).

Heat stress and drought/water excess are estimated, respectively, by the Heat Magnitude Day (HMD, Zampieri, Ceglar, et al., 2017) and the Standardized Precipitation Evaporation Index (SPEI, Vicente-Serrano et al., 2013). The SPEI is a proxy for soil moisture inferred by the local surface water balance (e.g., precipitation minus potential evapotranspiration).

These two indicators are computed on global gridded datasets derived from climate observations and available from 1980 to 2010. They are evaluated for each grid point containing rice paddy fields and using global crop distribution and calendar information from the MIRCA2000 dataset (Portmann, Siebert, & Döll, 2010) for the identification of the (crop-dependent) higher climate sensitivity period. MIRCA2000 dataset includes multiple cropping seasons, which can be quite important for rice especially in the tropics (Zampieri et al., 2018). The HMD is computed in the last month before harvesting. The SPEI is evaluated in the last 1, 2, or 3 months before harvesting, automatically choosing the configuration that maximises the skill (as in Ceglar et al., 2018).

We aggregate the HMD and SPEI time-series at country level, and we isolate the inter-annual anomalies of yield, HMD, and SPEI from the baseline trend through a non-linear trend estimation with locally weighted scatterplot smoothing (Cleveland & Devlin, 1988).

The bilinear combination of the standardised anomalies of HMD and SPEI, that is, the Combined Stress Index (CSI), is an estimator of the yield anomalies. The CSI is built with a bilinear ridge regression at country level by using yield data from FAOSTAT (www.fao.org/faostat/en/).

An alternative version of the CSI replaces the SPEI with an indicator of non-local water transport, that is, the Standardised River Discharge Index (SRDI), which is a proxy for surface water availability computed on a global gridded hydrological simulation driven by observations (see Zampieri et al., 2018). At the global level, the CSI with the SPEI explains 6.7% of rice global production variance, whereas the CSI with the SRDI explains the 32% of rice global production variance.

The comparison at country level, in terms of explained yield variability, of the CSI-SPEI and the CSI-SRDI identifies where rice is more sensitive to the local precipitation and evapotranspiration balance versus the non-local water balance determined in the basin upstream. The sign of the regression coefficients corresponding to the SRDI allows distinguishing the countries more prone to drought with respect to the countries more affected by water excess and related factors such as cloudiness and precipitation.

### 2.3 Yield–river discharge relationships in Northern Italy

Discharge data of the Po River in Piacenza have been downloaded from the Arpa Emilia Romagna website (www.smr.arpa.emr.it/dext3r/, accessed on 13/11/2018).

Po River discharge in Piacenza is compared with FAOSTAT rice yield data. This spatial scale difference does not compromise the analysis because most of the national rice yield production is carried on in Piedmont and Lombardy, upstream of Piacenza. Two well-distinct periods, with different correlation between yield and river discharge anomalies, are identified.

These two periods are further investigated with the observed meteorological data retrieved from the EC-JRC MarsMet Archive (Biavetti et al., 2014) and available at http://agri4cast.jrc.ec.europa.eu/. Climate indicators are computed with the meteorological data over rice paddy fields, aggregated at the province level, and related to yield data for Piedmont and Lombardy provided by Ente Nazionale Risi. Because FAOSTAT data at country level are derived from Ente Nazionale Risi data, the two datasets are consistent.

Non-linear trends are removed from the yield, river discharge, and climate indicators time-series before computing the linear correlations. Statistical significance is computed according to a two-sided t test (p < .1).

### 2.4 Climate change over rice paddy fields in northern Italy

#### 2.4.1 Observed and projected climate change

Climate change projections are computed combining an ensemble of four high-resolution (i.e., ~11 km horizontal resolution) simulations contributing to the EURO-CORDEX Initiative (http://www.euro-cordex.net/). This ensemble includes the CNRM-CCLM4 regional climate model driven by boundary conditions from the CNRM-

| Satellite | Sensor | Image | Acquisition date | Path | Row |
|-----------|--------|-------|-----------------|------|-----|
| LANDSAT-5 | TM     | LT051940281987052201T1 | 1987-May-22 | 194 | 28 |
| LANDSAT-5 | TM     | LT051940291987052201T1 | 1987-May-22 | 194 | 29 |
| LANDSAT-7 | ETM+   | LE07_L1TP_194028_20000517 | 2000-May-17 | 194 | 28 |
| LANDSAT-7 | ETM+   | LE07_L1TP_194029_20000517 | 2000-May-17 | 194 | 29 |
| LANDSAT-8 | OLI    | LC08_L1TP_194028_20160521_20170324_01_T1 | 2016-May-21 | 194 | 28 |
| LANDSAT-8 | OLI    | LC08_L1TP_194029_20160521_20170324_01_T1 | 2016-May-21 | 194 | 29 |
CERFACS-CM5 general circulation model, KNMI-RACMO22E driven by ICHEC-EC-EARTH, IPSL-INERIS-WRF331F driven by IPSL-CM5A-MR, MPI-CCLM4 driven by MPI-ESM-LR). These models do not account for land-use changes.

The climate change signal diagnosed in the recent period is compared with the corresponding estimate from the EC-JRC MarsMet data set.

2.4.2 Climate effects of dry-seeding estimated by regional climate modelling experiment

We design a simplified regional climate model experiment to provide a first estimate of the surface temperature response to paddy field flooding by using the WRF-ARW model version 3.6.1 (Shamarock et al., 2008). This model is implemented on a mesh composed by 100 × 100 grids of 10 × 10 km horizontal resolution, centred at 45°N and 10°E, and having 36 vertical levels with variable resolution, increasing close to the surface. The model parameterizations include the Noah land-surface model (Niu et al., 2011).

The model is initialised and driven by ERA-Interim reanalysis data (Dee et al., 2011) for 2003. The spin-up run starts the 1st of January. In April and May, two experiments are performed using different land cover categories over the area where the biggest reduction of flooding has been observed by using LANDSAT data (Figure 2). The ‘inland water’ category is used for the control run, corresponding to flooded areas in the period before 2000. Scenario model run is performed by replacing the above mentioned land use category with mixed cropland, as a proxy for conditions imposed by dry sowing in the rice paddy fields.

2.4.3 Climate effects of dry-seeding estimated by satellite data

To obtain an estimation of the temperature change induced by the change in management practice from traditional to dry-seeding, we analyse satellite time-series of land surface temperature (LST) over designated areas in the study zone.

The first step consists in identifying plausible fields in which either dry-seeding or conventional seeding has occurred. To do this, we use a series of Sentinel-2 multispectral imagery with a spatial resolution of 10 m to detect the plausible dates of the first observable flooding events. All available images during the period covering 1 April 2018 until 30 June 2018 have been downloaded from the Schub (https://scihub.copernicus.eu/). These images were atmospherically corrected using the Simplified Model for Atmospheric Correction algorithm (SMAC, Rahman & Dedieu, 1994) using the Aerosol Optical Density product (AOD, MYD04_3k collection 6) from the MODIS instrument as a dynamic input. Cloud and shadow detection was done based on the Sen2cor algorithm.

As in Section 2.1, flood occurrence is identified by applying the NDFI and selecting values exceeding 0.32. Areas of dry-seeding are then defined by constraining the first observable flooding event being after May 15, whereas areas where the first flooding event occurs before this date are tagged as traditional sowing. It should be noted that although this technique is able to detect flooding events with confidence, it cannot be expected to map exhaustively all events (some may be masked by clouds for instance). Therefore, the identified fields should be considered as a sample of existing fields and not as an exhaustive inventory.

FIGURE 2 (a) Paddy harvested areas by regions and by different sowing practices from official statistics (courtesy of ENTERISI). Rice flooded fields’ distribution derived from selected satellites images: (b) 1987 (LANDSAT-5 Thematic Mapper), (c) 2000 (LANDSAT-7 Thematic Mapper), and (d) 2016 (LANDSAT-8 Operational Land Imager) [Colour figure can be viewed at wileyonlinelibrary.com]
The LST values are obtained from the MODIS instrument on-board of both AQUA and TERRA platforms (collection 6 products MYD11A1 and MOD11A1; Wan et al., 2015). These data are available at 1-km spatial resolution but with a combined subdaily revisit frequency at four different times of the day (around 1:30 and 13:30 for MODIS AQUA and 10:30 and 22:30 for MODIS TERRA). Due to cloud cover and occasional suboptimal conditions of measurements, not all values of LST are usable. Here, we select only those flagged as having the highest levels of quality by the MODIS production team, resulting in time-series with gaps.

For each 1-km grid cell of this MODIS dataset, we calculate the fraction covered by either dry-seeding and traditional seeding, as identified from the Sentinel-2 images in the previous step. Because fields are usually smaller than 1 km² and not all fields can be identified, these fractions may underestimate the real proportion of the signal coming from a given rice management type. In absence of any systematic bias, we can assume that dry and traditional seeding are estimated with equivalent degrees of confidence. Time-series in which the proportion of dry sowing is larger than that of traditional sowing by more than 10% are considered to be dominated by dry-seeding, whereas the reverse is done to isolate population representing traditional sowing.

3 | RESULTS

3.1 | Study area and change of surface waters due to rice dry-seeding

Figure 1 shows the study area and the spatial distribution of rice paddy fields. The spatial distribution of irrigation channels reflects the strong level of anthropization in the region.

Figure 2 shows the footprint of dry-seeding adoption in northern Italy as seen by satellite and the related official rice harvested area statistics since 2004 (ENTERISI data, see also Figure S1 that shows the evolution of the total rice harvested area in Italy since 1961).

Dry seeded fields steadily increased until 2012. The sudden drop recorded in 2013 is a consequence of the intense precipitation events occurred during establishment (Cesari de Maria et al., 2017; Miniotti et al., 2016). In 2016, 44% of national rice paddy fields were dry seeded. In Piedmont/Lombardy, the transition characterised 28%–69% of fields (i.e., 32,000 ha/70,000 ha).

The reduction of surface water extent related to dry-seeding in Northern Italy is also evident from the analysis of individual satellite images in order to specifically diagnose the flooded rice paddy fields (Boscetti et al., 2014; Ranghetti et al., 2016, 2018) in May for the years 1987, 2000, and 2016 (Figure 2b–d; see Section 2). These images suggest a larger transition over Lombardy that is in agreement with the official statistics (Figure 2a). The larger reduction of flooded area occurred particularly after 2000, consistently with previous estimates (Ranghetti et al., 2018).

Similar analysis on the GSW data at the European scale reveals a larger area of spatially coherent surface water changes across year 2000 only in the Danube Delta region, because of a mix of natural and anthropogenic processes (Giosan, Constantinescu, Filip, & Deng, 2013; Habersack et al., 2015; Jugaru Tiron et al., 2009).

Although uncertainties and gaps affect satellite data especially in earlier times, this analysis strongly suggests that the adoption of rice dry-seeding in Northern Italy produced the second larger change of surface water of all Europe and the first one related to anthropic drivers only. The only larger change across year 2000 occurred in the Danube Delta, related to a mix of natural and anthropic drivers.

3.2 | Relationship between rice yields and surface hydrology in a global perspective

Figure 3 shows the characterization of the estimated relationship between rice yield anomalies and hydro-climatic indicators accounting for heat and water balance anomalies for the main rice producing countries.

Figure 3 shows the different amount of inter-annual yield variability that can be explained using a non-local water balance indicator (SRDI) instead of the local water balance indicator (SPEI).

There are countries (South Korea, Brazil, Peru, Mali, and Nigeria) where rice yield variability is better captured by the local water balance indicators (bottom quadrants in Figure 3) as expected for rainfed rice cultivations. The results for Japan are only partially consistent. On the other hand, there are important producers where the correlations
substantially improve by considering the non-local water balance indicator.

In China, India, Nepal, Bangladesh, and Thailand, yield variability is better captured by the SRDI, and the sign of the regression coefficient is positive (top right quadrant in Figure 3). This is the expected behaviour for irrigated rice in paddy fields where freshwater availability represents a limiting factor.

A third set of countries (Uruguay, Italy, Argentina, North Korea, and the United States) is better correlated to the SRDI than to the SPEI, but the sign of the regression coefficients is negative (top left quadrant in Figure 3). In these countries, rice paddy fields are not freshwater limited. Thus, high river discharge could be considered as a proxy of cold and wet seasons that are unfavourable for the vegetative phase. More detailed analysis using the observed river discharge data for Italy (Figure 4) from 1971 to 2016 also points to a statistically significant anti-correlation with rice yield anomalies (Figure 4b; \( r = -0.64, p \text{ value} < .01 \)). This correlation is stronger before 1995, but it depends on the integration period of river discharge (Table S1). The correlation starts being significant when May is included and increases when the period is extended until October. In the recent period, yield anomalies are correlated with the river discharge in October only.

The maximum yield loss in the available data occurred in 1977 with an anomalies of 1.5 tons/ha (28% of the baseline value). In that year, the maximum river discharge anomaly was observed with an integrated value of about 18 billion m³ from June to September (Figure 4b), associated with floods in Piedmont (Audisio & Turconi, 2011). The anti-correlation in the pre-1995 period remains significant removing 1977.

The lower river flows that occurred in 1990, 2003, 2005, 2007, and 2012 are associated to warm and dry seasons (Fontana, Toreti, Ceglar, & De Sanctis, 2015; Res et al., 2018).

During the period 1971–2016, yield has steadily increased from 5 tons per hectare to almost 7 tons per hectare (Figure 4a). At the same time, river discharge data exhibit an overall significant negative trend during the rice-growing season (Table S2). Nevertheless, yield and river discharge trends are not related with each other, as yield increase is mainly due to improved management, varieties, and CO₂ fertilization effect while water availability was not a limiting factor (see Section 4).

3.3 Rice yields and climate variability in Northern Italy

For Italy, we have found a sharp separation between two periods, suggesting that the sensitivity of yield anomalies to inter-annual climate variability suddenly disappeared in the mid-1990s (Figure 4). In order to explain the decoupling of rice yield and river discharge, we analyse the links between regional rice yields and meteorological indicators in the two 21-year periods (1975–1995 and 1996–2016) computed with the meteorological dataset MarsMet (see Section 2). Figure 5 shows the results for Piedmont and Lombardy.

In Piedmont, there were strong positive (negative) correlation between yield anomalies and daytime maximum temperature (precipitation) anomalies in July. The same link between precipitation and yield anomalies is found in Lombardy as well. Data suggest a negative influence of precipitation events in Piedmont in August as well. These statistically significant correlations between climate indicators and yield anomalies disappear after 1995.

This result is consistent with the change in correlation between yield and downstream river discharge anomalies discussed in the previous section. However, the inspection of the individual correlations between yield anomalies and the different climatic indexes in

![Figure 4](b) Anomalies w.r.t. the baseline values.
Piedmont and Lombardy during the growing season provides a more detailed description of the changes that occurred during the 1990s.

Increased sensitivity to minimum temperature is found during May in Piedmont after 1995. This feature could be related to changes in varieties or agro-management rather than to changes in climate (see Section 4.1). However, available data do not allow to fully explain it.

In Lombardy, after 1995, yields become positively correlated to temperature until September (consistently with the hypothesis that the crop is favoured by sunnier climate) and to precipitation in June (consistently with the additional water required by delayed flooding).

At the end of the growing season, in October, yields are negatively affected by warm temperature anomalies in Piedmont and especially in Lombardy, probably because of the shortening of the grain filling period. These relationships do not change between the two periods.

In the next section, we perform a deeper analysis of the climate change signal over rice field, shading light on some of the results obtained on the correlations between climate and yield inter-annual variability.

### 3.4 | Climate change over rice paddy fields in Northern Italy

Rice paddy fields in north-western Italy are characterised by a bimodal precipitation annual cycle with two peaks in spring and autumn of about 100 mm and large inter-annual variability (Figure 6a). Summers tend to be drier, as a reminiscence of the Mediterranean climate in this transition region (Zampieri et al., 2012; Zampieri et al., 2015). The seasonal cycle of maximum and minimum temperatures reaches its unique peak around July with 29°C and 18°C, respectively.

Figure 6b displays the difference of Oclimate observed between periods 1975–1995 and 1996–2016. In the last 21 years, a significant reduction of more than 20 mm of rain is found in May, July, September, and October. This drying trend very likely explains the reduction of sensitivity to high precipitation and low temperatures found in Piedmont and into a lesser extent in Lombardy.

Temperatures warmed up significantly during all the growing season. In spring, we diagnose almost 2°C warming during the day. Minimum temperatures passed from 6.7 ± 0.9°C to 7.9 ± 1.0°C in April from 10.7 ± 1.3°C to 12.2 ± 1.0°C in May, surpassing the minimum critical threshold for the suitability dry-seeding in cold climates (Sipaseuth et al., 2007).

Future climate change projections computed from an ensemble of regional climate models simulations (see Section 2.1) show a non-significant warming of less than 1°C for the near future (2021–2040) with respect to the current climate (i.e., 1996–2016), independently from the emission scenario (Figure 6c). Conversely, a statistically significant warming is estimated for 2051–2070 (Figure 6c). In this period, mean temperatures higher than 2°C with respect to the present climate can affect the growing season from the mid to the end under the higher emission scenario RCP8.5. The projected changes of precipitation are not significant.

Preliminary analysis of numerical simulations conducted with the regional climate model shows that the land-use change corresponding to dry-seeding contributed in the opposite way, especially during the night (see Figure 7). In particular, numerical experiments suggest that total conversion to dry-seeding would have resulted in a change of surface energy balance producing an average cooling of (−0.81 ± 0.31°C). The cooling is larger and more stable during the night (−1.1 ± 0.49°C). During the day, the cooling is reduced and more variable.
FIGURE 6  (a) Seasonal cycles of monthly precipitation (blue lines), maximum and minimum temperatures (red and green lines, respectively) estimated over rice paddy fields in Northern Italy (Piedmont and Lombardy, EC-JRC meteorological data). Thinner lines represent the two standard deviation ranges corresponding to the inter-annual variability. (b) Mean changes between the periods 1975–1995 and 1996–2016 derived using EC-JRC data. Projected changes in monthly precipitation cumulates, minimum and maximum temperature that for period 2021–2040 (panel c) and 2051–2070 (panel d) with respect to 1996–2016 according to regional climate models simulations for high (RCP8.5) and moderate (RCP4.5) emission scenarios. Black dots indicate whether the changes are statistically significant [Colour figure can be viewed at wileyonlinelibrary.com]

FIGURE 7  Mean surface temperature differences between regional climate model simulations imposing dry or flooded rice paddy fields in April and May 2003 [Colour figure can be viewed at wileyonlinelibrary.com]
Thus, the diurnal temperature range at 2 m is increased by dry-seeding, consistently with the expectations. The cooling signal due to dry-seeding was completely outbalanced by the regional rapid warming recorded in Northern Italy.

The effect of dry-seeding on land surface temperatures (LST) is also estimated from satellite observations for 2018 (Figure 8). When comparing nearby locations in cloud-free conditions, dry-seeding reduces night-time surface temperatures (−1.53 ± 0.37°C at 22:30 and −1.40 ± 0.19°C at 01:30) and increases daytime surface temperatures (1.44 ± 0.70°C at 10:30 and 1.69 ± 1.23°C at 13:30), amplifying the diurnal cycle compared with wet seeded fields in qualitative agreement with the regional model experiment (the model result reflects the difference in 2 m temperatures over all days, whereas the satellite result reflects the difference of surface temperatures on cloud-free days).

4 | DISCUSSION

4.1 | Concurrent changes accompanying dry-seeding in Italy

The combined changes affecting the rice agricultural system and the environment in the last 40 years are shown in Figure 9, grouped by the main aspects of the agricultural, environmental and climate system:

4.1.1 | Rice yield

Increasing yields and decreasing sensitivity to climate characterize the general evolution of rice cultivation in Northern Italy (Figure 4). Unfavourable weather conditions (i.e., cold and rainy days) were negatively affecting yields before 1995 (Figure 5). These conditions are common to the other main rice producers of the middle latitudes (Figure 3, upper left panel). Amongst other factors, rice yields increase because of the CO₂ fertilization effect of about a 0.088%/ppm (Ainsworth, 2008) to 0.095%/ppm (Kimball, 2016). Atmospheric CO₂ concentration passed from 330 ppm in 1970 to the current value of about 410 ppm (407 ppm in 2016), so it could be responsible for up to 6.8–7.3% increase of yield. Therefore, one fourth of the observed rice yield increase in Italy could be due to the increase of CO₂. The remaining portion is presumably due mostly to improved varieties and management.

4.1.2 | Climate

The region was characterised by a rapid warming and drying in spring and summer because of natural climate variability (i.e., positive shift of the Atlantic Multidecadal Oscillation occurred in the mid-1990s (Zampieri, Toreti, Schindler, Scoccimarro, & Gualdi, 2017) superimposed to the general global warming. The change in summer was very likely favourable for rice yields. In spring, preliminary results show that dry-seeding land-use change is associated to a significant
amplification of the diurnal temperature range and to a general cooling of the region, albeit smaller than the warming due to natural and anthropogenic climate change (Figures 6 and 7). If these results are confirmed, it would mean that dry-seeding partly compensated the warming produced by climate change and the change of circulations patterns. The negative temperature feedback associated to dry-seeding land-use change is represented by the solid upward arrow in Figure 9. The AMO shift in spring is also associated to larger rain versus snow ratio (Zampieri, Scoccimarro, & Gualdi, 2013) in the surrounding mountains and to the shift towards earlier river discharge (Zampieri et al., 2015).

4.1.3 | Agromanagement

The main change is constituted by the adoption of dry-seeding with no negative effects on yields and yields variability (Miniotti et al., 2016). This transition was accompanied by development in varieties and agromanagement practices (seeds amount, seeding patterns, fertilizations, etc.; Moletti et al., 1990). Land levelling with laser-equipped machine has been also implemented in the field preparation phase. Weed control has been evolved introducing new products (as only water-soluble products were available in the 1980s). The new varieties, however, require more fertilizer and are less competing with weeds. Since 2006, new genotypes selected in Louisiana that are less resistant to shock by low temperature in microsporogenesis started spreading and now cover a surface of 70,000 ha. Dry-seeding cropping system in Northern Italy decreases emission of methane but increase those of nitrogen oxide, with a combined effect of reducing the global warming potential of 56% (Peyron et al., 2016). This effect is represented by the dashed arrow in Figure 9.

4.1.4 | Water management

River discharged during the rice growing season decreased in the last 40 years as a result of drying climate (Zampieri et al., 2013; Zampieri, Toreti, et al., 2017). Dry-seeding saves about 20% of water at the beginning of the growing season when the water abundance in the river is still high. However, it requires larger irrigation in June to raise the water table and flood paddy field. This coincides with a period of lower water availability (Zampieri et al., 2015) and higher water competition with other crops such as maize (Zampieri et al., 2019). This factor constitutes the main limitation for the sustainability of dry-seeding adoption in Italy, which has already reached its maximum potential in this respect.

4.1.5 | Environment

Increase in environmental pollution from herbicides, needed in the dry-seeding practice (Rao, Johnson, Sivaprasad, Ladha, & Mortimer, 2007), is likely, but not quantified for Italy yet. On the other hand, high soil solution nitrate concentration is already identified as the greatest environmental constraint of dry-seeding cropping system (Miniotti et al., 2016), jeopardizing river and groundwater quality. However, nitrate concentration in the groundwater is almost everywhere contained below 25 L⁻¹ in Piedmont and Lombardy (EU Knowledge Hub Water and Agriculture https://water.jrc.ec.europa.eu/). An emerging constraint is the arsenic (As) concentration in the soils, as rice is an important pathway for inorganic As dietary intake and the rate of As absorption increases with dry-seeding (Tenni et al., 2017). However, monitored concentrations are still below the acceptable limits indicated by the EU, and agronomic strategies are being
investigated to control and ameliorate food safety (Tenni et al., 2017). Considering ecosystems, dry-seeding could bring some serious drawbacks as traditionally flooded rice paddy fields provide habitat for spring migrants and locally breeding birds (Imperio, Ranghetti, & Hardenberg, 2017). Noteworthy, the regional administrations (Regione Lombardia and Regione Piemonte) implemented effective alternatives for preserving wetlands ecosystems though ‘nature-based’ waste water and flood protection plants, albeit at a small spatial scale (Liquete, Udias, Conte, Grizzetti, & Masi, 2016).

4.2 | Future perspective

As for the future, climate projections results computed on an ensemble of high-resolution regional climate models suggest a slower warming compared with what has been already observed in the last decades. An emerging climate risk appears in the higher emission scenario after 2050 (Figure 6) as maximum daily temperature will exceed the 33°C threshold (Luo, 2011), offsetting the positive effect of higher atmospheric CO₂ concentrations (Chaturvedi, Bahuguna, Shah, Pal, & ET AL, 2016). The corresponding 1-month delay of paddy field flooding most probably produced the largest anthropic seasonal surface water reduction detectable in the whole Europe and corresponded to a significant decrease of greenhouse gases emissions (Peyron et al., 2016).

Local experiments have shown how dry-seeding can save water in the early stages of crop growth (Cesari de Maria et al., 2017) and that dry seeded rice yields are compatible with those ones obtained with the traditional continuous flooding practice (Miniotti et al., 2016). This agro-management change was made possible by several adaptation measures, but it was likely also favoured by rapid climatic change towards sunnier weather conditions that occurred in the mid-1990s (Zampieri, Toreti, et al., 2017). Our analysis also highlighted a sharp decrease of climate influence on yields’ variability during the 1990s.

However, rice dry-seeding could endanger sustainable water management in Northern Italy. In fact, the entire mountain ranges surrounding the region experienced rapid warming and drying trend (Zampieri et al., 2013) associated with earlier runoff generation (Zampieri et al., 2015) and decrease of water availability during the rice growing season (see Figure 4, Table S2). In addition, dry-seeding saves water at the beginning of the growing season (Cesari de Maria et al., 2017) when availability is high, whereas it requires more water later in the season (June/July) when the availability is lower (Zampieri et al., 2015) and the competition within the sector and with other sectors is higher. In this respect, dry-seeding has already reached its maximum potential (Associazione Irrigazione Est Sesia and Associazione Irrigazione Ovest Sesia, “Note for the Ministry of Agriculture, Piedmont Region and Lombardy Region,” 10th January 2018).

Furthermore, dry-seeding would increase nitrate water contamination (Miniotti et al., 2016) and disrupt wetland ecosystems (Imperio et al., 2017). For all these reasons, a sustainable balance between dry seeded field and conventionally flooded fields has to be attained.

Our analysis also highlights several issues for sustainability that are not directly related to dry-seeding (Figure 9). However, public monitoring tools are now provided by the European Union to raise awareness on environmental issues related to water and agriculture (https://water.jrc.ec.europa.eu/).

We have shown preliminary results diagnosing a significant local climatic effect due to the flooded rice paddy fields that are increasing the diurnal temperature range and cooling down the entire region (Figures 7 and 8). Ongoing research will better characterize and quantify the effects of paddy fields on cloudiness, precipitation, and runoff at larger scales as well.

Analysis of current climate and future scenarios suggest that high temperatures around flowering and during the grain filling period might represent an additional emerging constraint. Future projections do not show further significant changes of precipitation in the near future nor in the medium term. Further development of decadal prediction systems is going to bring significant support to shape sustainable and resilient cropping systems in the context of climate change.

4.3 | Final remarks

Rice cultivation in Italy was subject to profound agro-management changes in the last 40 years (Figure 9), the most prominent being the introduction of dry-seeding practice.

The corresponding 1-month delay of paddy field flooding most probably produced the largest anthropic seasonal surface water reduction detectable in the whole Europe and corresponded to a significant decrease of greenhouse gases emissions (Peyron et al., 2016).

CONTRIBUTIONS

M. Z., A. T., and A. C. designed the research. M. Z., A. C., G. M., E. S., and G. D. performed the analyses. C. R. and M. R. contributed with data. V. D. and Z. P. produced the regional climate model experiments. M. Z. drafted the manuscript, and all authors contributed to the final version.
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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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