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AGRIDE-c, a conceptual model for the estimation of flood damage to crops: development and implementation

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Abstract. This paper presents AGRIDE-c, a conceptual model for the assessment of flood damage to crops, in favour of more comprehensive flood damage assessments. Available knowledge on damage mechanisms triggered by inundation phenomena is systematised in a usable and consistent tool, with the main strength represented by the integration of physical damage assessment into the evaluation of its economic consequences on the income of the farmers. This allows AGRIDE-c to be used to guide the flood damage assessment process in different geographical and economic contexts, as demonstrated by the example provided in this study for the Po Plain (north of Italy). The development and implementation of the model highlighted that a thorough understanding and modelling of mechanisms causing damage to crops is a powerful tool to support more effective damage mitigation strategies, both at public and at private (i.e. farmers) levels.

1 Introduction

On a global scale, floods are among the most common and damaging natural hazards (EEA, 2017; CRED, 2019). As climate change continues to exacerbate extreme meteorological events, flood-prone areas and flood-related damage are expected to grow rapidly in the future (Van Alst, 2006; Wobus et al., 2017; Alfieri et al., 2018; Mechler et al., 2019). To cope with this increasing risk, the EU Floods Directive (Directive 2007/60/EC) requires member states (and, in particular, river basin districts) to periodically develop flood risk management plans, which are the operational/normative tools for the definition of flood risk mitigation strategies, including a blend of structural and non-structural measures. These measures must be identified on the basis of a reliable and comprehensive assessment of costs and benefits related to the implementation of alternative strategies (Jonkman et al., 2004; Mechler, 2016), i.e. on cost-benefit analyses (CBAs), which implies a public choice based on the assessment of welfare change associated with public investments. In fact, CBAs would require a comprehensive estimation of the costs and benefits produced by the adoption of different strategies (Jonkman et al., 2004; Mechler, 2016), with benefits consisting in the avoided losses to all exposed sectors and at different temporal scales (i.e. direct and indirect long-term damage).

Present damage modelling capacity is mainly focused on direct damage to people (injury, loss of life) and their property (for some exposed assets, typically residential buildings), thus preventing the possibility of performing comprehensive flood damage assessments and, consequently, CBAs (see e.g. Ballesteros-Cánovas et al., 2013; Saint-Geours et al., 2015; Meyer et al., 2013; Shreve and Kelman, 2014; Arrighi et al., 2018). On the contrary, the importance of developing new and reliable models for more inclusive flood damage assessments has been highlighted in recent investigations of past flood events (Pitt, 2008; Jongman et al., 2012; Menoni et al., 2016), showing that losses to the different sectors count differently according to the type of the event and the affected territory. To partially cover this gap, this paper deals with the estimation of flood damage to the agricultural

Table 1. Papers in the Scopus database for different research keywords (last access: January 2019).

Keyword search	Number of papers
"Flood damage"	4036
"Flood damage" and "crop"	81
"Flood damage" and "agriculture"	71
"Flood damage" and "building"	284
"Flood damage" and "infrastructure"	122

sector, by presenting a new conceptual model for the estimation of flood damage to crops.

In the literature on flood damage modelling, agriculture has received less attention than other exposed sectors so far, as demonstrated in Table 1, showing the number of papers in the Scopus database for different research keywords. Reasons may include (i) the (perceived) minor importance of agricultural losses compared to those of other sectors, especially because flood damage assessments are usually carried out in urban areas (Förster et al., 2008; Chatterton et al., 2016); (ii) the paucity of empirical data for understanding damage mechanisms and deriving prediction models; and finally (iii) a policy shift, especially in Europe after the 1980s, when the subsidies to agriculture were being challenged by the increase in agricultural surpluses under the Common Agricultural Policy, along with the incentivisation of insurance coverage for damage to farms, which led most public authorities responsible for damage compensation to be less interested in the agricultural sector. However, it must be stressed that flood risk management has been the concern of agricultural policies for many years, as since the 1930s, and probably up to the mid-1980s, agricultural policies were focused on land drainage (i.e. the removal of problems caused by the excess of water on/in the soil), of which flood protection was a critical part (Morris, 1992; Morris et al., 2008). Still, literature related to land drainage is often difficult to retrieve and did not converge in the more recent studies on flood damage modelling, as much of the work is reported in grey literature (see e.g. Hallett et al., 2016).

Available damage models for agriculture are not only few in number, but are also affected by many limitations, the major ones being the paucity of information/data for their validation and the large variability of the local features affecting damage (i.e. the strong linkage with the context under investigation), which limit their transferability to different contexts more than other exposed sectors such as the residential and commercial ones; accordingly, the first requirement for a new damage model is its possible application in a wide variety of geographical and economic contexts. Experience gained in flood damage assessment for other sectors highlighted that a broad generalisation is often not possible, as damage models must be able to capture the specificities of the investigated area, in terms of both hazard and vulnerability features (Cammerer et al., 2013). Still, a general conceptualisation of the problem is conceivable in terms of main variables influencing the damage mechanisms, cause–effect relationships, etc.

Based on these considerations, this paper presents AGRIDE-c (AGRIculture DamagE model for Crops), a conceptual model for the estimation of expected flood damage to crops (i.e. ex ante estimation). AGRIDE-c has the ambition of generality, i.e. to be valid in different geographical and economic contexts, supplying a useful framework to be followed any time the estimation of flood damage to crops is required, in which the main components of the problem at stake are identified as well as its relevant control parameters. While the model structure aims to be generally valid, the analytical expression of its components must necessarily be specific to the local physical characteristics of the area as well as to the standards of the agricultural practices and to the type of crops under analysis, given the large variability characterising the agricultural sector. The implementation of the conceptual framework of AGRIDE-c is exemplified in this paper in relation to the Po Plain – north of Italy. The case study is completed with a spreadsheet (available as supplementary material in Molinari et al., 2019b) for the calculation of damage to crops, which can be adapted to other contexts.

The paper is organised as follows. Section 2 reviews the state of the art of modelling of flood damage to crops, as the starting point of the research. Section 3 presents the AGRIDE-c model, while Sect. 4 describes in detail its implementation in the Po Plain. Section 5 provides a critical discussion on limits and strengths for the effective application of AGRIDE-c and conclusions are finally drawn in Sect. 6.

2 State of the art of flood damage modelling for crops

Prominent examples of damage models for crops are reported in Table 2. The analysis of the table indicates that the main differences among models are related to the input variables describing the inundation scenario (hazard) as well as the response of the exposed elements to flooding (vulnerability). Beyond hazard parameters usually considered in damage modelling for other exposed sectors (i.e. water depth, flow velocity, flood duration, sediment, and contaminant load), for crops a key role is played by the period of the year, generally the month of the flood event, as damage is strongly dependent on crop calendars (USACE, 1985; Morris and Hess, 1988; Hussain, 1996; Read Sturgess and Associates, 2000; Citeau, 2003; Dutta et al., 2003; Förster et al., 2008; Agenais et al., 2013; Shrestha et al., 2013; Vozinaki et al., 2015; Klaus et al., 2016) that, in their turn, depend on the climate of a region: this is one of the reasons that make damage models for crops strongly context specific. Indeed, crop calendars delineate the vegetative stage of the plants at the time of the flood (which strongly affects the damage suffered by the plants) for any crop type, with crop type being the only vulnerability parameter often considered by the models. In the case of mesoscale models (Kok et al., 2005; Hoes and Schuurmans, 2006), this parameter is replaced by the agricultural land use. No model in Table 2 considers the behaviour of farmers after the occurrence of the flood (e.g. the decision to abandon the production or to continue with increasing production costs), which has been shown to strongly influence the damage sustained by the farm (Pangapanga et al., 2012; Morris and Brewin, 2014).

With respect to the approach, only a few literature models are directly derived from field observations of flood consequences on crops: this is mainly due to the scarcity of observed damage data (Brémond et al., 2013; Chatterton et al., 2016) for models derivation/calibration. In fact, most of the models adopt a synthetic approach based on the expert investigation of causes and consequences of damage. In this regard, some models in Table 2 are labelled as "physically based", i.e. damage is first described in terms of physical susceptibility of the crop and consequent yield reduction, and then converted into economic impact on the income of the farmers. Instead, in "cost based" models damage is assessed only considering production costs sustained by farmers during the year, by implicitly assuming (according to our interpretation) that the yield is totally lost in case of flood, although in practice this not always happens (Posthumus et al., 2009; Penning-Rowsell et al., 2013; Morris and Brewin, 2014). Whatever the adopted approach, a comprehensive model for damage to crops should consider the (inter)correlation between the two aspects: actual yield reduction, as a function of hazard and vulnerability variables, and saved/increased production costs due to the occurrence of the flood (Pivot and Martin, 2002; Posthumus et al., 2009; Morris and Brewin, 2014).

With respect to the monetary evaluation, damage can be expressed as percentage of the net margin (USACE, 1985; Read Sturgess and Associates, 2000; Agenais et al., 2013; Shrestha et al., 2013) or of the gross output (Citeau, 2003; Dutta et al., 2003; Förster et al., 2008; Vozinaki et al., 2015; Klaus et al., 2016) for the farmer. From another point of view, some models express damage in absolute terms (thus depending on local prices and costs) while others express damage in relative terms, as a percentage of a maximum exposed value. Finally, the last column of Table 2 indicates that damage models for the agricultural sector are hardly validated, mainly due to the scarcity of empirical damage data discussed before; a partial exception is represented by the models by Förster et al. (2008) and Shrestha et al. (2013).

Overall, the state of the art depicts a fragmented scenario, characterised by the existence of a few, case-specific, and poorly documented models, only partly capturing the available knowledge on flood damage to crops, due to several simplifying assumptions. In this context, the use of existing models for the assessment of flood damage outside the contexts for which they were proposed is not a feasible option. Indeed, limited information on the rationale behind model development, like for instance on the adopted approach (whether empirical or synthetic, and, in the second case, whether physically or cost based), on the components of the model (in terms of included cost items, modelled physical processes), and on the characteristics of the region for which the model was derived (in terms of crop calendars, standard agricultural practices, etc.), prevents the identification of those models that may be suitable for application in a given study area. Nonetheless, it is not possible to implement existing models as "black box models" (for example, for a preliminary estimation of damage) due to the lack of observed damage data for their validation.

In order to exemplify possible problems arising in the application of existing models, we tested the approaches proposed by Förster et al. (2008) and Agenais et al. (2013) to estimate the relative damage to a 1 ha area cultivated with maize. The implementation was quite straightforward as both models supply damage in relative terms. Although the models are theoretically comparable, as they refer to similar contexts (Germany and France), sharing both climate characteristics and crop calendars (for maize, seeding in April and harvest in September–October), they produced significantly different results, as reported in Fig. 1, where the models are applied for three different values of the water depth and two different flood durations.

For example, for short-duration floods (3 d), Agenais et al. (2013) estimate the maximum damage in April–May for shallow water depths with a further peak of damage in July–August for higher water depths, while Förster et al. (2008) estimate the maximum damage in September–October, no matter what the value of the water depth is.

The main reason for this inconsistency lies in the different modelling approach adopted by the two models: physically based in the case of Agenais et al. (2013) and cost based in the case of Förster et al. (2008) Correspondingly, Agenais et al. (2013) estimate the maximum damage corresponding with the most fragile vegetative phases of the crop, i.e. growth (April–May) and flowering (July–August), while Förster et al. (2008) reproduce increasing costs sustained by farmers during the vegetative cycle well, resulting in maximum damage at the harvesting phase (September–October). A further source of inconsistency among the two models is related to the different set of input variables, as Agenais et al. (2013) consider water depth as a control parameter, while Förster et al. (2008) do not, thus leading to different damage estimations even for a given flood duration. At last, a further source of error may be represented by the conversion from relative to absolute damage; indeed, while the relative model by Agenais et al. (2013) is derived by referring to the net margin, the relative model by Förster et al. (2008) refers to the gross output. Given that conventions do not exist on translating relative damage into absolute terms, the choice of the wrong reference value could amplify inconsistency between the two approaches.

Table 2. Analysis of state-of-the-art flood damage models for crops.

State and country	Crop types	Hazard parameters	Vulnerability aspects	Modelling approach		Monetary evaluation approach	Validation
				Empirical vs. expert based	Cost vs. physically based		
AGDAM/Hazus (USACE, 1985) – USA	Generic crop	Duration, time of occurrence (month)	Crop type	Not specified	Cost based (supposed)	Relative – damage as a percentage of the net margin	Not specified
Morris and Hess (1988) – UK	Grassland	Time of occurrence (expressed in terms of vegetative stage)	Vegetative stage	Expert based	Physically based (i.e. damage functions give yield reduction due to the flood + information on additional/saved costs)	Absolute	No
Hussain (1996) – Bangladesh	Rice	Water depth, duration, sediment concentration, time of occurrence (growing stage)	Vegetative stage	Expert based	Physically based (i.e. damage functions supply yield reduction because of the flood)	Relative – no monetary evaluation	No
RAM (Read Sturgess and Associates, 2000) – Australia	Grassland, generic crop	Duration, time of occurrence (month)	Crop type	Expert based	Cost based	Absolute – damage as a percentage of the net margin	Not specified
Citeau (2003) – France	Maize	Water depth, duration, velocity, time of occurrence (month)	Crop type	Expert based	Cost based (supposed)	Relative – damage as a percentage of the gross output	No
Dutta et al. (2003) – Japan	Beans, Chinese cabbage, dry crops, melon, paddy, vegetable with roots, sweet potato, green leave vegetables	Water depth, duration, time of occurrence (month)	Crop type	Empirical	Not specified; in fact, the model can be adapted to both a cost-based and a physically based approach by varying the loss factor related to the time of the year	Relative – damage as a percentage of the gross output	No
Standard method (Kok et al., 2005) – the Netherlands	Generic agricultural land	Water depth	Agricultural land use	Expert based	Not specified	Relative – not specified	Not specified
Hoes and Schuurmans (2006) – the Netherlands	Maize, orchards, cereals, sugar beet, potatoes, other crops	Water depth	Agricultural land use	Not specified	Not specified	Relative – not specified	No
Förster et al. (2008), Klaus et al. (2016) – Germany	Grain crops (wheat, rye, barley, corn), oilseed plants (canola), root crops (potatoes and sugar beets), and grassland	Duration, time of occurrence (month)	Crop type	Mixed (empirically expert based)	Cost based (supposed)	Relative – damage as a percentage of the gross output	Yes, for one flood event
Agenais et al. (2013) – France	Wheat, barley, canola, sunflower, maize, vegetables, grassland, alfalfa	Water depth, duration, time of occurrence (week)	Crop type, vegetative stage	Expert based	Physically based (i.e. damage functions give yield reduction due to the flood + information is supplied on additional/saved cultivation costs)	Absolute	No
Shrestha et al. (2013) – Mekong Basin	Rice	Water depth, duration, time of occurrence (expressed in terms of vegetative stage)	Vegetative stage	Not specified	Not specified	Relative – damage as reduction of the gross output	Yes (partial)
Vozinaki et al. (2015) – Greece	Tomatoes, green vegetables	Water depth, flow velocity, time of occurrence (month)	Crop type, vegetative stage	Expert based	Physically based (i.e. damage functions supply yield reduction due to the flood)	Relative – damage as a percentage of the gross output	No

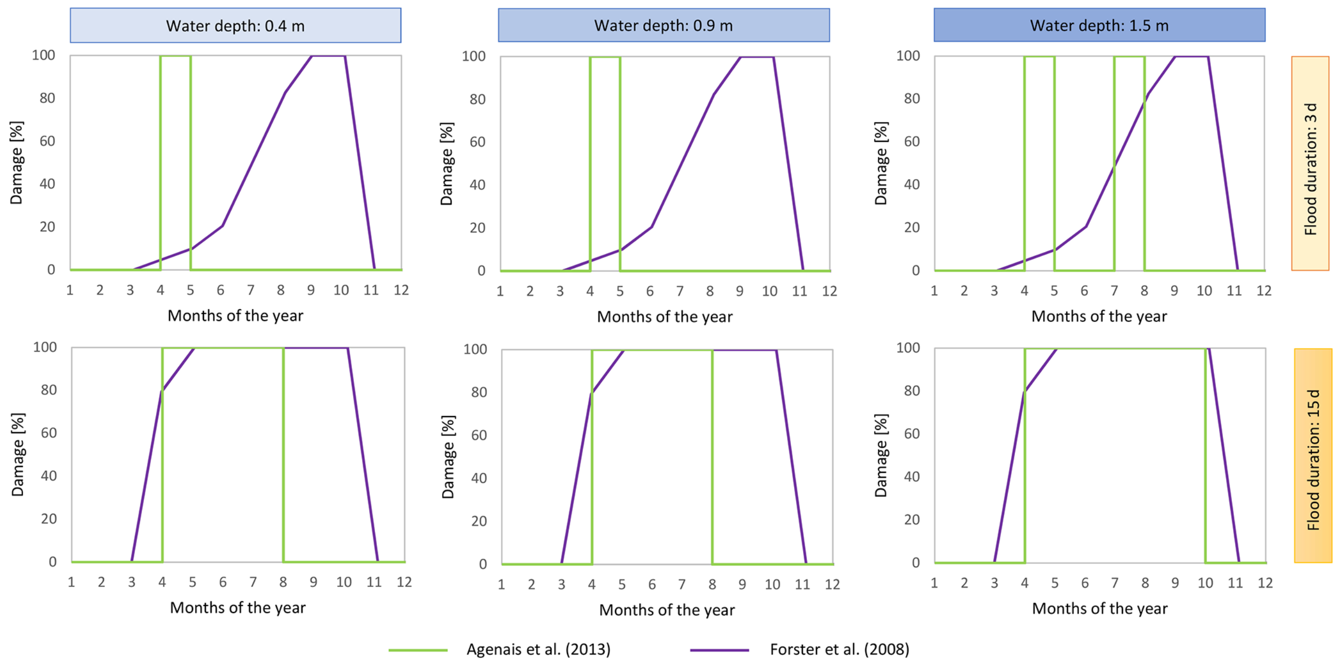

Figure 1. Comparison between relative damage supplied by Förster et al. (2008) and Agenais et al. (2013) for a 1 ha maize plot, for two values of flood durations and three values of water depth.

In view of the above considerations, there is a need to organise available knowledge on flood damage mechanisms in a comprehensive and general framework that can be adapted to any context, by taking into account the specificities of the area under investigation. This was the main reason which led us to develop the AGRIDE-c model, described in detail in the next section.

3 Conceptual model of AGRIDE-c

AGRIDE-c has been developed by adopting an expert-based approach, encapsulating and systematising the available knowledge on damage mechanisms triggered by inundation phenomena, as well as on their consequences in terms of income for the farmers. The result of this process is a general, conceptual framework, which identifies the different aspects to be modelled for the assessment of flood damage to crops, their (inter)connections, and the variables at stake. Still, as stressed before, the implementation of the model (that is the derivation of an analytical expression for each of its components) must be context specific, as damage to crops depends on many local features that cannot be generalised. An example of the implementation of the model for the Po Plain is supplied in Sect. 4.

Knowledge at the base of AGRIDE-c has been derived by a thorough investigation of the literature (Sect. 2) and by consultation with experts. More specifically, experts were involved to support the definition of the conceptual model, by following an iterative process. In the first step of the process, a semi-structured interview was conducted, by asking experts about the main damage mechanisms/phenomena for crops in case of flood, important explicative variables, and possible interconnections among them; moreover, results from the literature review were proposed for their judgement. In the following step, experts were asked to evaluate a draft version of the conceptual model drawn according to the literature review and results from first interviews. Then, there was an iterative revision of improved versions of the model until an agreement on its final structure was reached. Three kinds of experts were involved in the process: (i) a representative of one of the Italian regional authorities responsible for agricultural damage management and compensation, with more than 20 years of expertise in the management and compensation of flood damage to farms in the Lombardy Region; (ii) two agronomists of a local association of farmers (Coldiretti Lodi), with specific knowledge of the Po Plain context and with direct experience in managing floods in the last 20 years (the viewpoints of several individual local farmers who experienced flooding in the past years were also included in the analysis, as the two agronomists asked them for direct data and information to support their considerations); and (iii) an academic economist, with specific expertise in agriculture.

It must be highlighted that the conceptual model has been designed to supply an estimation of flood damage only to annual crops (i.e. not including perennial crops) under the following assumptions:

- infrequent flooding events (i.e. effect of two, or more, consecutive floods is not considered);
- flooded agricultural plot devoted to a single crop type, with possible reseeding using the same crop type in case of flood;
- time frame of the analysis limited to one productive cycle: long-term damage, in particular, reduction of soil productivity in the following cycles, is not taken into account.

In addition, AGRIDE-c does not consider damage to other components/elements of the farm that may induce additional damage to crops, such as, for instance, damage to machinery and equipment (e.g. irrigation system) that may prevent cultivation for a period (Dunderdale and Morris, 1997; Posthumus et al., 2009; Agenais et al., 2013; Brémond et al., 2013; Morris and Brewin, 2014). Only short-term impacts on soil are included, based on the evidence that, during a flood, damage to soil and crops is concurrent, different from damage to the other components, which can occur or not independently from the damage to the vegetal material. As a consequence, damage to soil and crops is modelled together, while damage to the other components can be modelled as separated factors.

The model structure is depicted in detail in Fig. 2. Absolute damage (D) for an individual farmer is expressed as the difference between the reduction in the gross output (ΔGO) and the increase or decrease in production costs (ΔPC), as a consequence of the flood of a specific crop. This is equal to considering absolute damage as the change in the net margin (NM = GO − PC, where GO is gross output and PC indicates production costs over a production cycle, typically a year) due to the flood, compared to the case when no flood occurs (i.e. Scenario 0):

$$D = \mathrm{NM}_{\mathrm{noflood}} - \mathrm{NM}_{\mathrm{flood}} = (\mathrm{GO}_{\mathrm{noflood}} - \mathrm{GO}_{\mathrm{flood}}) - (\mathrm{PC}_{\mathrm{noflood}} - \mathrm{PC}_{\mathrm{flood}}) = \Delta\mathrm{GO} - \Delta\mathrm{PC} \quad . \qquad (1)$$

Accordingly, relative damage (d) can be obtained by dividing the absolute damage by the net margin in the Scenario 0 ($\mathrm{NM}_{\mathrm{noflood}}$).

$$d = D/\mathrm{NM}_{\mathrm{noflood}} = 1 - \mathrm{NM}_{\mathrm{flood}}/\mathrm{NM}_{\mathrm{noflood}} \qquad (2)$$

AGRIDE-c combines a physical and an economic model to evaluate the absolute damage. In this way, the problems of consistency among physically based and/or cost-based models discussed in Sect. 2 are overcome, with both aspects being explicitly taken into account.

The physical model (identified by the yellow dashed box in Fig. 2) is composed of two sub-models, for the evaluation of physical damage to crops (i.e. the plants) and impact on soil. In fact, as previously stated, among the different components/elements of the farm that may induce damage to crops, only damage to soil is considered in AGRIDE-c.

The model for the assessment of physical damage to soil calculates the amount of soil that is damaged, the kind(s) of damage suffered by the soil and the reduction of soil fertility, as a function of the duration of the flood, the water velocity, the sediment, the salinity (in the case of coastal flooding), and the contaminant load. In particular, the model takes into account processes like erosion, deposition of sediments, and contamination (which affect the costs for soil restoration) as well as the soil fertility (which affects the quality and the quantity of the harvest). In addition, the model estimates the effect of possible waterlogging, as a consequence of an increase in the level of the field water table, in terms of soil fertility reduction and (prolonged) soil saturation, which may increase costs for restoration because of the necessity of land drainage. It must be noted that, although in the European context floods usually have a negative effect on soils, some studies (e.g. Tockner et al., 1999; Hein et al., 2003) pointed out that such events can also have clearly positive effects, namely in the form of an increase in soil fertility, explained by a (re)distribution of river sediments and organic matter in the course of flooding that replenishes carbon and nutrients in topsoil.

The model for the assessment of the physical damage to crops calculates the reduction in the amount and quality of the harvest due to the flood, as a function of the features of the flood (i.e. time of occurrence and intensity) and of the type of affected crop. Indeed, the occurrence and the severity of damage mechanisms leading to yield decline (like root asphyxiation, contamination, development of diseases, and parasites) mainly depend on flood intensity, i.e. water depth, water velocity, flood duration, sediment, salinity and contaminant load, and field water table; still, different crops withstand flood impacts in different ways according to their physical features as well as their vegetative stage at the time of occurrence of the flood (Rao and Li, 2003; Setter and Waters, 2003; Zaidi et al., 2004; Araki et al., 2012; Ren et al., 2016).

The economic model of AGRIDE-c (identified by the green dashed box in Fig. 2) consists of two sub-models as well: one for the evaluation of the reduction in the gross output and one for the assessment of the increase or decrease in production costs compared to the no-flood scenario, whereas production costs include direct, avoidable costs, like field operation costs, and direct fixed costs. The first model calculates ΔGO as the reduction in the gross output due to a reduced yield and to a decrease in the price of the crops because of a lower-quality harvest; the second model evaluates ΔPC as the additional costs required to restore the flooded soil (including land drainage costs) and to carry out additional cultivation practices for continuing the production (typically, reseeding), as well as saved costs in the case of abandoning crops. Indeed, farmers can react in different ways to alleviate flood damage, according to the vegetative stage at the time of occurrence of the flood and the physical damage suffered by the plant (Agenais et al., 2013; Pivot et al., 2002). The

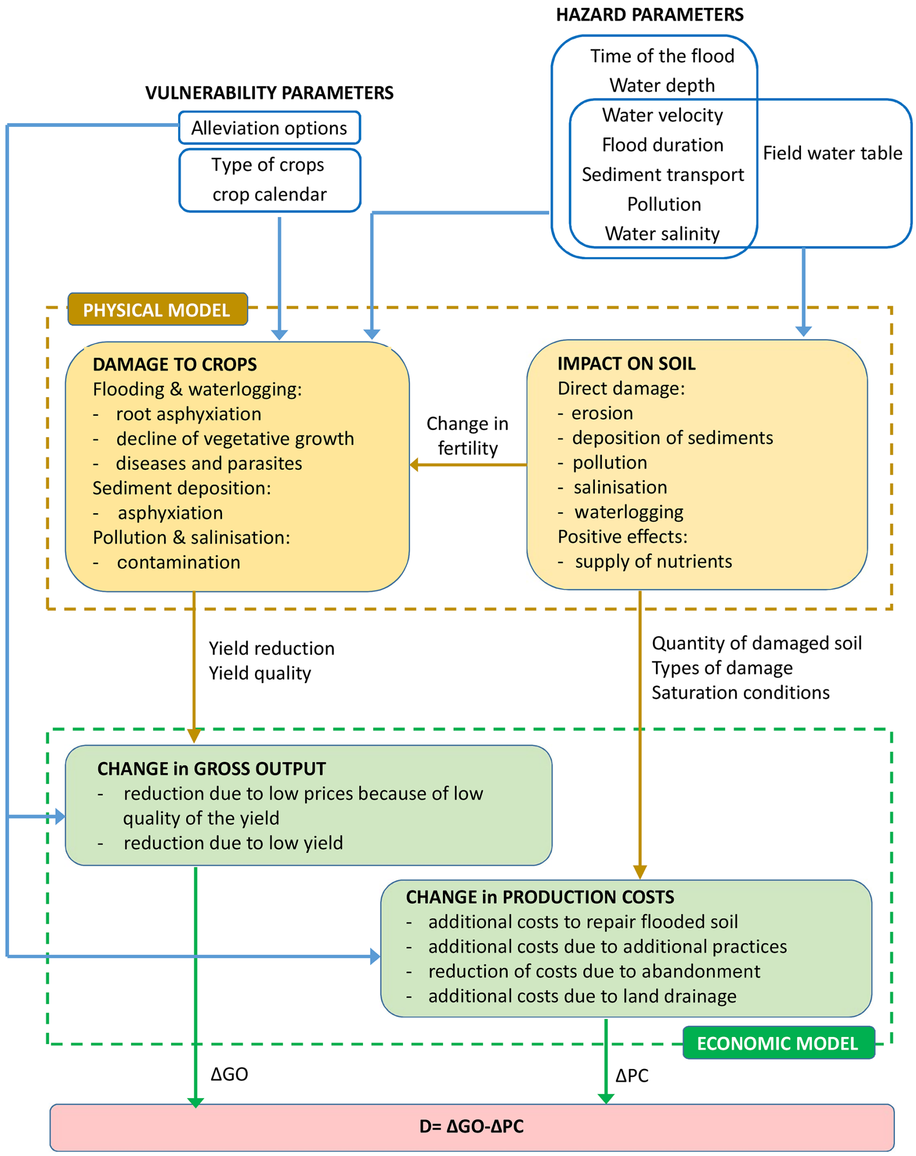

Figure 2. Conceptual model of AGRIDE-c.

first possible strategy is continuing when flood damage implies none or minor yield loss. The second strategy is reseeding a new (late) crop; this strategy is possible only in certain periods of the year according to the vegetative cycle of the crop. Finally, when the yield loss is severe, farmers can decide to abandon the production. ΔPC strongly depends on the strategy adopted by the farmer which, in turn, depends on the actual yield loss. For example, after an event causing a physical loss corresponding to 50 % of the expected yield, a farmer can decide to continue the production or to abandon it. In the first case, the yield reduction will be just 50 % of the expected yield, while the farmer must sustain all the costs which are still necessary to conclude the vegetative cycle. The second case will result instead in a total crop loss (100 %), the additional cost of restoring soil, and saving part of the production costs.

4 Implementation of the model for the Po Plain

As previously discussed, while the conceptual structure of AGRIDE-c has a general validity for different geographical and economic contexts, the analytical expression of its sub-models must be context specific. In this section, we provide an example of implementation for the Po Plain – north of Italy – which can serve as guidance for the definition of the sub-models of AGRIDE-c in other regions. The first step for the development of the model in a given area consists in the identification of the typical features of flood events occurring in the area as well as the main cultivated crops. The second step consists in the calculation of the net margin for the farmer in Scenario 0, by considering the amount of production (yield), selling prices of the crops, and time and costs of cultivation practices in the absence of any flood. Third, analytical expressions for all the processes shown in Fig. 2 are derived, and then, starting from Scenario 0, flood effects on crops (i.e. the damage) are evaluated for different times of occurrence, flood intensities, and damage alleviation strategies.

Table 3 summarises the main general data required by the conceptual model and the values and information used in the application for the Po Plain (example of maize). Data sources are clarified in the following subsections.

The implementation of the conceptual model in the Po Plain was supported by specific knowledge of local experts. In particular, several individual meetings were organised with the aim of obtaining context-specific information related to crop calendars, yields and prices, type, timing, and costs of the different cultivation practices.

4.1 Hazard and vulnerability features in the Po Plain

In order to identify the representative features of the floods and the main crops cultivated in the investigated area, we chose the province of Lodi (Lombardia region) as representative of hazard phenomena and agricultural activities in the Po Plain.

The last significant event that occurred in the province, i.e. the flood of the Adda River in November 2002 (AdBPo, 2003, 2004; Rossetti et al., 2010; Scorzini et al., 2018), highlighted riverine long-lasting floods, characterised by medium to high water depths (mean value: 0.9 m), low flow velocities (mean value: 0.2 m s^{-1}) and low sediment and pollution loads in the flooded areas as typical of the region; accordingly, the main hazard parameters to be included in the analytical expression of AGRIDE-c for the Po Plain are limited to water depth, flood duration, and time (month) of flood occurrence.

The analysis of the agricultural cadastral data (supplied by the regional authority) in a buffer of 1 km around the Adda River indicated grain maize, wheat, barley, and grassland as the most common crops in the area; the model for maize is discussed hereinafter, while the models related to other crops are reported in the Supplement.

4.2 Characterisation of Scenario 0

Scenario 0 is characterised in terms of the annual net margin for the farmer, per hectare, in the case that no flood occurs; this implies the estimation of the annual gross output and the distribution of production costs over the year.

Given that the vegetative cycle of grain maize in the Po Plain covers 1 year, the gross output is estimated as the product between the average yield and price for grain maize

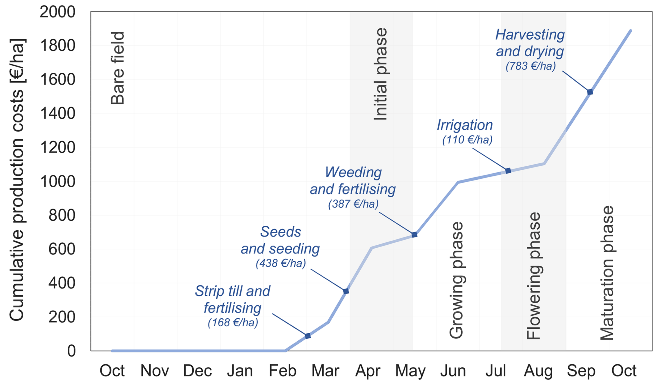

Figure 3. Po Plain case: production costs over the year for grain maize, in the case of minimum tillage.

over the period 2013–2017 (data sources: Regione Lombardia and Borsa Granaria di Milano; Milan crop stock market), equal to 175 q ha^{-1} (here "q" refers to a quintal, or 100 kg) and EUR 16.92 q^{-1}, respectively. In addition, we also consider the annual EU contributions for agriculture as a further potential income for the farmer and, in detail, the subsidies given to agricultural activities in case of the application of minimum tillage and crop rotation, equal respectively to 300 and EUR 150 ha^{-1} (data source: PSR – Programma di Sviluppo Rurale, Regione Lombardia: http://www.psr.regione.lombardia.it, last access: 16 November 2019).

Concerning production costs, the type, period of the year and costs of the different cultivation practices for grain maize were identified with the support of discussions with experts and consultation of regional price books (data source: APIMA – Associazione Provinciale Imprese di Meccanizzazione Agricola delle Province di Milano, Lodi, Como, Varese: Tariffe 2013–2017 delle lavorazioni meccanico agricole c/terzi, i.e. price lists for agricultural operations by contractors). All agricultural operations have been considered to be direct, avoidable costs, as interviewed local experts indicated that in Lodi province most field operations are carried out by contractors. Figure 3 reports the distribution of costs over the year, with indication of the corresponding vegetative stages of the plant.

Finally, fixed costs sustained by farmers (like management costs) are assumed to be a portion (5 %) of the gross output. Based on these data, the analysis results in a net margin for the farmer in case of no flood equal to EUR 1376 ha^{-1} yr^{-1}.

It is important to stress that, in the case of application of AGRIDE-c as a tool for supporting investment decisions, both costs and prices need to be adjusted to a common price base (year N) in order to account for the effect of inflation, if appropriate.

Table 3. Summary of input data required by AGRIDE-c: exemplification for the Po Plain.

Conceptual model		Implementation for the Po Plain (example of maize)	
	Input parameters	Modelling and input values	Data sources
Physical model			
Damage to crop	As shown in Fig. 2	Transferred and adapted from Agenais et al. (2013)	Agenais et al. (2013) and expert consultation
Impact on soil	As shown in Fig. 2	Soil restoration considered as a fixed cost (EUR 500 ha^{-1})	APIMA (2013–2017) and expert consultation
Economic model			
Gross output	Crop yield	175 q ha^{-1}	Regione Lombardia (2013–2017)
	Unit price for crop	EUR 16.9 q^{-1}	Borsa Granaria di Milano (2013–2017)
	Other (e.g. EU contributions)	EUR 150 ha^{-1} for crop rotation; EUR 300 ha^{-1} for minimum tillage	PSR Regione Lombardia
Production costs			
Variable costs	Depend on crop type and cultivations practises/strategies	As shown in Fig. 3 and Table 4	APIMA (2013–2017) and expert consultation
Fixed costs		Assumed equal to 5 % of the gross output	Experts consultation

4.3 Damage to crops

Physical damage to crops is estimated by the physical model developed in France by Agenais et al. (2013). This choice is supported by different considerations. First, the independent hazard variables considered by the authors (for maize water depth and flood duration) are coherent with the typical flooding characteristics identified for the Po Plain (Sect. 4.1), i.e. riverine long-lasting floods with low flow velocity. Second, their model can be easily transferred to other regions, independently from crop calendars, as they use the vegetative phases of the crop (and not the months of the year) as the time variable for the occurrence of the flood. Finally, local agronomists expressed a favourable opinion on the suitability of this model in the examined region, as emerged from discussions held during the interview process.

An example of the physical damage model for maize is depicted in Fig. 4 (adapted from Agenais et al., 2013). The model consists of susceptibility functions giving the yield reduction due to the flood (as a percentage of the yield in Scenario 0), on the basis of water depth and flood duration, for four different vegetative stages (i.e. seeding, growing, flowering, and maturation). Let us consider, for example, the growing stage: for a flood lasting less than 5 d the model gives a null yield loss, independently from the water depth; conversely, a flood lasting more than 12 d results in a total loss. For floods with intermediate duration, in absence of specific information in the original model and in accordance with the opinion of local experts, we assumed a linear yield reduction (from 0 % to 100 %) between 5 and 12 d, adapting the model to the context under investigation. The use of this model implies that, at present, we do not take into account either the reduction in the quality of the yield due to the flood or the effect of damage to soil (i.e. reduction of soil fertility) on yield quality and production; reason for such limitations is simply the lack of literature and data on these topics (see also Sect. 4.4).

4.4 Impact on soil

Concerning the physical impact on soil, only the negative effects of floods were computed as, according to local experts, increase in soil fertility due to floods is infrequent in northern Italy. Likewise, waterlogging after floods is not relevant in the investigated area and has been neglected.

For the estimation of physical damage to soil, no models were found in the literature investigating the complex chemical and mechanical processes leading to soil erosion, contamination and asphyxiation due to sediment deposition. Also, interviewed experts were not able to parameterise the possible types of damage, the amount of damaged soil, and the reduction in soil fertility as a function of hazard features. For these reasons, at present, the model is based on the simplified assumption that soil always requires restoration in case

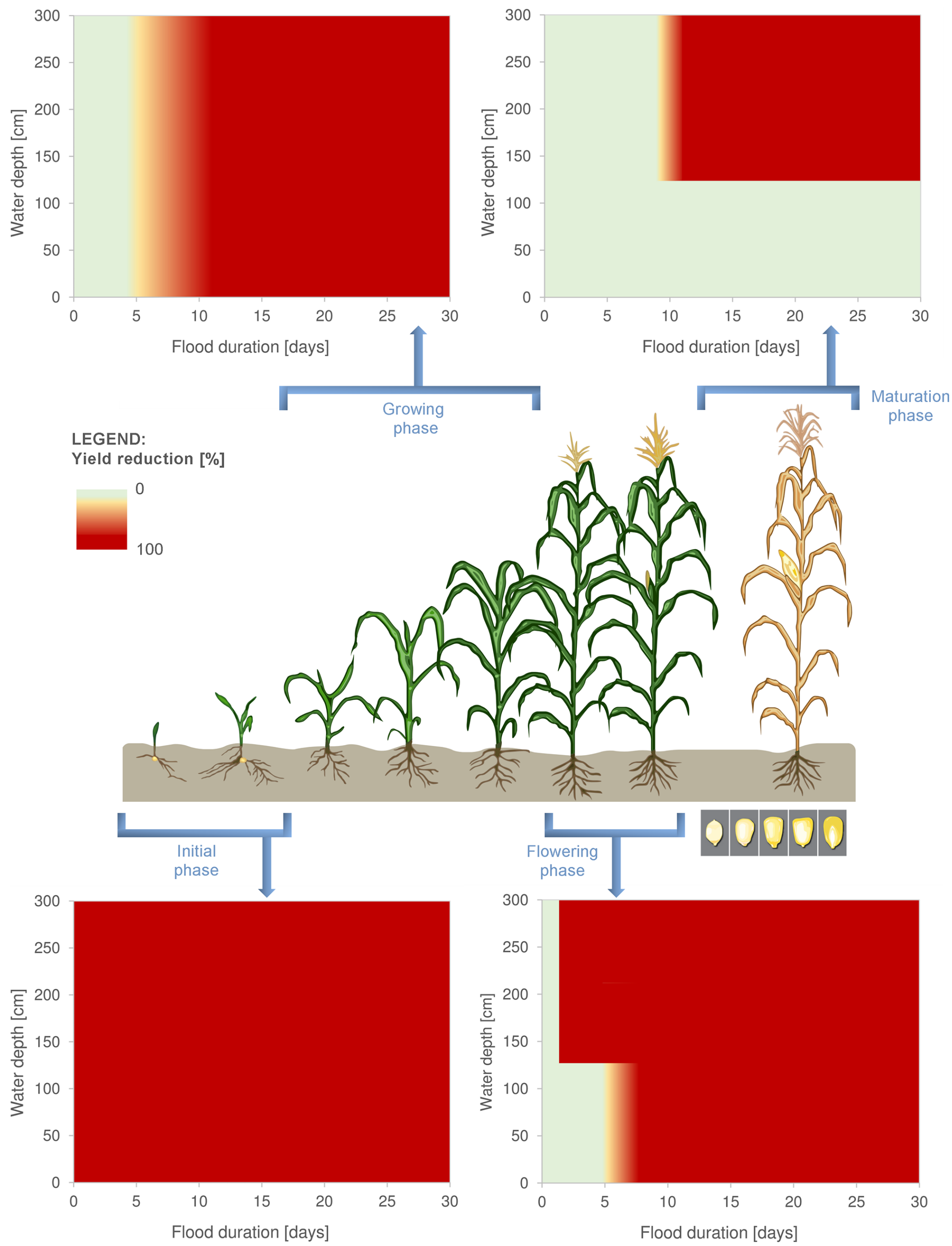

Figure 4. Physical damage to maize as a function of vegetative stage, flood depth, and duration (adapted from Agenais et al., 2013).

of flood (consisting in the removal of sediments and in the levelling of terrain) and that no reduction in soil fertility occurs. Indeed, in the context under investigation, erosion and contamination are not expected because of the low velocity and limited contaminant load characterising typical floods in the region (see Sect. 4.2).

The choice to include the damage-to-soil component in the implementation of AGRIDE-c, although in this simplified way, was driven by two main reasons: comprehensiveness of the model and importance of this subcomponent in the overall flood damage figure to agriculture. In particular, this last point clearly emerged during the interviews with local experts, who pointed out the occurrence of such damage even for flood events characterised by shallow water depths and not particularly high flow velocities. According to estimation of necessary operations supplied by interviewed experts and regional price books (data source APIMA), restoration costs have been considered here, in a first instance, as fixed costs equal to EUR 500 ha^{-1}.

4.5 Alleviation strategies

After the recession of the flood, farmers make a choice among the possible strategies that can be adopted to alleviate damage; literature investigation and discussions with experts indicated three main strategies, their feasibility being necessarily linked to the damage suffered by the plants, which, in its turn, depends on the flood intensity and the vegetative stage of the plants at the occurrence of the flood: continuing the production, abandoning the production, reseeding. The choice among these strategies influences both yield reduction and production costs because of additional or avoided cultivation practices consequent on continuation or the abandonment of the production; such practices and related costs have been identified for the Po Plain, with the support of experts and regional price books (Table 4).

Continuing the flooded crops is suggested when flood damage implies none or minor yield loss; in this case, yield reduction is equivalent to that supplied by the physical model of Fig. 4 as a function of hazard features, while additional costs are only due to soil restoration (see Sect. 4.4). Abandoning the production can be an option when flood damage is severe. This strategy always leads to a 100 % yield reduction; soil restoration is still required, but some production costs can be avoided according to the time of the occurrence of the flood (i.e. remaining time to harvest). Reseeding is an alternative strategy to abandoning when flood damage is severe, but it is possible only until June, by using late maize crops. Results presented in this paper are obtained by adopting the simplified assumption that late reseeding does not imply a yield reduction, in either quantity or quality. In fact, the use of late crops generally implies a yield reduction with respect to traditional crops, reduction that increases as the time of reseeding approaches the maturation phase, and that varies with the different species of late crops and climates, generally ranging from 10 % to 30 % (Lauer et al., 1999; Tsimba et al., 2013; Dobor et al., 2016; Abendroth et al., 2017). Given the high variability of yield loss with these two variables (i.e. time and species), a reference value was not identified in the literature or in discussion with experts; however, users of AGRIDE-c have the option to set a proper value of the expected yield reduction for late (re)planting for the context under investigation, in the spreadsheet supplied in the Supplement (Molinari et al., 2019b). Beyond additional costs required to restore the flooded soil, reseeding implies further additional costs related to the preparation of the terrain, the purchase of new seeds, and the seeding operations.

4.6 Damage estimation

According to the conceptual model in Sect. 3 and assumptions described in the previous subsections, damage (D) is estimated for different times of occurrence of the flood (i.e. month), flood intensities (i.e. water depth and flood duration), and damage alleviation strategies as the difference between ΔGO and ΔPC:

$$D = D\ (\text{month, water depth, flood duration, alleviation strategy}) = \Delta\text{GO} - \Delta\text{PC} \quad . \tag{3}$$

In detail, ΔGO and ΔPC are calculated on the basis of yield reduction and additional and avoided costs, as reported in Table 4. The resulting damage function has a fixed component due to soil restoration costs, to be added to the costs, which varies with the flood characteristics and the alleviation strategy.

As an example of damage estimation, Fig. 5 shows changes in production costs and gross output for maize cultivation, for three different flood scenarios. Values of the annual gross output and of cumulative production costs are reported for both Scenario 0 and the flood scenario under investigation, with respect to every alleviation strategy farmers can implement according to the intensity of the flood, its time of occurrence, and the physical damage suffered by the plant. Differences of production costs and turnover between "flood" and "no-flood" scenarios allow the calculation of the damage D for the farmer.

The first scenario (Fig. 5a) refers to a November flood. In this month, the plant is in the break stage, so no yield loss is expected for any flood intensity (Table 4). Farmers will then continue the production with additional costs limited to those required to restore the flooded soil for a total of EUR 500 ha^{-1} (Table 4), which is the absolute damage sustained by farmers.

The second scenario (Fig. 5b) refers to a flood in June, when the plant is in the growing stage. According to the physical model described in Fig. 4, in this phase damage depends only on flood duration, while water depth has no effect on it. Figure 5b refers to a 5 d flood, which leads, as given by the physical model, to a yield reduction of 12.5 %. Given the low physical damage, farmers can decide to continue the production or to reseed. In the first case (green line), the gross output decreases by 12.5 % (due to yield reduction), while production costs increase due to additional costs for soil restoration, resulting in an absolute damage for the farmer equal to about EUR 870 ha^{-1}. In the second case (blue line), no reduction in the gross output occurs because reseeding would allow 100 % of the yield, while additional production costs include both soil restoration and reseeding costs, resulting in an absolute damage of EUR 1106 ha^{-1}. Figure 5b shows that, although possible in theory, abandoning the production is not a reasonable choice as absolute damage equals EUR 2568 ha^{-1} due to a yield reduction of 100 % (the only income for the farmer consists of the EU contributions for cultivation) against a saving of production costs of about EUR 389 ha^{-1}.

Finally, Fig. 5c refers to a flood occurring in September; in this period (i.e. maturation phase of the plant), damage depends on both water depth and flood duration. Figure 5c refers in particular to a 10 d flood with a water depth above

Table 4. Yield reduction and change in production costs for grain maize on the basis of damage alleviation strategy adopted by farmer.

Time of the flood	Vegetative stage	Alleviation strategy	Yield reduction (%)	Additional costs	EUR ha^{-1}	Avoided costs	EUR ha^{-1}
November–March	Bare field	Continuation	0	Soil restoration	500		
April–May	Initial phase	Abandoning	100	Soil restoration	500	Weeding and fertilising Irrigation Harvesting and drying	387 110 783
		Reseeding	0	Soil restoration Strip till and fertilising Seeds and reseeding	500 168 438		
June	Growing phase	Continuation	see Fig. 4	Soil restoration	500		
		Abandoning	100	Soil restoration	500	Irrigation Harvesting and drying	110 783
		Reseeding	0	Soil restoration Strip till and fertilising Seeds and reseeding	500 168 438		
July–August	Flowering phase	Continuation	see Fig. 4	Soil restoration	500		
		Abandoning	100	Soil restoration	500	Irrigation Harvesting and drying	55 783
September–October	Maturation phase	Continuation	see Fig. 4	Soil restoration	500		
		Abandoning	100	Soil restoration	500	Harvesting and drying	783

1.30 m. According to the physical model (Fig. 4), this flood scenario leads to a 50 % yield loss. Farmers then have two choices.

If production is continued the gross output decreases by 50 % and additional costs are required to restore the flooded soil, resulting in an absolute damage equal to EUR 1980 ha^{-1}. In case of abandonment, absolute damage equals EUR 2677 ha^{-1} because of a yield reduction of 100 % and saving of production costs of EUR 283 ha^{-1}.

Previous considerations can be repeated for the different months of the year and hazard scenarios. Figure 6 displays the ensemble of the results of damage estimation for all the investigated cases, thus defining the AGRIDE-c model for the Po Plain, for grain maize crops. In particular, the figure reports the relative damage with respect to the net margin in the case of no inundation, $d = D/\mathrm{NM}_{\mathrm{noflood}}$, estimated by the model, for the different months of flood occurrence, flood intensities (i.e. water depth and flood duration), and damage alleviation strategies. The "dash" symbol means that the corresponding strategy cannot be adopted or is not reasonable in the flood scenario under investigation. For example, in the "bare field" season, reseeding is not possible because of climatic reasons, nor is continuation possible as no cultivation is in place; continuation does not make sense when a 100 % yield loss is expected as in the "initial phase" or in the "flowering" stage when $h \geq 1.3$ m; reseeding with late crops is possible only until June. Equivalent tables for the other investigated crops are reported in the Supplement.

5 Discussion

The AGRIDE-c model, by enabling the estimation of the expected direct damage to crops in the case of flood, represents a powerful tool to support more informed decisions on flood risk management for both public and private stakeholders. AGRIDE-c contributes to overcoming the limitations of present CBAs, by providing a more comprehensive estimation of flood damage, thus supporting a better definition and choice of public actions for risk mitigation. In addition, the inclusion of damage to agriculture in CBAs is fundamental, especially when the interventions involve floodplains devoted to agricultural activities, including "integrated river basin management" projects and river restoration actions (Morris and Hess, 1988; Morris et al., 2008; Rouquette et al., 2011; Brémond et al., 2013; Massaruto and De Carli, 2014; Guida et al., 2016). Clearly, the tool must be critically used, e.g. by considering possible transfers of losses/gains between farmers from an economic perspective, according to the temporal and spatial scales of the analysis.

The development of AGRIDE-c and its implementation in the Po Plain highlighted that a thorough understanding and modelling of damage mechanisms to crops (i.e. of the interaction between damage-influencing factors and characteristics of exposed elements leading to a loss) are also useful to orient the behaviour of farmers towards more resilient practices, such as the selection of the most resilient crops to be cultivated in areas prone to flooding, the choice of the best alleviation strategy to be followed once flooding occurs,

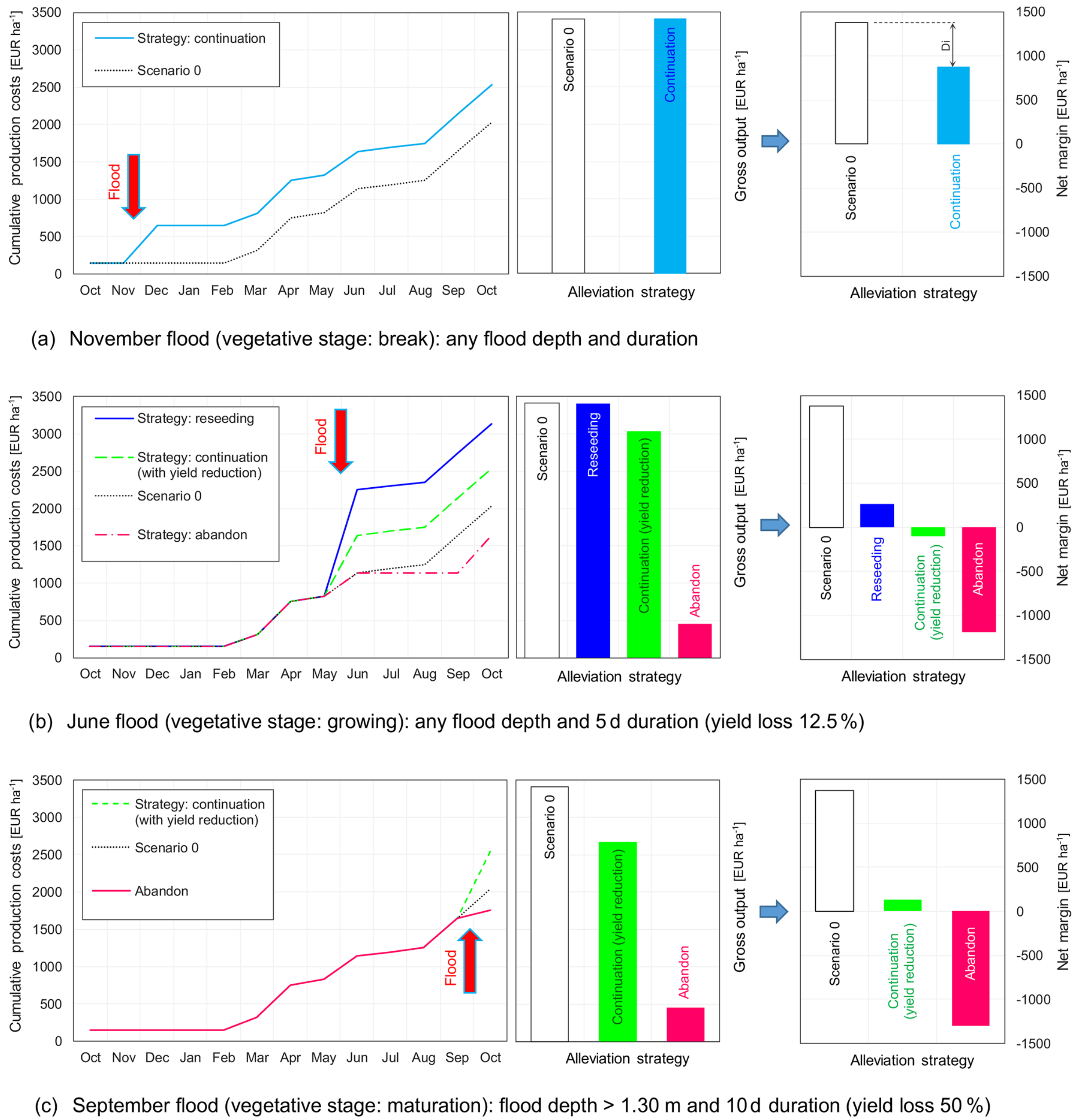

Figure 5. Po Plain case: distribution of cumulative production costs for grain maize during the year and annual gross output and net margin in Scenario 0 and in the case of a flood occurring in different months. Colours refers to the different possible strategies the farmer can adopt according to the time of occurrence of the flood, intensity (water depth and duration), and physical damage. The absolute damage for the farmer (D) is obtained by the difference of the net margin in Scenario 0 and in the investigated scenario, as exemplified in Fig. 5a.

the evaluation of the opportunity to ask for a flood insurance scheme, and the definition of the premium. For example, for the context and crop types investigated in the case study, Fig. 6 highlights that abandoning the production is always the worst strategy, leading to a relative damage greater than 100 % in any vegetative stage and for any flood intensity, due to the combined effect of the total loss of the gross output (if excluding the EU contributions, also obtained by the farmer without any yield) and the costs incurred by the farmer before the flood. On the other hand, when flood intensity implies significant yield loss, reseeding (if possible) must be preferred to continuation, limiting the relative damage to 80 % (where "relative" refers to NM, according to Eq. 2); nevertheless, the positive advantage of reseeding over continuation becomes smaller when including a yield penalty for late (re)planting: results obtained by using the AGRIDE-

<table>
<tr><th rowspan="2" colspan="2">Water depth < 130 cm</th><th rowspan="2">Strategy</th><th colspan="9">Flood duration [d]</th></tr>
<tr><th><5</th><th>5</th><th>6</th><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>>11</th></tr>
<tr><td rowspan="9">Bare field</td><td rowspan="3">Jan</td><td>c</td><td colspan="9">36 %</td></tr>
<tr><td>r</td><td colspan="9">-</td></tr>
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<tr><td rowspan="6">Initial phase</td><td rowspan="3">Apr</td><td>c</td><td colspan="9">-</td></tr>
<tr><td>r</td><td colspan="9">80 %</td></tr>
<tr><td>a</td><td colspan="9">158 %</td></tr>
<tr><td rowspan="3">May</td><td>c</td><td colspan="9">-</td></tr>
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<tr><td rowspan="3">Growing</td><td rowspan="3">Jun</td><td>c</td><td>36 %</td><td>63 %</td><td>90 %</td><td>117 %</td><td>144 %</td><td>171 %</td><td>198 %</td><td>225 %</td><td>-</td></tr>
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<tr><td rowspan="6">Flowering</td><td rowspan="3">Jul</td><td>c</td><td>36 %</td><td>90 %</td><td>144 %</td><td>198 %</td><td colspan="5">-</td></tr>
<tr><td>r</td><td colspan="9">-</td></tr>
<tr><td>a</td><td>-</td><td colspan="8">191 %</td></tr>
<tr><td rowspan="3">Aug</td><td>c</td><td>36 %</td><td>90 %</td><td>144 %</td><td>198 %</td><td colspan="5">-</td></tr>
<tr><td>r</td><td colspan="9">-</td></tr>
<tr><td>a</td><td>-</td><td colspan="8">191 %</td></tr>
<tr><td rowspan="6">Maturation</td><td rowspan="3">Sep</td><td>c</td><td colspan="9">36 %</td></tr>
<tr><td>r</td><td colspan="9">-</td></tr>
<tr><td>a</td><td colspan="9">-</td></tr>
<tr><td rowspan="3">Oct</td><td>c</td><td colspan="9">36 %</td></tr>
<tr><td>r</td><td colspan="9">-</td></tr>
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<tr><td rowspan="6">Bare field</td><td rowspan="3">Nov</td><td>c</td><td colspan="9">36 %</td></tr>
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<tr><td>a</td><td colspan="9">-</td></tr>
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<tr><th rowspan="2" colspan="2">Water depth ≥ 130 cm</th><th rowspan="2">Strategy</th><th colspan="9">Flood duration [d]</th></tr>
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<tr><td rowspan="3">Dec</td><td>c</td><td colspan="9">36 %</td></tr>
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Figure 6. Po Plain case: relative damage (Eq. 2) to maize crops (in the case of minimum tillage) for the different combinations of time of occurrence of the flood (i.e. month), flood intensities (i.e. water depth and flood duration), and damage alleviation strategies (c: continuation; r: reseeding; a: abandonment). Results shown for the "r" option are obtained by assuming a null yield penalty for late (re)planting.

c spreadsheet indicate a relative damage of 102 % and 145 % for a yield reduction of 10 % and 30 %, respectively.

The model presents some limitations that must be addressed in future research works and must be carefully taken into account in its implementation. The first is related to data requirements: the number and typology of input parameters may prevent its use in data-scarce areas. However, it must be stressed that highly detailed tools like AGRIDE-c should be adopted only at an advanced stage of the analysis, when the costs of collecting site-specific data may be justified by the expected results (i.e. the choice of the best mitigation strategy); in other cases, like preliminary damage analyses for the identification of priority intervention areas or post-event assessments, rapid tools (e.g. based on standardised damage/costs) should be preferred.

A second limitation concerns the high uncertainty characterising the input data required by AGRIDE-c, even in a specific context. An example is the estimation, based on a few parameters (see Sect. 4.5), of the expected yield reduction due to late (re)seeding, which may be problematic as it is very variable and dependant on many factors (among others, type of late hybrids used). This implies that damage estimation may be affected by significant uncertainty, which is hardly quantifiable due to the limited availability of data for model validation (see Sect. 2); this uncertainty can even be amplified by the inherent uncertainty of the sub-models implemented in AGRIDE-c, like the economic or physical models for the estimation of flood damage to soil and crops.

This suggests, as for other damage models, the use of AGRIDE-c in a CBA context not in absolute terms (i.e. to evaluate the effectiveness of a specific measure) but as a tool to compare and choose among several alternatives (Scorzini and Leopardi, 2017; Molinari et al., 2019a).

Likewise, a sensitivity analysis of input variables should always be performed, to obtain an idea of the robustness of findings. For example, for maize, the model developed for the Po Plain reveals (not shown here) that even a reduction of 10 % of the yield in Scenario 0 (with respect to the value adopted in the analysis) impacts the damage scenarios, leading to a relative damage greater than 100 %, even in the case of reseeding in April and June and continuation in July and September (when yield loss is expected). The same occurs if the selling price decreases more than 12.5 %, or EU contribution for the minimum tillage is not considered or production costs increase more than 10 %. The "new" damage scenarios change the relative convenience associated with the different mitigation strategies; in particular, continuation may be more appropriate than reseeding for short-duration floods. Sensitivity analysis also allows investigation of the effect on damage of possible changes in the physical and economic context in which the farm is located. In fact, all of the scenarios analysed in the previous example are globally representative of the context under investigation, but they can significantly vary among different farmers and different years: physical productivity is spatially non-uniform within the subregions of the Po Plain; prices and costs are highly variable in time and specific locations; only a few farmers apply for EU contributions for the minimum tillage.

A third limitation concerns the time frame of the analysis, focused on one productive cycle; this prevents the comprehensiveness of the damage assessment by neglecting long-term indirect damage, like those related to the low productivity of soil in the following years after the flood event. This limitation must be carefully considered when the tool is implemented for the choice of risk mitigation strategies, as the expected damage can be significantly underestimated.

Finally, comprehensiveness of damage assessment is limited by the lack of consideration of other farm components which may be damaged in the case of flood like perennial plants, livestock, stock, equipment and machinery, buildings, permanent equipment, and farm roads (Brémond et al., 2013; Posthumus et al., 2009; Morris and Brewin, 2014) as well as of their systemic interaction (i.e. damage induced to one component by another one). Further research is required on the topic as well as post-event data to calibrate and validate models.

The development of AGRIDE-c also highlighted some challenges for the hydrology and hydraulic community. In fact, application of the model requires a relatively detailed set of hazard input variables, which are often not supplied in existing flood hazard maps (de Moel et al., 2009). Such knowledge would require a shift from traditional 1-D steady hydraulic models to 2-D unsteady hydraulic models – coupled with suitable sediment and contaminant transport models – in all flood-prone areas, which is not easily achievable in a short time because of both technical and economic constraints. Thus, rapid approximate methods for the estimation of hydraulic variables of interest should be developed (e.g. Scorzini et al., 2018). In addition, a further problem arises with respect to the estimation of the probability of occurrence of the different inundation scenarios. Given the importance of the time of the year, risk estimates should be based not only on annual probabilities, but also on seasonal probabilities (Förster et al., 2008; Klaus et al., 2016; Morris and Hess, 1988; USACE, 1985); this would imply changing present conceptualisation of flood return periods. It is worth noting that the key role played by the time of the event also affects the identification of crops of interest, as the risk analysis should take into account which crops are actually in place when the event occurs. In fact, because of rotation techniques, it may happen that several different crops can exist on the same plot at different times of the year.

6 Conclusions

This paper presented AGRIDE-c, a conceptual model for assessing flood damage to crops and its implication for farmers. The model has been exemplified in the Po Plain – north of Italy, for which a spreadsheet (partly customisable by users) for the calculation of damage has also been developed.

By organising the available knowledge on flood damage to crops in a usable and consistent tool that integrates physical and economic approaches, AGRIDE-c constitutes an advancement in flood damage modelling, supplying a general framework that can potentially be applied across different geographical and economic contexts. This aspect is the main strength of the model, given the fragmented and not consolidated literature on the topic. On the other hand, the development of the model highlighted different challenges for the scientific community to achieve reliable estimations of flood damage to crops. Indeed, the exercise carried out for the Po Plain pointed out that further investigations on the modelling of damage mechanisms are required to fully implement AGRIDE-c in a specific context: at present, (over)simplifications are made, for instance, regarding the physical damage to soil and its effect on crops or the influence of flood intensity on yield quality reduction.

Despite current limitations, the case study demonstrates the usability of the conceptual model; at the same time, it represents an example of how the model can be adapted to different geographical or economic contexts, given that all the assumptions and hypotheses made in the sub-models are clearly described; importantly, the model is based on the vegetative cycle of the crops, allowing its transferability to contexts characterised by different crop calendars or climate conditions. Finally, according to our knowledge, the model represents the first tool for the estimation of flood damage to crops in the Italian context, and in particular in the Po Plain region.

Further research efforts will be focused in three directions: (i) a better understating of damage mechanisms; (ii) the validation of the model, even for other contexts of implementation; and (iii) the extension of the model to the other components of a farm.

Data availability. The AGRIDE-c simulator with data for the Po Plain can be downloaded at https://data.mendeley.com/datasets/js6xbx4whw/1 (last access: 16 November 2019; Molinari et al., 2019b).

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