Manuscript nhess-2019-61 "AGRIDE-c, a conceptual model for the estimation of flood damage to crops: development and implementation" – Point by point response to referee 1 comments

We would like to thank the referee both for his appreciation of our paper and for the work he did on our manuscript; we greatly appreciate his comments as they may contribute to increase the manuscript robustness and, in general, to improve its quality and readability. In the following, we supply a point by point answer to the general and specific comments raised by the referee.

General comments:

RC1: Please briefly discuss and justify the consideration of the element "damage to soil" in the model framework against the background that no approach to estimate this damage type as yet exists. From a theoretical point of view the implementation of this damage type is fully comprehensible and reasonable as 1) it ensures a comprehensive view of potential consequences of flooding in the agricultural sector, and 2) damage to soil can significantly contribute to overall flood damage in this sector. However, from a practitioners perspective, the fact that the consideration of damage to soil is suggested on the one hand, but no concrete approach for such an estimation is provided (since not existent) on the other hand, can cause ambiguities. Further, a consideration of damage to soil in the model application using rough assumptions and proxies for this variable could introduce noise to the overall loss estimation rather than valuable information.

Answer: We thank the reviewer for this comment and we fully agree with him on this point. Indeed, our choice to include the "damage to soil" component in AGRIDE-c, although in a simplified way, was driven by the two main reasons also raised by the reviewer: comprehensiveness of model structure and importance of this sub-component 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 damages even for flood events characterised by shallow water depths and not particularly high flow velocities. We have included these considerations in Section 4.4 in order to justify the necessity of modelling this sub-component and we will also include in Section 5 a critical discussion of possible impacts of the modelling assumptions on the overall loss estimation.

RC2: The AGRIDE-c spreadsheet plays a central role in the model concept. It is currently provided to the reader via a hyperlink to a project website in Italian language. Due to language constraints of non-Italian-speakers as well as potential expiry of the hyperlink I suggest to additionally provide the spreadsheet in the supplement of this paper, if technical requirements of NHESS can be met or bypassed (Excel sheets cannot be uploaded to NHESS supplements). This would ensure unlimited availability and better access of the spreadsheet.

Answer: The NHESS editorial support office confirmed that spreadsheets cannot be uploaded as supplement material. For this reason, we have created an open folder including the spreadsheet and a new developed user manual. The tools are now easily accessible at: https://tinyurl.com/yyj2arhp

Specific comments:

RC3: Page 2, l. 6-8: The given characteristics of limited model transferability and applicability are not exclusive for agricultural sector, but rather represent general difficulties in flood damage modeling, i.e. often also apply to models for e.g. the residential or the commercial sector. I suggest to rephrase the sentence to avoid the impression that these aspects are exclusive problems of agricultural models.

Answer: We agree with the reviewer that the transferability of damage models represents a general issue in flood damage modelling, affecting all exposed sectors. Agriculture is probably one of the most

critical in terms of transferability, due to large variability of the features affecting damage mechanisms for this sector. For more clarity, in the new version of the manuscript we have revised the original L.6-8 in P.2 as follows: "Available damage models for agriculture are not only few in number, but are also affected by many limitations, the major 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, as the residential and commercial ones".

RC4: Page 2, l. 23: "The paper is organized in four parts" is a bit confusing. To match this number, the exclusion of the sections "introduction" and "conclusion" is required. Moreover, in the subsequent sentences you list five different sections. Please rephrase the sentence towards a more unambiguous statement. For example, "the paper is organized as follows".

Answer: The reviewer is right. We have revised the sentence as suggested in the new version of the manuscript

RC5: Page 3, l. 1: "The main available damage models [: : :]". This statement is unclear to me. Do you mean "prominent examples of damage models"? Please clarify

Answer: Yes, we do. We have revised the sentence as suggested in the new version of the manuscript.

RC6: Page 9, l. 27-30: Although in a European context floods usually have a negative effect on soils, the studies of e.g. Hein et al. (2003) and Tockner et al. (1999) show that such events can also have clearly positive effects, namely in the form of an increase of soil fertility. The fertility increase is explained by a (re-)distribution of river sediments and organic matter in the course of flooding. These river sediments replenish carbon and nutrients in topsoil and, hence, can make agricultural lands more fertile. I suggest to briefly discuss this aspect in the paper. An adaptation of Figure 2, where the box "damage to soil" currently states only the negative effect of flooding, could also be considered.

Answer: We thank the reviewer for this important comment. In the original version of the manuscript we only referred to negative flood effects on soils, because in Italy these are the most common impacts observed from past events. However, we fully concur with the reviewer on the importance of including also positive effects (e.g. increase of soil fertility) in the general conceptual model represented in Figure 2, which has been revised accordingly. In the revised version of the manuscript, we have also included some discussion on this point in subsection 4.4 (in addition, the title "Damage to soil" has been changed to "Impact on soil" in order to be more comprehensive).

Technical corrections:

Page 12, l. 16, w. 11: Grammar issue. "nor" should be replaced by "neither".

Page 19, l. 2, w. 13-15: Consider rephrasing "in another terms". For example, into "in other words".

Answer: These technical corrections have been fixed in the revised version of the manuscript.

Manuscript nhess-2019-61 "AGRIDE-c, a conceptual model for the estimation of flood damage to crops: development and implementation" – <u>Point by point response to referee 2 comments</u>

We would like to thank the referee both for appreciation of our work and for carefully reading our manuscript; we greatly appreciate the insightful comments as they may contribute to increase the manuscript robustness and, in general, to improve its quality and readability. In the following, we supply a point by point reply to the general and specific comments raised by the referee.

General comments:

RC1: There is scope to improve the structure of the paper:

- by separating the introduction of context and rationale, including statement of research objectives, and statement of methods to cover literature search, review of knowledge and construction of the analytical framework.
- There should be a critique of the approach.
- The case study then becomes results (reordering some results that currently occur in discussion).
- Discussion can then follow on both the case and the validity or otherwise of generic framework.

Some items currently in the conclusion, particularly on gaps/further development, can go in discussion (they appear to be recommendations). Conclusion on what has gone before can focus whether the objectives (regarding the tool, its application and its prospects) have been met, rather than introducing new elements into discussion.

Answer: We tried to address at our best the suggestions provided by the referee, especially regarding a better ri-organisation of the contents of the introduction/methodological part, and discussion/conclusions. Still we think that the present organisation of the sections is appropriate for the explanation of the conceptual model and its exemplification. Of course, if the editor thinks that a change in the structure of the paper is required to better meet the journal standards, we will re-organise the paper as suggested.

RC2: It probably would be best to be more cautious and modest about the claims made about the comprehensiveness and novelty of the approach, and its suitability to all circumstances and contexts.

Answer: After reading the referee comment, we realised that the "scope of use" of our model was not well specified in the original version of the paper, which could lead to incorrect interpretations of our work. Indeed, without such specifications our claims appear as too wide and, therefore, we have been more specific in the revised version of the manuscript in presenting the conceptual model of AGRIDE-c. In fact, the conceptual model has been designed to supply an estimation of flood damage:

- to annual crops (i.e. not including perennial plants)
- by considering one single culture (i.e. by not considering replacement of one culture with another one)
- by limiting the time frame of the analysis to one "productive cycle" (i.e. not considering long term damages, e.g. loss of soil productivity in the following cycle/years);
- for infrequent flooding (i.e. effect of two, or more, consecutive floods is not considered)

Nonetheless, as specified at page 9 line 11-19 of the original manuscript, AGRIDE-c do not consider damage to other components/elements of the farm that may induce additional damage to crops, as, for instance, damage to machineries and equipment (e.g. the irrigation plant) that may prevent cultivation for a while. Only damage to soil is considered from the evidence that, during a flood, damage to soil and plants occurs always at the same time, differently from damage to the other components which can

occur or not, independently from the damage to plants; as a consequence, damage to soil and plants is modelled together, while damage to the other components could be modelled as separated factors, not included in the conceptual model.

We have specified all these aspects in the new version of the paper (Section 3), by hopefully clarifying what we mean with "generality" and "transferability" of the approach. We never referred in the paper to "novelty" or "comprehensiveness" of the approach, but we highlighted the fact that we are trying to encapsulate and systematise the available knowledge on damage mechanisms (to annual crops) triggered by inundation phenomena, as well as on their consequences in terms of income for the farmers.

RC3: Further clarity on its potential application, either in cost benefit analysis of (publically funded) investments at the landscape scale in flood risk management, or in guiding individual farm-scale responses would be appropriate. The two applications are different in purpose and detail of approach. There is a difference between, for example, economic and financial appraisals. There is also a difference between ex ante appraisal and ex post evaluation, which is implied. This will support the important point made that insufficient ex post evaluation is undertaken to provide sound ex ante decisions

Answer: The CBA of flood risk mitigation strategies would require a comprehensive estimation of benefits associated to the adoption of different strategies, i.e. of the avoided loss to all exposed sectors and at different temporal scales (i.e. direct and indirect/long term damages). However, present damage modelling capacity is mainly focused on direct damage to people and some exposed assets (typically residential buildings), thus preventing the possibility of performing comprehensive flood damage assessments. In such a context, by allowing the estimation of the expected loss to crops in a specific flood scenario, AGRIDE-c may support more comprehensive CBAs of public risk mitigation strategies. Clearly, to meet such an objective, the tool must be critically used, e.g. by considering possible transfers of losses/gains between farmers in an economic perspective, according to the temporal and spatial scales of the analysis. Regarding individual responses, by supplying the expected damage for different types of crops and alleviation strategies (according to the expected yield reduction for different flood intensities and period of occurrence), AGRIDE-c may support individual farmers exposed to flood risk in preventing losses by supporting: the choice of the most resilient crops to be cultivated, the choice of the best alleviation strategy to be followed once flooded, the evaluation of the opportunity to ask for a flood insurance scheme and the definition of the premium. The model was not designed to be used ex-post. This explanation has been included in the Introduction and Discussion sections of the revised manuscript.

RC4: One particular issue requires attention, namely the importance, especially in temperate climates, of agricultural land drainage. The control of water levels in the soil, and particularly the removal of excess water and below surface 'flooding', including during the post flood phase before field return to 'normal' is an important aspect of agricultural flood risk management and assessment. Impacts and land management responses are often driven by seasonal waterlogging and drainage problems as much as they are by surface flooding. This is certainly the case in northern Europe and North America. There should be coverage of this aspect, and the implications of not explicitly allowing for it in this model framework. Many areas of strategic importance are pump drained.

Answer: We thank the referee for highlighting these important aspects for flood risk/damage assessment and management (that were erroneously not included in the original version of the paper), and for supplying some of the related literature. In the new version of the manuscript, the conceptual model has been modified in order to take into account of the effect of waterlogging on both the yield and the soil, as well as on the corresponding effect on the revenue and costs for the farmer, and then

on the final flood damage (see Figure 2 and Section 3). Still, these aspects were not considered in the application of the model to the Po Valley because, according to experts' opinion, waterlogging after floods is not common in the area.

RC5: Saline flooding, a major issue in coastal and tidal areas, should be referred to with implications for costs, especially regarding remediation and subsequent year impacts

Answer: The conceptual model was originally not conceived to cover coastal floods but we have decided to extend the context of applicability of the model in the revised version, by including water salinity load among the hazard parameters, and salinization as possible effect on soil (see Figure 2 and Section 3). However, the model will still be focused on "one" productive cycle/year. We have discussed limitations of this hypothesis in the discussion section.

RC6: Surprising the authors do not mention climate change as a driver of concern or a factor affecting damage costs and responses. This seems an omission given the topic.

Given that the model is focused on "one" productive cycle, long term effects of climate change are not considered in the model. Anyway, we have included a paragraph in the introduction on the importance of climate change in exacerbating future flood damages.

RC7: Further clarity is required regarding the definition of measurements of damage. A more detailed listing, upfront, of the revenue and cost related parameters would help: these emerge in the case application later on.

Answer: A comprehensive list of all revenue and cost related parameters cannot be compiled in the framework of the conceptual model, as most of them, especially those related to costs, are context-specific. Still, some examples were already included in the description of the conceptual model (e.g. yield and price of the crops regarding the revenue, and soil restoration and reseeding regarding the costs) and we added more in the new version of the paper (e.g. land drainage costs). A detailed description of all parameters have been instead supplied with reference to the case study (see also answer to RC8).

RC8: A table would be good to summarise the main elements of cost estimation processes /assumptions/ algorithms and where they come from. In the main, the methods draws on published data from Sub-sector models of crop damage or additional costs, such as Agenias et al. What other ones are used to transfers changes in yield, revenue and cost responses?

Answer: A table have been added (Table 3 in the revised version of the manuscript) that summarises the main input data required by AGRIDE-c and its exemplification in the Po Plain

RC9: Further clarity would help regarding the use of the terms 'turnover' and 'gross profit', ie exactly what is in these terms? They are not universally applied in farm business accounting, where the terms gross output (or gross revenue), gross margin and net margin are often used. (Turnover can for example include sales from previous production periods – just to be clear). And the definition of gross profit may or may not include elements of farm level fixed costs, such as machinery and buildings costs (again to be clear, so that the methods can be generally applied). The use of 'relative' Gross profit measured at negative % values is difficult to interpret and doesn't mean a lot.

Answer: we really thank the referee for the suggestion. According to the literature suggested, we have changed the terms "gross profit" and "turnover" in "net margin" and "gross output", respectively. As specified in the revised manuscript (Section 4.2 and new Table 3), all agricultural operations have been

considered as direct, avoidable costs, as interviewed local experts indicated that in Lodi province most of field operations are carried out by contractors.

RC10: On flood scenarios, the treatment presumably here is for one-off relatively infrequent flooding on a land use that is not hitherto constrained by flood exposure. An increase in flood frequency, associated with climate change for example, or withdrawal of flood defences, could lead to increased flooding with a range of outcomes, permanent abandonment, repeat annual losses or a switch to more flood tolerant land use. How are these to be handled by the model?

Answer: As explained before (RC2) the model considers damage to one productive cycle for infrequent floods. Limits of these assumptions have been discussed in the new version of the paper (Section 5).

RC11: The paper refers to spreadsheets and supplementary data containing both data and estimation methods. I had difficulty locating these and understanding them when I did. This is probably my fault. It would be good to explain what is in them and how they can be reliably accessed.

Answer: Because the journal does not allow to upload spreadsheets as supplementary material, we have created an open folder including the AGRIDE-c spreadsheet and a new developed user manual. The tools are easily accessible at: https://tinyurl.com/yyj2arhp

RC12: There is a need to strengthen the treatment of inherent variation and uncertainty in the estimates.

Answer: We have included a deeper discussion on model uncertainty in the discussion section.

RC13: there is a need to provide a more systematic critique of the model and the resultant damage estimates, and implications for use and improvements

Answer: see answer to RC2, RC3 and RC12

RC14: The authors report that their work draws on systematic review of multiple sources, including expert judgement. This aspect, especially the latter, is under reported. Did the research approach follow a particular methodology that can be supported by literature, especially engaging experts?

Answer: Experts were involved with two main objectives. The first one is to support the definition, and validate the quality, of the conceptual model. The second one is to give suggestions/information on the implementation of the model in the Po Valley, above all regarding expected physical damage and costs. With respect to the first objective, an iterative process was followed. First, a semi-structured interview was conducted, by asking experts about the main damage mechanisms/phenomena in case of flood, possible interconnections among them, important explicative variables. In this phase, results from the literature review were proposed to experts for their judgment. In the following step, experts were asked to evaluate a draft version of the conceptual model we draw according to the literature review and results from first interviews. Then, there was an iterative revision process of improved versions of the model until an agreement on its final structure was reached.
With respect to the second objective, several individual meetings were organised with the aim of asking experts about context-specific information on: crops calendars, yields and prices, type, timing and costs of cultivation practices. In this phase, the transferability of the model by Agenais et al. was also discussed.
Three kinds of experts were involved. One representative of the Regional Authority 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. Two agronomists of the local association of farmers (Coldiretti Lodi), with specific knowledge on the investigated context

and with direct experience in managing floods in the last 20 years. During the work, the two agronomists asked for data/information also to individual local farmers that were flooded in the past years, including also their viewpoint in the process. Finally, an academic economist, with specific expertise in agriculture, has been involved in validating the final model.

This information explaining the whole process of experts' involvement has been included in Section 3 and 5 of the revised manuscript.

Specific comments (we noted that for some comments the reviewer made a wrong reference to page/line number of the original manuscript; in the following, we made our best to locate the comments in the proper point of the paper)

RC15: Abstract. I think the abstract would better begin with a statement of context and purpose, and how the proposed model seeks to make a contribution to decision support. I think it best to avoid giving the paper an identity by using 'this paper….' as a writing style here and in the manuscript itself ; it is the authors who are reporting their work. As above, I think some cautious modesty would be advisable. CBA implies welfare assessment. Farmer decision support is something else.

We have revised the abstract according to reviewers' suggestion. We would like to maintain the impersonal writing style within the paper as there are not specific indications about in the Journal guidelines, or a common trend in published articles. However, in this respect, we are available to follow editor's suggestions, if any. See also reply to general comments RC2-RC3.

RC16 (P1.L20): What are flood risk management plans, and what is the implication of CBA ?. This implies public investment at the landscape scale, often funded through the public purse, as implied by CBA.

According to the EU Floods Directive, Flood Risk Management Plans are the operational/normative tools by which Member States (and in particular River District Authorities within each State) must implement flood risk management, including a blend of structural and non-structural risk mitigation strategies, to be implemented at different spatial and temporal scales. Such measures must be identified on the bases of a reliable and comprehensive assessment of costs and benefits associated to alternative strategies. We have better clarified this point in the revised manuscript (Section 1).

RC17: I would avoid, 'in this paper', here and elsewhere.

Answer: See reply to RC15.

RC18 (P1.L25): River restoration usually implies rejoining the river to its floodplain and set back of (previously installed) flood defences in the conventional sense. See:

Morris J, Bailey AP, Lawson CS, Leeds-Harrison PB, Alsop D, Vivash R (2008) The economic dimensions of integrating flood management and agri-environment through washland creation: A case study from Somerset, England. J Environ Manage 88:372-381

Rouquette JR, Posthumus H, Morris J, Hess TM, Dawson, QL, Gowing DJG (2011) Synergies and trade-offs in the management of lowland rural floodplains: an ecosystem services approach. Hydrol Sci J 56(8):1566-1581

Is the context to justify of guide decisions in flood risk management infrastructure and operations made at the landscape/sub catchment/shoreline scale , with support from the public purse. This is the case in

many parts of northern Europe and north America. Getting a handle on damage costs to agriculture is part of this ?

Answer: We thank the reviewer for the suggested references, which support our statement regarding the importance of including damage costs to agriculture when dealing with floodplains devoted to agricultural activities. The two references have been included in the revised version of the paper.

RC19 (P1.L29): I think this is partly reflecting a limitation of the use of selected key literature search terms and also confinement to formal academic, rather than grey literature and institution-based activities and outputs. There is a history here in this topic: Since the 1930s, and probably up to the mid1980s, the focus in this area in northern Europe was on 'land drainage' of which flood protection , (rather than 'flood risk management'), was a part. Major investments, including large scale pumping schemes, were made to control /remove excess soil water and simultaneously alleviate surface flood from river, tidal and shore line sources. Many of these investments were 'land reclamation (for agric) projects' often involving major river works (and not river restoration). Thus land drainage and flood control were and are inextricably integrated (just as irrigation and drainage are). The authors should in my view show an understanding of this nexus, and consider how, without undermining what they have done, it can be incorporated here. Including the terms agricultural/land drainage in the search would go some way towards this, as would 'flood risk'. Much of the work was carried out by research institutions as part of national programmes and is reported in sources that are not as easy to access.

A bit dated , but see for example, *Morris, J. 1992. Agricultural land drainage, land use change and economic performance: Experience in the UK. Land Use Policy Volume 9, Issue 3, July 1992, Pages 185-198.*

And for decision support: *See Chapter 9 Flood Risk Management for Agriculture, in: Penning-Rowsell, E., Priest, S., Parker, D., Morris, J., Tunstall, S., Viavattene, C., Chatterton, J. and Owen D. (2013) Flood and Coastal Erosion Risk Management: A Manual for Economic Appraisal, Routledge, Abingdon, Oxford*

Answer: Thank you. In the revised version of the manuscript we tried to explain this nexus as a possible reason of the limited literature on flood damage to agriculture (Section 1).

RC20 (P2.L5): I think also there has been a policy shift, especially in Europe post 1980s when agricultural surpluses increased under EU CAP and the subsides to agric were being challenged , and urban flood damage increased in absolute as well as relative importance. Also the drainage link is important here : the emphasis in Europe and N America was on drainage land and reclamation.

Answer: Thank you for this comment. We have included these points in the revised version of the manuscript (Section 1).

RC21 (P2.L15): Some of the comments here seem premature: we haven't yet explained the approach and the model, but seem to be drawing conclusions , unless these are objectives . The authors might want to consider a clear statement of the objectives of the work reported here, and then subsequently review the extent to which they have been able to meet them

Answer: In the lines indicated by the reviewer we briefly introduced AGRIDE-c, the need for its model structure and its usefulness. In order to avoid ambiguity, we have rephrased P2.L17-19 of the original manuscript as follows: "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".

RC22 (P2.L25): Should table 1 be part of methods ? What of 'flood risk' and 'drainage' as key search terms ? And using experts to identify sources ?

Answer: We think that the use of "flood risk" and "drainage" as key search terms is misleading as it results in different kinds of paper, often not linked to flood damage to agriculture. For this reason, we did not include the results of this research in Table 1 but we commented on the link between the literature on land drainage and that on flood protection in Section 1 (see also response to RC19). We think Table 1 should not be moved in the methodological section of the paper, as we used it only to support our preliminary statement on the need to improve damage modelling for the agricultural sector. Experts were not involved in this literature research (almost all of them were not academics), but they were interviewed for model development and assessment (see also response to RC14).

RC23 (P3): Would be good to clarify the perspective and purpose of the assessment of damage costs: ex ante or ex post, and the implications : the term ex post is used later without explanation.

Answer: In the Introduction of the revised version of the manuscript we explained that AGRIDE-c is a tool for an ex-ante (i.e. expected) estimation of flood damage to agriculture, while we have replaced the term "ex-post" within the paper with "observed" or "empirical".

RC24 (P3.L20): Agree there is paucity of data on actual flood impact costs , recorded during and post flood. This observation is not confined to the agricultural sector (Chatterton et al, for the English cases for example, including agricultural damage)

Chatterton, J; Clarke, C; Daly, E; Dawks, S; Elding, C; Fenn, T; Hick, E; Miller, J; Morris, J; Ogunyoye, F; Salado R. .2016. The costs and impacts of the winter 2013 to 2014 floods. Report SC140025/R1. Environment Agency, Bristol. http://rpaltd.co.uk/uploads/report_files/the-costs-and-impacts-of-the-winter-2013-to-2014-floods-report.pdf

There is a large, albeit now dated literature on drainage/water logging impacts on agricultural production that should be referred to, with modelling of the link between soil- water, crop growth and yields, and particularly linked to water level management in the context of land drainage and associated flood control measures.

Answer: Thank you. We have included the suggested reference in the revised version of the manuscript. In addition, we included aspects related to drainage and waterlogging impacts in the enhanced version of the conceptual model represented in Figure 2 (see also response to RC4).

RC25: See Chapter 9, section 9.5, p336 in Penning-Rowsel, opcit
For FLOODFARM, that assesses the cost of flooding at the farm scale
Where FLOODFARM = (costs associated with flood impacts on) ARABLE+GRASS+LIVESTOCK+OTHER.
See also: *Dunderdale J A L and Morris J. 1997. The Benefit: Cost Analysis of River Maintenance. Water and Environment Journal. Volume11, Issue 6 Pages 423-430 https://doi.org/10.1111/j.1747-6593.1997.tb01375.x*

Answer: We thank the referee for the suggested literature that we will include in the new version of the manuscript. Still, our model is only focused on the crops component of flood damage to farms as explained in answer to RC2.

RC26 (p.3, L25): I am not sure the assumption of full loss is true here. The Posthumus, and the Morris and Brewin examples, based on farmers reported assessment of damages, incorporated 'partial' losses, and also losses in the following years. And also on farms adapting to flood risk:

Pivot J.M., Josien E. & Martin P. Farms adaptation to changes in flood risk: a management approach. J Hydrol 2002, 267, 12–25.

The ex-ante estimation methods described in Penning Rowsel above, for use in the appraisal of flood investments for agriculture, explicitly build in allowance for seasonal variation in yield loss between different crops (including grass) and livestock.

Answer: Thank you. We have a included a comment based on the suggested references of the revised version of the paper.

RC27 (P7.L29): Should define Gross profit as gross output minus direct costs. The term Gross Margin is widely used in agricultural /farm business accounting circles. (there is an interesting accounting challenge here: what is considered a direct, avoidable cost in the context of flood impacts, especially when lots of field operations are carried out by contractors)

Answer: See reply to comment RC9. All agricultural operations have been considered as direct, avoidable costs and priced based on contractors' price lists for the different operations (experts told us that in Lodi province most of field operations are carried out by contractors). This point has been made clearer in the revision of the manuscript and reference to the price books has been included as well.

RC28 (P9.L7): Is this a tautology ?

Answer: The sentence "the first provides information on the physical damage, while the second converts the physical effects of the flood into monetary terms" has been deleted in the revised manuscript.

RC29 (P9.L9): Should this be' and/or': with respect to data source, estimation and valuation methods: eg some models have both physical quantities and unit monetary values.

Answer: We have replaced "and" with "and/or" in the revised paper.

RC30 (P9.L10): Implies that this would be good idea? Again need to set in context of the purpose of the 'modelling', high level or detailed assessment ? A number of Environmental bodies use very high level 'cost calculators' to derive quick assessments of flood impacts at the large scale , eg using 'standardised' damage costs $/ha, for example to respond to immediate questions by politicians post flood. There is guidance on this > The UK Environment Agency use a Flood Cost Calculator, European Commission are promoting a standard approach to disaster observation, see for example
http://publications.jrc.ec.europa.eu/repository/bitstream/JRC110489/loss-database-architecture jrc110489.pdf

Answer: We agree with the reviewer that the required level of detail of a model depends on the context and use. So, not always an ultra-detailed, multi-parameter model can be the best option. We think however that it is not appropriate to comment on this point in the methodological part of the paper, but we included some comments on this in the discussion section of the revised paper.

RC31 (P12.L12): Says Agenais model is physically, presumably yield based , but then says it uses gross profit (gross output (turnover) less direct costs : isn't this monetary (cost) based. Some further clarity of the distinction between physical and monetary estimation would be useful with definition of terms used

Answer: The model implemented in the case study is the physical model included in Agenais et al. (2013), specifically in the annex (pg. 200-202), and reported in Figure 4 of the paper. As explained in Section 4.3, such model supplies an estimation of the relative damage as a percentage of the yield in the Scenario 0. By multiplying this percentage by the crop yield and the unit price of the crops, the reduction in the gross ouput can be calculated. Still, Agenais et al. (2013) includes also absolute damage functions (at pg. 51), at

which Table 1 refers, supplying the absolute damage as the reduction in the net margin, calibrated from the French context. In the new version of the paper, we have specified that we adopted only the physical model of Agenais et al. (2013).

RC32 (P12.L15): They both imply that duration is probably more important than depth ?

Answer: Yes, for the crop under investigation (maize). But this depends on crop type.

RC33 (P13.L5): Some more detail on the methods used to define the boundary of investigation, and the methods used to elicit important parameters and values from experts and other sources. Was a formal research method used? Was the research review for example formally a 'systematic' review, and were the experts 'systematically' engaged? Would be good explain how the research topic was framed and bounded , and the issues arising. What is the implication of an expert based approach here? This is an important methodological aspect, and liable to bias that needs to be managed ?

Answer: See response to comment RC14.

RC34: How is turnover defined . For the purpose here is it Gross Output (Q x P) specifically for the damage to crop outputs in a given period. Turnover in an accounting sense can be something else. Need to explain.

Answer: We have replaced "turnover" with "Gross output" throughout the text of the revised manuscript, with a more detailed definition of the terms used. See reply to comment RC9.

RC35 (P9.L32): Need to be explicit on definition of production costs here. Presumably the concern with a costs across the farm business (non revenue items), including replacement and remedial costs, net of savings in uncommitted costs Gross profit is usually after direct costs (or the cost of good sold) , but much depends on how overheads/fixed costs are categorized .How are changes in machinery operating costs, or 'other' damage costs to machinery, buildings and infrastructure being assessed, or are they not included here , given the implied focus on 'field' scale costs?
I think a table to support equation 1 should show the revenue and cost items that are used in the assessment : what is in and what is not ? Lots of jobs are done by contractors : how are these valued ? what of within season reseeding costs, reduction in gross output or profit associated with crop substitution , clean up and remedial works, following year impacts? A list would be good . I see these come later for the Po example, but a classification for the model would be useful; Elements are suggested in figure 1 , but it is not clear which are explicitly measured revenue and cost items

Answer: See reply to comment RC2, as AGRIDE-c assesses only damage to annual crops and not to other farm components (machinery, buildings, infrastructure), and RC7 regarding revenue and cost items. Prices of agricultural operations are based on contractors' price lists (experts told us that in Lodi province most of field operations are carried out by contractors and that this would have been the most suitable option for pricing the different operations).

RC36 (Figure 2): Useful diagram. Where would salinity fit, and field flooding/waterlogging as it affects field access and timing of operations both within and beyond the immediate flood period? Not all elements are 'valued' in the model

Pri'c'es.

Answer: See response to RC2, RC4 and RC5. Figure 2 have been amended with the correct spelling of "prices", thank your for noting that.

RC37: Does the model include grassland and associated grassland management and livestock systems? If so, how are flood impacts assessed?

Answer: No, AGRIDE-c only estimate damage to crops; this have been clarified in the revised version of the manuscript (see response to RC2).

RC38: A summary of estimation parameters and algorithms would be helpful, possibly linked to the table of estimation items referred to earlier, summarizing the estimation basis . Presumably these are listing in the supporting spreadsheets: I tried but had difficulty accessing. See my comment on the Po case later : the approach is one of 'estimation transfer' . And there are some implicit criteria for transfer that could be made more explicit It would be good to say what is not in there: are damage costs to farm infrastructure, crops in store, included ?

Answer: Ok, a summary table have been included in the revised version of the manuscript. See also response to RC2.

RC38 (P13.L2): Are there thresholds for assumptions on crop switching/reseeding ?

Answer: Yes, this was implicitly reported in Table 3 (alleviation strategy vs month) and already specified in the original text of paper (original P12-L30.31).

RC39: So the scenario is for a single freshwater flood occurring in a given production year ?

Answer: Yes, this has been clarified in the revised manuscript (see response to comment RC2).

RC40 (P11.L5): Implications of grassland?

Answer: Only damage to crop are considered in AGRIDE-c. See response to RC2.

RC41 (P11.L10): What year price base is used ? Were annual price series inflation adjusted to a common year ? similarly with costs?

Answer: As stated in P11.L11 of the original manuscript prices and costs were averaged over the last five years (2013-2017: this has been better specified in the new version of the paper) and were not adjusted for inflation (negligible change over the considered period).

RC42 (P11.L15): 'annual EU contributions for agriculture as a further income for the farmer and, in detail, the subsidies given to agricultural activities in…' Not clear how these are being treated. Presumably farmers get decoupled income support at the farm scale under CAP and these are unaffected by the flood, so can be left out for a single flood event. What of production subsidies: will not these also continue for the year of the flood, so from a farmers viewpoint costs (and cost savings) are net of subsidies?

Answer: Experts explained us that EU contributions do not depend on actual production. If a farmer abandons the production of a year due to a flood, he still receives the contribution.

RC43 (P11.L17): consultation of regional price books: reference?

Answer: Reference to regional price books has been added in the revised manuscript (APIMA – Associazione Provinciale Imprese di Meccanizzazione Agricola delle Province di Milano, Lodi, Como, Varese: Tariffe 2013-2017 delle lavorazioni meccanico agricole c/terzi).

RC44 (P11): Is the assumption that all the costs shown in Fig 3 are direct costs (and therefore included in Gross profit as defined here) and are potentially 'avoidable' . This might be the case if farmers are using contractors , but if they are using own equipment and labour, how much of these are avoidable costs. Some explanation of the treatment of field operations and related costs would be useful. Some costs are more direct than others. The reference to fixed costs on the next page suggests that most costs are regarded as direct. The estimates are very sensitive to assumptions about the treatment and behaviour of costs : a tricky subject. I don't quite follow: I got E927 using the numbers presented , but there may be other costs not shown. Even so, the gross profit as defined for maize seems high > maize farmers in the Po Valley are doing well.

Answer: Yes, all field operations are considered as direct costs and priced based on contractors' price lists See also response to RC35. The reviewer is right in obtaining 927 Eur = 175x16.92 + 150+400 – (175x16.92)*0.05 – (sum of production costs). The results in terms of "gross profit" (now defined in the revised paper as "net margin", according to reviewer's suggestion) reflect the ones observed in the Province, as also confirmed by interviewed local experts and farmers.

RC45 (P12.L10): This approach should be more fully explained in describing the model above , that algorithms are judiciously 'transferred' from research applications elsewhere according to suitability/relevance, and availability

Answer: In the original manuscript we already stated that "local agronomists expressed a favourable opinion on the suitability of this model in the examined region". In the revised manuscript we have stressed this point by including the following sentence "[…] as emerged from discussions held during the interview process".

RC46 (P12.L16): Delete first 'nor'

Answer: Fixed, thanks.

RC47 (P12.L25): According to regional price books, restoration costs have been estimated to be equal to 500 €/ha (see Table 3). Would be good to reference these sources: Were contractors contacted? These seem very high unit costs . As for that matter do field operating costs , eg Harvesting at almost E800 /ha?

Answer: See previous response to comments regarding reference to contractors' price lists and experts' opinions. This has been also better clarified in Section 4.4 of the revised manuscript.

RC48 (P12.L25): So the damage to soil box in Figure is aspirational?

Answer: Yes. See also response to RC1 of Reviewer 1.

RC49 (P14.L10): I am surprised that a yield (and possibly price) penalty is not included in the assessment of reseeded crops, given the importance of timing of operations. There are generic yield functions available for timeliness that would support a relative estimate of yield and gross output loss. This is one topic where local experts and farmers would have an empirically based view. The comment about variation and uncertainty in the estimates is valid for the modelling as a whole, and should be made as part of the method critique

Answer: For simplicity, in the presentation of results in the original version of the manuscript we did not consider a yield reduction for late planting in case of reseeding (Figure 5). In addition, interviewed experts told us that this is very variable and dependent on many factors (among others, type of late

hybrids used) and difficult to estimate based on few parameters. These considerations are also confirmed by results from the literature (references have been included in the new version of the manuscript – see below). However, as already stated in the original paper, in the AGRIDE-c spreadsheet users have the option to set the most suitable value for the expected yield reduction due to late (re-) planting to take this phenomenon into account. We have clarified this point in the revised manuscript, by also including information on experimental results reported in the literature (generally observed yield reductions: -10% ÷ -30%). In addition, a comment on the possible effect of yield reduction on the results shown in Figure 6 has been included in the revised manuscript: "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%; nevertheless, this positive advantage of reseeding over continuation becomes smaller when including a yield penalty for late (re-)planting: results obtained by using the AGRIDE-c spreadsheet indicate a relative damage of 102% and 145% for a yield reduction of 10% and 30%., respectively"

Abendroth L.J., Woli K.P., Myers A.J., Elmore R.W. (2017) Yield-based corn planting date recommendation windows for Iowa. Crop, Forage & Turfgrass Management, 3(1), 1-7,.

Dobor, L., Barcza, Z., Hlásny, T., Árendás, T., Spitkó, T., & Fodor, N. (2016). Crop planting date matters: Estimation methods and effect on future yields. Agricultural and Forest Meteorology, 223, 103-115.

Lauer, J. G., Carter, P. R., Wood, T. M., Diezel, G., Wiersma, D. W., Rand, R. E., & Mlynarek, M. J. (1999). Corn hybrid response to planting date in the northern corn belt. Agronomy Journal, 91(5), 834-839.

Tsimba, R., Edmeades, G. O., Millner, J. P., & Kemp, P. D. (2013). The effect of planting date on maize grain yields and yield components. Field Crops Research, 150, 135-144.

RC49 (P15.L16): Break stage? There is no crop in the field? Presumably also depends on crop rotation .

Answer: Yes, we are considering only a single crop type in field. This has been better explained in the revised version of the manuscript (see also response to comment RC2).

RC50 (P15.L22): In my view gross output or gross revenue would be a better term than turnover, throughout. (Turnover refers to total sales in a period, sales may include items from other production periods)

Answer: Ok. See response to RC9.

RC51 (P15.L25): Seems unlikely that there would be no yield penalty for delayed planting Furthermore, reseeding would probably not be feasible immediately post flood because of field conditions . Penalty delay functions could be used .

Answer: See response to comment RC49.

RC52 (P15.L30): Finally?

Answer: Ok, thanks.

RC53 (P16. Figure5): Would be good to make the axes consistent amongst the graphs , and for cost and turnover estimates. Would also be good to indicate net margin (or gross profit) , although this might complicate the graph. If a read it correctly, for a june flood, reseeding will not make sense , especially if there is (likely) yield penalty: I note for this graph the two 'y' scales are common

Answer: Figure 5 has been amended in the revised manuscript by taking into consideration reviewer's suggestions.

RC54 (P17.L9): This raises the question about likely average annual damaged according to the likelihood of a flood occurring within given months : where information is available on annul flood probability, and seasonal distribution, and to complicate further, whether seasonal distributions vary according the severity of the flood ? I see this is raised later

Answer: Yes. The importance of knowing "seasonal" return periods of floods is commented in the Discussion section.

RC55 (P16. Figure5): Is this really a table. The title does not explain that it is relative gross profit : this is difficult to interpret when the preceding assessment was made with respect to turnover ad costs, so some clear explanation is required. Is a relative loss of gross profit greater than 100% a helpful measure?

Answer: In the revised manuscript, the caption and the text referring to Figure 6 has been made more explicit. The numbers [%] reported in the figure express the relative damage, defined in Equation 2 of the paper, i.e. $d=D/NM_{noflood}$. Reference to Eq.2 has been included in the revised caption of Figure 6.

RC56 (P17.L15): The use of the term CBA needs explanation: it implies public choice and assessment of welfare change associated with public investments .

Answer: See response to comment RC3.

RC57 (P17.L16): Quite consolidated practices. Meaning

Answer: We mean that cost assessment in CBA is not very problematic, as all cost data can be easily determined. This sentence was removed in the new version of the manuscript.

RC58 (P17.L18): limited to the direct avoided damage to people and some exposed items . this is not clear

Answer: In the revised manuscript we have paraphrased this sentence as follows: "Present damage modelling capacity is mainly focused on direct damage to people and some exposed assets (typically residential buildings) thus preventing the possibility of performing comprehensive flood damage assessments and then reliable CBAs".

RC59 (P17.L24): The points here are not clear. I suggest the whole paragraph might be recrafted to advantage, with some examples to support the argument

Answer: The whole discussion sections have been redraft in order to better support our critical analysis of the model and its implementation (See Section 5)

RC60 (P17.L30): I am not convinced Figure 6 does this. What does the greater than 100% refer to: is this the gross profit estimate in Figure 6. Assumption of no yield loss with (delayed) reseeding probably underestimates losses . There may be opportunities for reseeding with a different crop, especially between winter sown and spring sown crops

Answer: 100% refers to the relative damage, as defined in Equation 2, i.e. $d=D/NM_{noflood}$. Reference to Eq.2 has been included in the revised Figure caption, where we have also clarified that "Results shown for the "r" option are obtained by assuming a null yield penalty for late (re-)plating". Regarding reseeding with a different crop, we have better explained in the revised version of the manuscript (see reply to

RC49) that we assume only a single crop type in field (reseeding with a different crop is considered not possible).

RC61 (P17.L30): Apart from EU contributions? Not clear

Answer: With "apart from EU contributions" we meant "if excluding the EU contributions" (which will still be obtained by the farmer). We have clarified this point in the revised version of the paper.

RC62 (P17.L30): Sustained? Already committed/incurred

Answer: Ok. This has been changed with "incurred" in the revised manuscript.

RC63 (P19.L0-10): These are valid and critical points, and fundamentally concern the underlying variation and uncertainty in the estimates (that have been single values so far). In my view it would be more appropriate to include the treatment of variation and uncertainty in the description of methods and the presentation of results of the case, rather than raise it for the first time here in discussion, where the purpose is to critical discuss the methods and results.

Answer: See reply to general comments regarding the reorganization of the paper. In our opinion, this specific point on uncertainty of estimations should remain in the Discussion section of the paper, as here, after the presentation of model structure, description of input parameters and data, we make comments of strengths and weaknesses of the adopted approach.

RC64 (P19.Fig7): This is results and should go there above. The figure is presumably for the Po case? The likely effect of a 10% penalty that would most likely arise due to (delayed) planting is apparent : negative gross profit. A figure showing absolute changes in gross profit (as defined here) might be useful in the results section.

Answer: See replies to general comments regarding the reorganisation of the paper. Figure 7 has been removed to increase the readability of the paper

RC65 (P19.L16): Rather than saying 'must' it would be better to say why, identifying the advantage of doing so.

Answer: We explained the need of developing rapid approximate methods just in previous lines of the original manuscript (P19.L11-16): "The development of AGRIDE-c highlighted some challenges for the hydrology and the 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 1D steady hydraulic models to 2D 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, both for technical and economic constraints".

RC66 (P19.L18): Perhaps rather than 'no more' , 'not only.... but also' seasonal probabilities Is the Morris and Hess ref 1988?

Answer: The reviewer is right. The sentence and year of Morris and Hess paper have been fixed in the revised manuscript.

C67: This paper? The reference to the spreadsheet and to supplementary data needs further support : these are mentioned in passing

Answer: "This paper": It is a writing style preference, as already discussed in replies to previous comments. In revising the paper, we have better emphasize reference to the spreadsheet and supplementary data.

RC68 (P20.L5): It depends how far the Authors have looked, and with the information presented here it is difficult to judge whether they can substantiate the claim. It might be fair to say they see advantage in developing a generic framework that can potentially be applied across different geographical and economic contexts , and they have made progress in this respect. For example, in more temperate part of Europe, land drainage is a particularly critical component of the land use: flooding nexus, and is particularly critical during post flood periods .

Answer: We have revised the sentence according to reviewer's suggestion. The issue of land drainage has been be discussed as well (see reply to general comments).

RC69: It would be useful to have a description of the sub models used , as referred to earlier. A summary table showing the estimation methods and sources would be particularly helpful, linked to supplementary data.

Answer: See answer to RC8.

RC70: Damage mechanisms- Meaning ? Drainage and soils might be important also. And also salinity issues in coastal areas, as referred earlier.

Answer: With damage mechanisms we mean the interaction between damage influencing factors and characteristics of exposed elements leading to a loss. This explanation has been included in the new version of the manuscript. Issues related to soil drainage and salinity have been included as well (see answers to general comment RC4-RC5).

Manuscript nhess-2019-61 "AGRIDE-c, a conceptual model for the estimation of flood damage to crops: development and implementation" – <u>Point by point response to referee 3 comments</u>

We would like to thank the referee for the work he did on our manuscript. We think that several of his comments can contribute to increase the manuscript robustness and, in general, to improve its quality and readability. Conversely, we partly or do not agree on some specific comments. In the following, we supply a point by point reply to referee comments.

RC1: My main concern is on the innovation provided by the article compared to precedent studies. From precedent studies, referred in the state of art section, it can be seen that many bricks presented in the article were already existing. For instance, a "conceptual model" has yet been formalized since the 80's in the USA, combining in a certain way "physical damage" and their "economic implications" in terms of loss of added value. Even if all detail are not given, many specifications are provided (see the user's manual of AGDAM, link provided below). Part of those details may be available from other studies. For instance, in our works (Agenais et al., 2013), we explicit completely how we link "physical damages" with "economic implications". Thus, I recommend that the article should be more specific on what it gets from previous studies, and what it added.

Answer: We agree with the referee when he states that "many bricks presented in the article were already existing". In fact, our effort was to organise "this fragmented knowledge" in a "generic" tool that could potentially improve the reliability and ease the procedure of flood damage assessments to crops in future studies. As stated at pg. 7 line 20-25 "AGRIDE-c has been developed by adopting an expert-based approach, encapsulating and systematising all the available knowledge on damage mechanisms triggered by inundation phenomena, as well as on their consequences in terms of income for the farmers. Information has been derived by a thorough investigation of the literature and by consultation with experts (i.e. agronomists and representatives of the authorities responsible for agricultural damage management and compensation). The result is a general, conceptual model, which identifies the different aspects to be modelled for the assessment of flood damage to crops, their (inter)connections as well as the variables at stake".

We would not define contents included in the AGDAM manual as "a conceptual model". AGDAM is a software and what is included in the manual is a diagram showing software inputs and outputs (pg. 4), and the theoretical background of its calculations. We do also not agree that AGDAM combines physical damage with economic implication. Loss functions in AGDAM are cost-based and assume the total loss of the revenue (pg. 16). The only physical aspect that is considered is the percentage of affected crops according to flood duration, on which base loss functions are weighted, but no reference to the reduction in the yield and/or its quality is made, according to different hazard and vulnerability variables. Given that the translation of physical damage into monetary terms can be challenging and not univocal, we strongly support the implementation of both a physical and an economic model. In fact, the distinction/link between physical and economic damage is present in several past works even if not explicitly (beyond Agenais et al. 2013, in Pivot et al. (2002), Morris and Hess (1988), Morris et al. (2014)); they are all quoted in the paper. We embraced this modelling approach in AGRIDE-c as we did in our previous work on flood damage to residential buildings, following a synthetic approach (Dottori et al., NHESS, 2016).

RC2: in their conclusion (page 20), the authors state that "According to authors' knowledge, AGRIDE-c represents the first attempt to organize all the available knowledge on flood damage to crops in a usable and consistent tool (i.e. the model integrates physical and economic approaches) that can be implemented to guide the flood damage assessment process, in different geographical and economic contexts." I do not master totally the American approach, but it has been developed to be used in different context (USA is a large country...) and has been developed as a tool used by USACE (ADGDAM). Another example is coming from Hess and Morris (1988), that also organized their work on grasslands in a framework comparable to that of AGRIDE-c and included it in a tool (SCADE). Last example, concerning our work, I can specify that in

chapter 3, the presentation of the methodological framework gives a clear explanation that damage are considered as loss of added value and how to link them to physical effects of flood.

Answer: we stress our opinion that AGDAM cannot be considered a conceptual model; moreover, its transferability to other (economic) contexts is limited by the fact that there are not specific guidelines on how to create or adapt loss functions. The work by Hess and Morris (1988) is instead very specific on grassland and is included on a tool for the evaluation of land drainage strategies. We agree that in chapter 3 of Agenais et al., 2013 damage is defined as loss of added value, as other authors did (e.g. Morris and Brewin, 2014; Pivot et al. 2002; Morris and Hess,1988), and that a brief discussion is included on how to link it to physical effects of flood; still, this cannot be considered a conceptual model in our point of view.

RC3 In chapter 4, we give some precision on modelling of damage to sub-component of farms (which include crops, vegetal material, soil, equipment). For crops, we explain how to take into account farmers' strategies (continuation, abandoning, reseeding for instance), depending on when the flood occurs compared to the crop calendar.

Answer: Our model includes knowledge coming from Agenais et al. 2013, as it is stated in the paper. Although, we did not specify in the manuscript which works have been already taken into considerations farmers' strategies (like Agenais et al., 2013 but also Pivot, et. al 2002); we added these specific references in the paper (Section 3). Still, we want to stress that alleviation strategies are not explicitly taken into account in existing damage models, neither in the functions reported in chapter 5 of Agenais et al., 2013. In the implementation of AGRIDE-c in the Po Valley, we make explicit the effect of strategies on flood damage as well as when the different strategies can be implemented or not (Figure 6).

RC4 In chapter 5 we explain that all this has been implemented in a tool called floodam (now floodam-agri), which aim is to help to adapt damage modelling to different context, including prices, crops calendars, and even also the question of the typology of culture to best fit with typology of GIS.

Answer: We cannot appreciate the potentialities of floodam as we could not find it online. According to our understating, chapter 5 of Agenais et al., 2013 is about the adaptation of national French functions to local French contexts.

RC5 I want also to point that the authors present results for 4 types of crops, whereas both the American and the French approaches deal with many more types (including permanent crops)

Answer: After reading the referees' comments, we realised that the "scope of use" of our model was not well specified in the original version of the paper, which could lead to incorrect interpretations of our work. In fact, the conceptual model has been designed to supply an estimation of flood damage:
-      to annual crops (i.e. not including perennial plants)
-      by considering one single culture (i.e. by not considering replacement of one culture with another one)
-      by limiting the time frame of the analysis to one "productive cycle" (i.e. not considering long term damages, e.g. loss of soil productivity in the following cycles/years);
-      for infrequent flooding (i.e. effect of two, or more, consecutive floods is not considered)
Nonetheless, as specified at page 9 line 11-19, AGRIDE-c do not consider damage to other components/elements of the farm that may induce additional damage to crops, as, for instance, damage to machineries and equipment (e.g. the irrigation plant) that may prevent cultivation for a while. Only damage to soil is considered from the evidence that, during a flood, damage to soil and plants occurs always at the same time, differently from damage to the other components which can occur or not, independently from the damage to plants; as a consequence, damage to soil and plants is modelled together, while damage to the other components could be modelled as separated factors, not included in the conceptual model. We

thank the referees to highlight this limit of the original manuscript that we addressed by specifying all these aspects in the new version of the paper (Section 3).

Regarding the implementation in the Po Valley, its objective was not to create a comprehensive model for the estimation of flood damage to crops in the area, rather it was to exemplify how the conceptual model can be implemented in a specific context.

RC6 I feel uncomfortable with the articulation of the two parts of the article, "conceptual model" and "implementation". From figure 2, it is expected that implementation of AGRIDE-c shall take into account all the phenomena described. But when coming to the implementation, it appears that many of those phenomena are not taken into account (loss of fertility due to sedimentation or loss of quality for instance). This shall be exposed in a clearer way not to induce false expectations on the scope of the study.

Answer: We thank the referee to highlight this lack of clarity in the paper. The idea of dividing the conceptual model from its implementation was also conceived with the objective of highlighting the gap between the available knowledge on damage mechanisms and their drivers/explicative variables, and their present modelling capacities. In fact, in order to be generally valid in any specific context, the conceptual model must include all the phenomena which affect the final loss figure. Then, its implementation must take into account not only the specific features of the investigated context (and then the relevant phenomena) but also modelling and data availability. In the Po Valley, data and models are required to properly take into account damage to soil and loss of quality; in their absence we made simplified assumptions, highlighting also research needs (see Conclusions). A table summarising the main elements and sources of revenue and cost estimation processes (i.e. model input data), considered in the application of the model in the Po Valley has been added in the new version of the paper (Table 3)

RC7 Third, I think that the conceptual model is incomplete, at least for perennial crops (such as vineyard, but also grassland). First, it does not seem clear that the authors get that for some culture it may be useful to separate crops (fruits) and vegetal material (trees). This is not restricted to vineyard and orchards, but may also be important for asparagus, and even certain type of grasslands. If vegetal material is affected by flood, there may be at least two types of effect that last more than one year. For a given plot, if some plants are to be "destroyed" by a flood, it is expected that yield reduction and thus of products, but also variations of charges occur during the following years. This type of effects are for instance implicitly taken into account in Agenais et al.

Answer: see answer to RC5

RC8: Forth, I think there are not sufficient description of the role of the direct consultation of experts for the current work. It is only said (page 7) that some experts were consulted (agronomists and representatives of the authorities responsible for agricultural damage management and compensation), that this expertise were used to produce the production costs for normal activity (page 11, figure 3), the 3 possible strategies after a flood occur (pages 12-13) and an opinion on the suitability of yield reduction model coming from our works for maize grain (page 12). As many of the implementation seem to rely on the consultation of experts, I think a much more detailed description of this consultation shall be provided: how many experts has been consulted? What were their precise expertise, especially concerning flood impacts? What were their opinions on the data they provided? Have they been consulted on the results? What were their opinion on those results? What were their opinion on the transferability of those results on other context? This would strengthen this part of the work, that is almost invisible at the moment

Answer: We really thank the referee to highlight this lack in the original version of the manuscript. Experts were involved with two main objectives. The first one is to support the definition, and validate the quality, of the conceptual model. The second one is to give suggestions/information on the implementation of the model in the Po Valley, above all regarding expected physical damage and costs.

With respect to the first objective, an iterative process was followed. First, a semi-structured interview was conducted, by asking experts about the main damage mechanisms/phenomena in case of flood, possible interconnections among them, important explicative variables. In this phase, results from the literature review were proposed to experts for their judgment. In the following step, experts were asked to evaluate a draft version of the conceptual model we draw according to the literature review and results from first interviews. Then, there was an iterative revision process of improved versions of the model until an agreement on its final structure was reached.

With respect to the second objective, several individual meetings were organised with the aim of asking experts about context-specific information on: crops calendars, yields and prices, type, timing and costs of cultivation practices. In this phase, the transferability of the model by Agenais et al. was also discussed.

Three kinds of experts were involved. One representative of the Regional Authority 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. Two agronomists of the local association of farmers (Coldiretti Lodi), with specific knowledge on the investigated context and with direct experience in managing floods in the last 20 years. During the work, the two agronomists asked for data/information also to individual local farmers that were flooded in the past years, including also their viewpoint in the process. Finally, an academic economist, with specific expertise in agriculture, has been involved in validating the final model.

This information explaining the whole process of experts' involvement has been included in Section 3 and 5 of the revised manuscript.

RC9: I would therefore recommend to be less ambitious in terms of interest of the article and to reorient it on the question of what has been necessary to adapt from previous works to a specific context. I invite the authors to be more precise on what they really include in their model, not on what they would have liked to include, because this makes things unclear for the reader. Another perspective would be to make a clear list of what that have not included. I also invite the authors to be more specific on how they have really implement their "local" model, by precising all the steps about consultations of experts. This seems important, especially for a expert-based approach. For those reasons I recommend a major revision.

Answer: we thank the referee for the comment as we think that, by addressing it, we could better specify (in the new version of the paper) which is the added value of the work (i.e. the conceptual model of available knowledge), which are its limits (i.e. the focus on the only crops component, the time frame of the analysis to one "productive cycle", the existing gaps between knowledge and modelling) and the implemented methodologies, above all with respect to expert 's consultation (see also answer to RC5, RC6 and RC7)

RC10 Given the scope of the article, I am not totally convinced that the state of the art analysis should be done in such a detailed way. This is more convenient for a kind of review articles. If this section should stay in such a detail version, some imprecision needs to be corrected. For instance: - P3-L16. "No model in Table 2 considers instead the behavior of farmers after the occurrence of the flood (e.g. the decision of abandoning the production or to continue with increasing production costs)..." Agenais et al. does (see chapter 4) - P3-L22. The distinction between "physically based" and "cost based". is not clear. As formulated "cost based" models appears as simpler models where yield reduction is always total, which is not the case for "physical based" models. But for "physical based" models consequences in terms of production costs are considered. - Table 2. I am not convinced by the way some works are classified. For instance AGDAM cannot be said as "cost based", as it also consider some physical aspects on flood for yield reduction. I have not the time to check for all the works. Thus, I am not confident by what is presented in table 2. - P5-Table2 Agenais et al. present damage functions for 14 crops type, based on a detailed model of 50 crops types.

Answer: We think that the detail of the state of art is required in order to highlight research needs and then the objective of our work. We verified imprecisions suggested by the referee, individual comments are supplied:

- The model by Agenais et al. (i.e. functions in chapter 5) does not explicitly take into account alleviation strategies in damage estimation.
- According to us the distinction between physically-based and cost-based model is clear, laying in considering or not the estimation of physical damage. Accordingly, the AGDAM model must be correctly classified as "cost-based"
- Table 2 refer only to (annual crops); this will be specified in the new version of the paper

RC11 I haven't seen the demonstration of what is promised in the abstract about "comprehensive cost-benefit analyses of risk mitigation actions". What is said in the discussion (page 17) is just that AGRIDE-c provide a way to estimate direct damage to crops, but in fact, it is only one contributions among others. I also feel that the authors did not get that for CBA purpose, it should be considered a "collective perspective", without considering possible transfers. This is not clear (see remarks on the "spreadsheet" tools). I think that should be reformulated.

Answer: The objective of the paper is to present a model and to discuss its potentialities, not demonstrating its usability. In fact, another manuscript is under preparation on the use of AGRIDE-c for the CBA of flood risk mitigation strategies in Lodi. We agree with the referee that including the potentialities of the work for CBA in the abstract can lead to misunderstanding of papers' results and findings. In the new version of the paper, we removed reference to CBA in the abstract, limiting its discussion in the introduction/discussion sections. The CBA of flood risk mitigation strategies would require a comprehensive estimation of benefits linked to the different strategies, i.e. of the avoided loss to all exposed sectors and at different temporal scales (i.e. direct and indirect/long term damages). Present damage modelling capacity prevents comprehensive flood damage assessments, which usually include only direct damage to people and some of the exposed assets (typically residential buildings). In such a context, by allowing the estimation of the expected loss to crops in a specific flood scenario, AGRIDE-c may support more comprehensive CBAs of public risk mitigation strategies. Of course, to meet such an objective, the tool must be critically used, e.g. by considering possible transfers of losses/gains between farmers in an economic perspective, according to the temporal and spatial scales of the analysis. With respect to other available tools, we think that AGRIDE-c, by conceptualising the whole damage estimation process, may lead to more reliable and transparent estimations. More comments have been added on this point in the new version of the paper (Section 1 and Section 5).

RC12 I haven't seen neither the demonstration that AGRIDE-c is a "a powerful tool to orient farmers' behaviour towards more resilient damage alleviation practices". I do not know in detail what is the context of management of flood and agriculture in Italy. It is not presented in the article. But, this context may have some implications on what strategy would be follow by farmers, independently of what AGRIDE-c shall demonstrate. For instance, in France, if a farmer expect to receive some compensations from "Calamités Agricoles" (a State compensation scheme) or from "Assurances Récoltes" (Private insurance), he shall have to follow some recommendations concerning what he can follow as a strategy. If he does not, he may not receive any compensation. Also, it is not clear that the consequences presented are really those supported by the farmers. If there exists some compensations in Italia, this shall be included to provide a true "financial perspective" (point of view of the farmers).

Answer: We stress that the objective of the paper is to present a model and to discuss its potentialities, not demonstrating its usability. By supplying the expected damage for different types of crops and alleviation strategies (according to the expected yield reduction for different flood intensities and period of occurrence), AGRIDE-c may help individual farmers exposed to flood risk in preventing losses by supporting: the choice of the most appropriate crops to be cultivated, the choice of the best alleviation strategy to be followed once flooded, the evaluation of the opportunity to ask for a flood insurance scheme and the definition of the premium. This is a specific finding of the paper that have been better specified/commented in the new version of the manuscript (Section 5).
Insurance in Italy is not compulsory and is not linked to specific recommendations/strategies to be followed in case of flood.

RC13 I am not convinced by the starting line 19 on page 19, concerning the necessity of "sediment and contaminant transport models" as the authors said before that they did not find available models to estimate the effects of sediment and contamination. This appears not coherent.

Answer: The effect of sediments and contaminants transported by flooding water on the yield is well documented in the literature (see Agenais et al., 2013; AGDAM, 1985, The Multi Coloured Manual, 2013, Hussain, 1996), as stressed in the paper. Accordingly, we included this effect in our conceptual model, although (of course) the importance of the phenomenon varies from place to place, being negligible in some areas like the one investigated in the manuscript. However, hazard assessments (i.e. flood hazard maps) usually do not supply estimates of sediments and contaminants load, even in such contexts when the phenomenon plays a crucial role, avoiding the estimation of its effect on flood damage to crops. This is a limit of present tools that we want to highlight in the paper.

RC14 I think that some of the figures presenting the results shall be changed. In fact, in the title, the authors say that they analyze "damage to crops" but none of the figures clearly present a "net" damage. The reader has to make a mental effort to understand what are the damage from those figures (5 and 7): - make a difference between last point of the curve of scenario 0 and last points of three other curves for the production costs part - make a difference between a value given by a bar for scenario 0 and 3 other values for the "turnover" part - and then make a difference between the difference of turnover and the difference of production costs... Well, this should be done for the reader! This could allow to have a representation of the flood damage depending on the season of occurrence (as a function).

Answer: We thank the referee for the comment. We have amended Figure 5 (while Figure 7 was removed to increase the readability of the paper), explicating the value of the absolute damage, by showing also changes in gross profit (i.e. net margin in the revised paper, after reviewers' indication). However, we want to stress that Figure 5 does not represent the damage model but it is only functional to the description of the process leading to it. The final output of the damage model is displayed in Figure 6. From this, the calculation of the damage is immediate, by multiplying the relative damage by the net margin of the specific farm.

RC15 Concerning figure 1, the authors announce that relative damage is supplied by our works (Agenais et al. 2013), but this is not the case. Our results are expressed in absolute damage (see page 51 of our report). Thus, the figure 1 is an interpretation of what we have done, but this interpretation is not explained. Moreover, this interpretation is necessary incorrect, as our results are presented on a seasonal time step (3 months) whereas the time scale in the figure 1 is one month. Moreover, as seen in our reports, relative damage are maximum only in summer, for long duration, and height over 130 cm, thus it is impossible to have relative damage of 100 % for any other case. I have not verified what is announced about the presentation of the results of Forster et al., but it shall be verified.

Answer: The referee is right as we did not use absolute damage functions at pg. 51 of Agenais et al., 2013 but relative "physical damage functions" supplied in the annex (pg. 200-202), and reported in Figure 4 of the paper. In fact, the objective was to highlight differences between physically-based and cost-based approaches. On the other hand, we choose the two models to allow a direct comparison in terms of relative damage, avoiding possible errors in transferring relative damage to absolute damage and vice versa. The physical damage functions in Agenais et al., 2013 are expressed for vegetative stages of the plant (not for three months) that we have linked to the months of the year, according to the Italian climate and cultural calendars (Initial phase: April-May, Growing phase: June, Flowering phase: July-August, Maturation phase: September-October, see Table 3). According to the functions, for a 3 days flood, a 100% physical damage occurs in the Initial phase (for any water depth value) and in the flowering phase for water depth greater than 130 cm. This is reflected in the first row of Figure 1 with a 100% peak of damage in April and July, which are representative, respectively, of the initial and flowering phases. For a 15 days flood, a 100% physical damage occur in the Initial, growing and flowering phase (for any water depth value) and also in the maturation phase, for water depth greater than 130 cm. This is reflected in the second row of Figure 1 with

a 100% damage from April to July (for water depth equal to 0.4 e 0.9 m) and from April to October (for water depth equal to 1.5 m), which are representative, respectively, of the initial, growing and flowering phases, and of the whole cultural cycle. To be more clear, we replaced Figure 1 with the following where 100% damage is reported for the whole duration of the different vegetative stages.
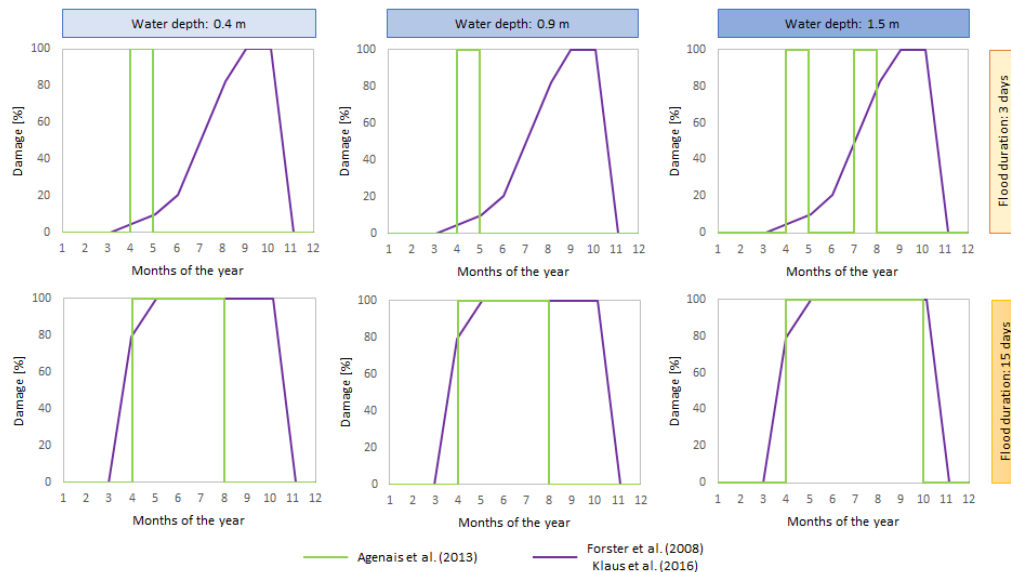
Although an explanation was required to clear referee doubts, we do not think that the detailed explanation of how we implemented the model must be included in the paper, as it is out of the scope of the meaning of Figure 1. Foster et al. was implemented at the best of our understanding.

RC16 I had a look at the "spreadsheet" tool, and I share some comments on it, as I understood that all the application where made thanks to it: - There is not a manual to help people use the tool, it would be nice (necessary?). - Technically this tool is not designed to produce damage function but to estimate damage for specific value of hazard. This is not very practical for a user interested in a "damage function".

Answer: The tool was designed to support analysts in the calculation of damage for a specific hazard and vulnerability context, by implementing the damage functions we derived for the Po Valley, and which are reported in Figure 6 and in the Appendix. Such functions are included in the spreadsheet but can be also partly modified (by changing revenue and costs parameters). A user-manual have been added in the new-version of the paper to explain and increase its usability

RC17 I have some questions on how the value coming from "Agenais" were filled, as I cannot remember that the authors asked for those values, which are not detailed in our report. - For instance, in some cases (maize, germination) yield reduction may occur for flood with a duration of 0 day, and in other cases (maize, flowering) there is no yield reduction for such flood with duration of 0 day. This may be a misunderstanding of what we developed. This leads to possible damage for a flood of 0 day and 0 cm for maize, which has no sense in our works. Such a flood is typically a flood with no consequences.

Answer: The referee is right when he says that the report by Agenais et al. does not detail model's values, which is a limit for its transferability. He is also right in saying that we did not ask for such values. In fact, given the simplicity of the functions, we made some assumptions that were supported by local experts' opinions. In particular, we used the relative physical damage functions reported in the Agenais report at pg. 200-202 (and also reported in our Figure 4) by assuming a linear increase of damage from 0 to 100% when required (see pg. 12 line 15)
According to such functions, in the initial phase, any flood will lead to a 100% damage (see pg. 200 of the Agenais et al. report), and it is in this sense that figure 4 must be read, with respect to the red square related

to the initial phase. On the contrary, in the flowering phase, a flood with a duration of 0 days will not lead to damage, and this is correctly reported in Figure 4 as in pg. 201 of the Agenais et al. report.

While tuning the model for the Po valley we started from the model of Agenais et al., 2013 we kept the same structure, we approximated trends with very simple functions (straight lines) while defining limits of such lines by a comparison of the original model and opinions of local experts. Due to the strong imprinting of Agenais et al. 2013 on our model, we considered as honest to declare the latter as an adaptation of the former. However, if the reviewer (and the editor) consider our model to be too loosely connected with the original one, we have no problem to indicate our model as freely inspired to that of Agenais et al., 2013 thus avoiding claiming any responsibility of the original one on our results.

RC18 Another thing is that it is not specified that all data used from Agenais et al. are only specified for negligible flow velocity. This is particularly important for maize, wheat, and barley, that are very sensitive to this parameter. This may induce a bad use of the tool.

Answer: The referee is right. In fact, this is one of the reason for which we chose the model by Agenais et al., 2013, for the Po Valley, where riverine long-lasting floods are the typical flooding events. We have better specified this in the new version of the manuscript. See section 4.3: "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 (Section 4.1), i.e. riverine long-lasting floods with low flow velocity.".

RC19 One of the aspects that may change from site to site is the list of actions inside the crop management sequences. There are many reasons for which those actions may differ, not only in value but also in nature. This aspect is not taken into account, and doesn't seem to be easily taken into account with the provided tool.

Answer: The referee is right. By referring to the model we implemented for the Po Valley, the spreadsheet allows changing revenue and costs parameters, but not the type of cultivation practices. Still, as an open tool it can be easily modified to take into consideration of other context-specific cultivation practices.

RC20 In the tool, "EU contributions for agriculture" are included. This is more oriented for a financial analysis (point of view of a specific farmer, including transfers) than for a Cost-Benefit Analysis (collective point of view, excluding transfers). I think a clear precision on the usage of damage produced should be added. If a financial perspective is to be promoted, all insurance or compensations mechanisms should be also included to give a better view of net consequences for the farmer.

Answer: The tool refers to the model implemented for the Po Valley where insurance is not compulsory. However, in order to use the tool in a financial perspective for a specific farm with an insurance, the tool can be easily adapted to include also this form of revenue/cost. Otherwise, if required, the tool can also be used for CBA of public mitigation strategies, by resetting cost parameters that may be included in transfers.

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

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10 **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 with 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 damage mechanisms to crops is a powerful tool to support more effective damage mitigation strategies, both at public and at private (i.e. farmers) level.

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 damages 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 benefits produced by the adoption of different strategies (Jonkman et al., 2004; Mechler, 2016), consisting in the avoided losses to all exposed sectors and at different temporal scales (i.e. direct and indirect/long term damages).

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Present damage modelling capacity is mainly focused on direct damage to people and 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 opposite, the importance of developing new and reliable models for more inclusive flood damage assessments

5   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 weigh 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 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 so far less attention than other exposed sectors, as

10   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 post 1980s, when the subsides to agriculture were being challenged by the increase of agricultural surpluses under

15   the Common Agricultural Policy, along with the incentivisation of insurance coverage for damage to farms, that led most of 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 middle 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 et al. 2008; Morris 1992). Still, literature

20   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 the 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 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

25   exposed sectors 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, both in terms of 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

30   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

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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

5   of Italy. The case study is completed with a spreadsheet (available as supplementary material at https://tinyurl.com/yyj2arhp) 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 art on flood damage modelling to crops, as the starting point of the research. Section 3 presents the AGRIDE-c model, while Section 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

10   finally drawn in Section 6.

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

2 State of art on flood damage modelling for crops

15   Prominent examples of damage models for crops are reported in Table 2. The analysis of the table indicates that 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

20   (USACE, 1985; Morris and Hess, 1988; Hussain, 1996; RAM, 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 which makes 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, the latter being the only vulnerability parameter often considered by the models. In the case of meso-scale

25   models (Kok et al., 2005; Hoes and Schuurmans, 2006), this parameter is replaced by the agricultural land-use. No model in Table 2 considers instead the behaviour of farmers after the occurrence of the flood (e.g. the decision of abandoning 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 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 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; RAM, 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 in relative terms, as a percentage of a maximum exposed value. Finally, 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).
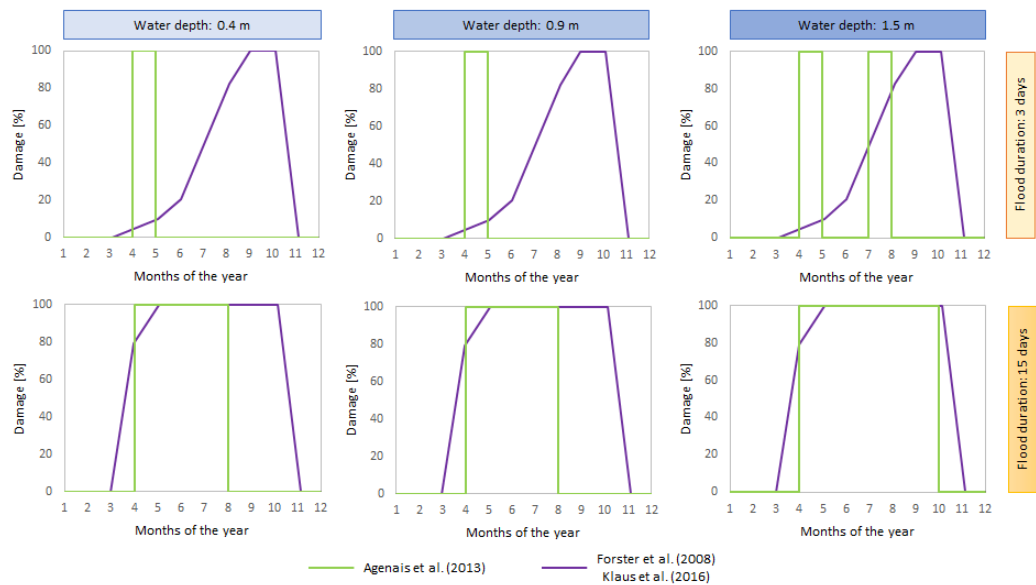
Study and country	Crop types	Hazard parameters	Vulnerability aspects	Modelling approach		Monetary evaluation approach	Validation
				Empirical vs. expert based	Cost vs. physically based		
AGDAM/ Hazus (USACE 1985) - USA	Generic crop	Duration, time of occurrence (month)	Crop type	Not specified	Cost based (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

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

Overall, the state of art depicts a fragmented scenario, characterised by the existence of 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, e.g., 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 to be applied 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 Figure 1, where the models are applied for three different values of the water depth and two different flood durations.

Figure 1. Comparison between relative damage supplied by Forster 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

For example, for short duration floods (d=3 days), Agenais et al. 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. estimate the maximum damage in September-October, whatever is the value of the water depth.

The main reason for this inconsistency lays in the different modelling approach adopted by the two models: physically-based
5   in the case of Agenais et al. and cost-based in the case of Förster et al.. Coherently, Agenais et al. estimate the maximum damage in correspondence of the most fragile vegetative phases of the crop, i.e. the growth (April-May) and the flowering (July-August), while Förster et al. well reproduce increasing costs sustained by farmers during the vegetative cycle, 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. consider water depth as a control parameter, while Föster et
10   al. do not, thus leading to different damage estimation 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. is derived by referring to the net margin, the relative model by Förster et al. refers to the gross output. Given that conventions do not exist on how translating relative damage into absolute terms, the choice of the wrong reference value could amplify inconsistency between the two approaches.

15   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

20   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 as well as 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
25   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 Section 4.

Knowledge at the base of AGRIDE-c has been derived by a thorough investigation of the literature (Section 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
30   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 judgment. In the following step, experts were asked to evaluate a draft version of the conceptual model drawn according to the literature review and results

8

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

5   of farmers (Coldiretti Lodi), with specific knowledge on the Po Plain context and with direct experience in managing floods in the last 20 years; the viewpoint of several individual local farmers who experienced flooding in the past years was also included in the analysis, as the two agronomists asked them for direct data and information to support their considerations; (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

10   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 damages, in particular, loss reduction of soil productivity in the following cycles is not considered;

15   In addition, AGRIDE-c does not consider damage to other components/elements of the farm that, on turn, may induce additional damage to crops, as, for instance, damage to machineries and equipment (e.g. irrigation system) that may prevent cultivation for a while (Dunderdale and Morris, 1997; Posthumus et al., 2009; Agenais et al., 2013; Bremond et al., 2013; Morris and Brewin, 2014). Only short term impacts on soil are included, based on the evidence that, during a flood, damages to soil and crops are concurrent, differently from damages to the other components which can occur or not, independently from

20   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 Figure 2. Absolute damage (D) for an individual farmer is expressed as the difference between the reduction in the gross output (ΔGO) and the increase/decrease in production costs (ΔPC), as a consequence of the flood of a specific crop. This is equal to consider absolute damage as the change in the net margin (NM =

25   GO– PC, where GO = gross output and PC = production costs) due to the flood, compared to the case when no flood occurs (i.e., Scenario 0):

$$D = NM_{noflood} - NM_{flood} = (GO_{noflood} - GO_{flood}) - (PC_{noflood} - PC_{flood}) = \Delta GO - \Delta PC \qquad (1)$$

Accordingly, relative damage (d) can be obtained by dividing the absolute damage by the net margin in the Scenario 0 ($NM_{noflood}$)

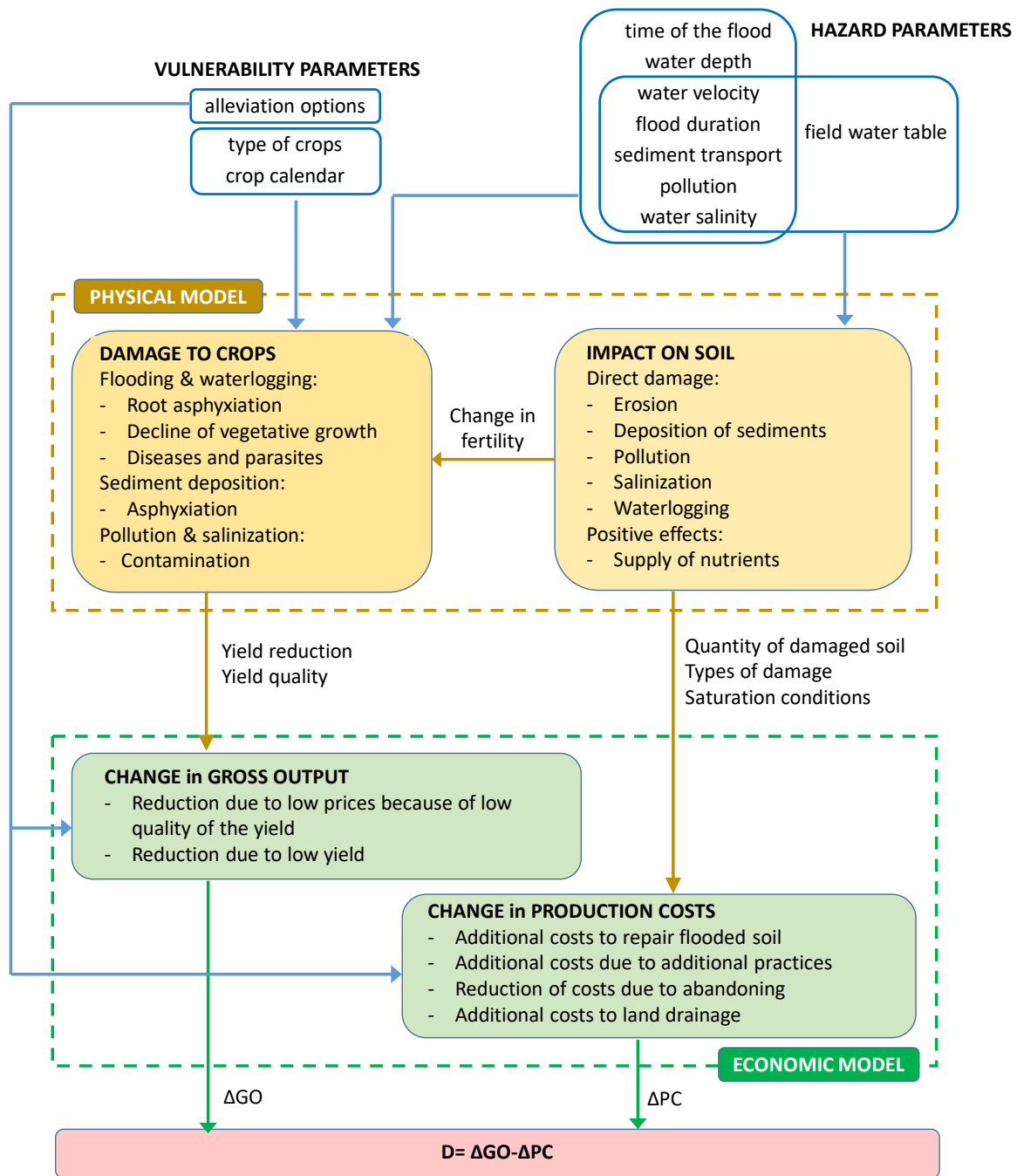30 $$d = D/NM_{noflood} = 1 - NM_{flood}/NM_{noflood} \qquad (2)$$

9

Figure 2. Conceptual model of AGRIDE-c

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 Section 2 are overcome, being both aspects explicitly taken into account.

The physical model (identified by the yellow dashed box in Figure 2) is composed of two sub-models, for the evaluation of physical damage to crops (i.e. the plants) and impact on soil, respectively. 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 case of coastal flooding) and the contaminants load. In particular, the model takes into account of processes like erosion, deposition of sediments and contamination (which affect the costs for soil restoration),as well as of 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 of soil fertility, explained by a (re-)distribution of river sediments and organic matter in the course of flooding that replenish 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 contaminants 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 Figure 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/decrease in production costs compared to the no flood scenario, whereas production costs include direct-avoidable costs, like field operations 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. Indeed, farmers can react in different ways to alleviate flood damage, according to the vegetative stage of the plant at the occurrence of the flood, and of the physical damage suffered by the plant (Agenais et al., 2013; Pivot, et. al 2002). The 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, on 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,

5 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 in the saving of 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

10 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 the Scenario 0, by considering the amount of production (yield), selling prices of the crops, time and costs of cultivation practices in the absence of any flood. Third, analytical expressions for all the

15 processes shown in Figure 2 are derived and then, starting from the 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 / information used in the application for the Po Plain (example of maize). Data sources are clarified in the following sub-sections.

The implementation of the conceptual model to Po Plain was supported by specific knowledge of local experts. In particular,

20 several individual meetings were organised with the aim of obtaining context-specific information related on 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.

25 The last significant event occurred in the province, i.e. the flood of the Adda River in November 2002 (AdBPo, 2003; AdBPo, 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) and low sediment and pollution loads in the flooded areas as typical of the region; accordingly, 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 those related to other crops are reported in the supplement.

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 experts consultation
Impact on soil	As shown in Fig.2	Soil restoration considered as a fixed cost (500€/ha)	APIMA (2013-2017) and experts consultation
Economic Model			
Gross output	Crop yield	175 q/ha	Regione Lombardia (2013-2017)
	Unit price for crop	16.9 €/q	Borsa Granaria di Milano (2013-2017)
	Other (e.g. EU contributions)	150 €/ha for crop rotation; 300€/ha for minimum tillage	PSR Regione Lombardia
Production costs			
Variable costs	Depend on crop type and cultivations practises / strategies	As shown in Fig.3 and Tab. 4	APIMA (2013-2017) and experts consultation
Fixed costs		Assumed equal to 5% of the gross output	Experts consultation

4.2 Characterisation of the Scenario 0

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

10 Given that the vegetative cycle of grain maize in the Po Plain covers one year, the gross output is estimated as the product between the average yield and price for grain maize over the period 2013-2017 (data sources: Regione Lombardia and Borsa Granaria di Milano (Milan Crops Stock Market)), equal to 175 q/ha and 16.92 €/q, respectively. In addition, we also consider the annual EU contributions for agriculture as a further 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 150 €/ha (data source:

15 PSR - Programma di Sviluppo Rurale, Regione Lombardia: http://www.psr.regione.lombardia.it).

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

20 operations have been considered as direct, avoidable costs, as interviewed local experts indicated that in Lodi province most

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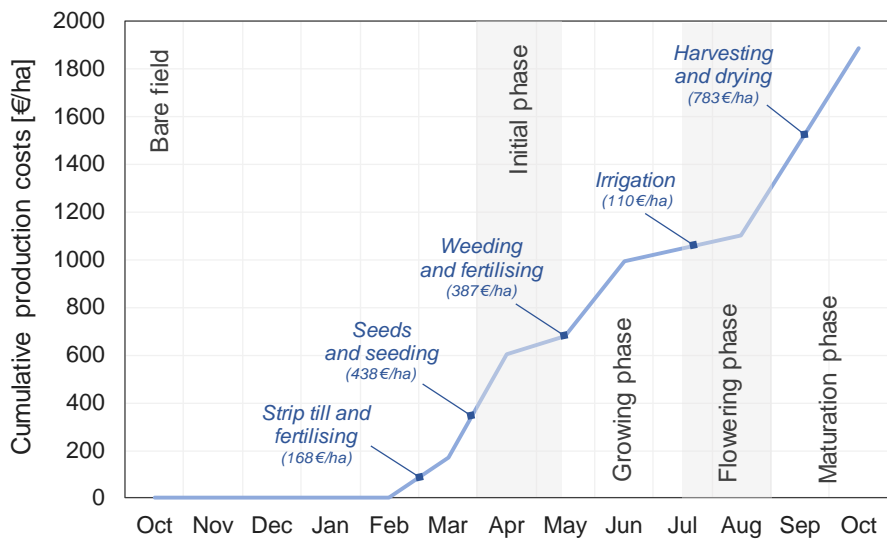
Figure 3. Po Plain case: production costs over the year for grain maize, in case of minimum tillage technique

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 famer in case of no flood equal to 1376 €/ha per year.

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 (Section 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 Figure 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 the 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 days the model gives a null yield loss, independently from the water depth; on the opposite, a flood lasting more than 12 days 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

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experts, we assumed a linear yield reduction (from 0 to 100%) between 5 and 12 days, adapting the model to the context under investigation. The use of this model implies that, at present, we do not take into account neither the reduction in the quality of the yield due to the flood nor 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 Section 4.4).
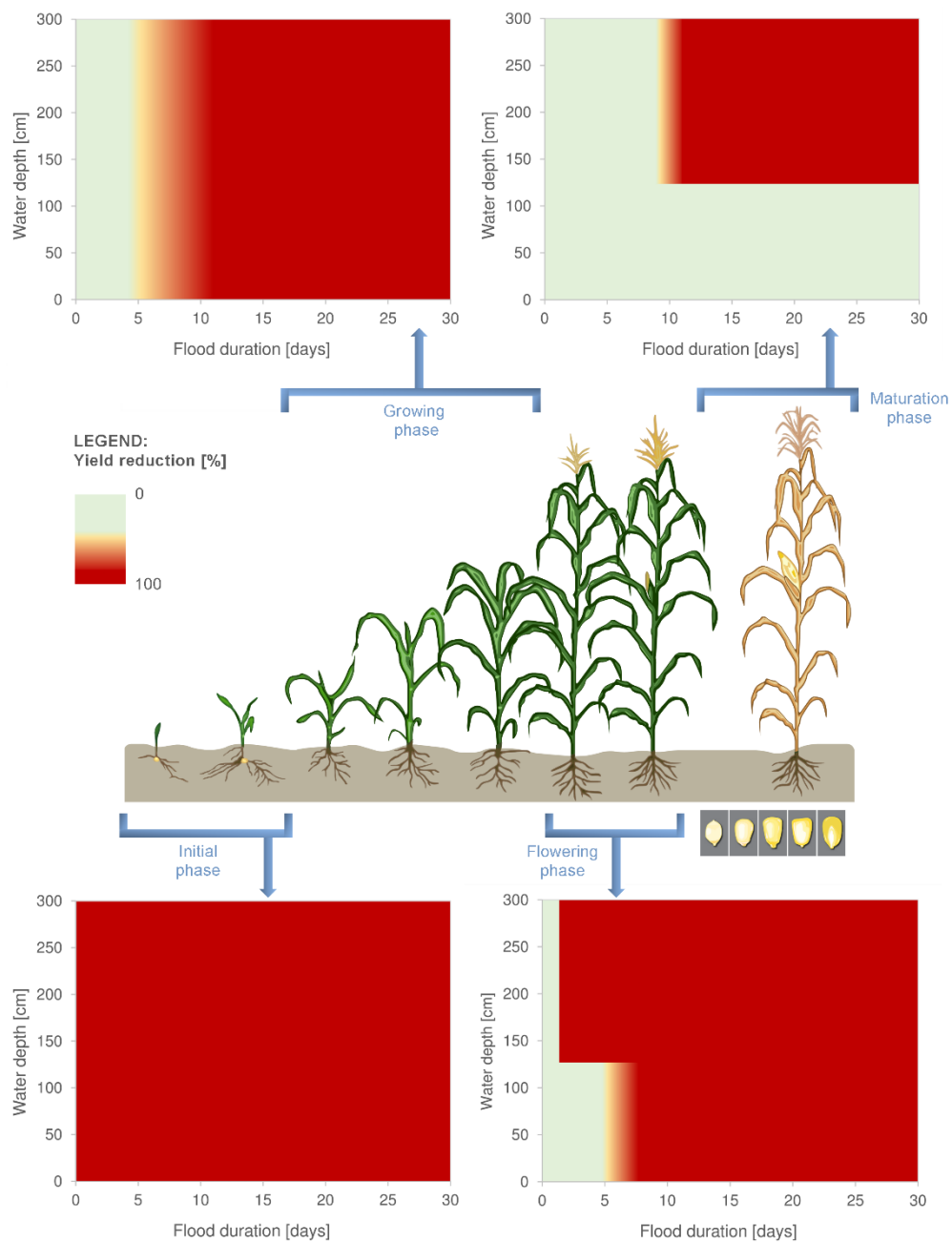
4.4 Impact on soil

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 parametrise 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 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 Section 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 sub-component 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 damages 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 500 €/ha.

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 the continuation or the abandon 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).

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

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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	€/ha	Avoided costs	€/ha
November - March	Bare field	Continuation	0	Soil restoring	500		
April - May	Initial phase	Abandoning	100	Soil restoring	500	Weeding and fertilising	387
						Irrigation	110
						Harvesting and drying	783
		Reseeding	0	Soil restoring (	500		
				Strip till and fertilising	168		
				Seeds and reseeding	438		
June	Growing phase	Continuation	see Fig. 4	Soil restoring	500		
		Abandoning	100	Soil restoring	500	Irrigation	110
						Harvesting and drying	783
		Reseeding	0	Soil restoring	500		
				Strip till and fertilising	168		
				Seeds and reseeding	438		
July - August	Flowering phase	Continuation	see Fig. 4	Soil restoring	500		
		Abandoning	100	Soil restoring	500	Irrigation	55
						Harvesting and drying	783
September - October	Maturation phase	Continuation	see Fig. 4	Soil restoring	500		
		Abandoning	100	Soil restoring	500	Harvesting and drying	783

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 Figure 4 as a function of hazard features, while additional costs are only due to soil restoring (see Section 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, neither in quantity nor in 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 neither 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 as supplementary material (https://tinyurl.com/yyj2arhp). 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 Section 3 and assumptions described in the previous sub-sections, 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:

5    $D = D$ (month, water depth, flood duration, alleviation strategy) = ΔGO - ΔPC   (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, Figure 5 shows changes in production costs and gross output for maize cultivation, for

10   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 calculating the damage D for the farmer.

The first scenario (Figure 5a) refers to a November flood. In this month, the plant is in the break stage, so no yield loss is

15   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 500 €/ha (Table 4), which is the absolute damage sustained by farmers.

The second scenario (Figure 5b) refers to a flood in June, when the plant is in the growing stage. According to the physical model described in Figure 4, in this phase damage depends only on flood duration, while water depth has no effect on it. Figure 5b refers to a 5 days flood which leads, as given by the physical model, to a yield reduction of 12.5%. Given the low physical

20   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 870 €/ha. 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 1106 €/ha. Figure 5b shows that, although possible in theory, abandoning the

25   production is not a reasonable choice as absolute damage equals 2568 €/ha, due to a yield reduction of 100% (the only income for the farmer consists in the EU contributions for cultivation) against a saving of production costs of about 389 €/ha.
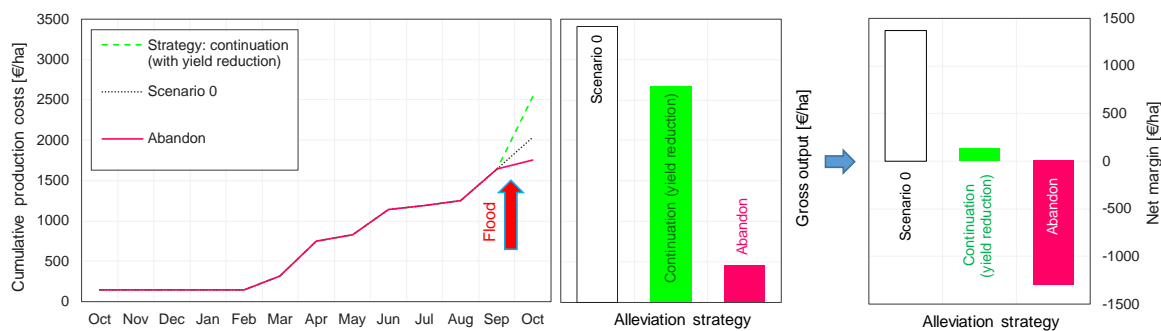
Finally, Figure 5c refers to a flood occurring in September; in this period (i.e. maturation phase of the plant), damage depends on both water depth and flood duration. Figure 5c refers in particular to a 10 days flood with a water depth above 1.30 m. According to the physical model (Figure 4), this flood scenario leads to a 50% yield loss. Farmers have then two choices.

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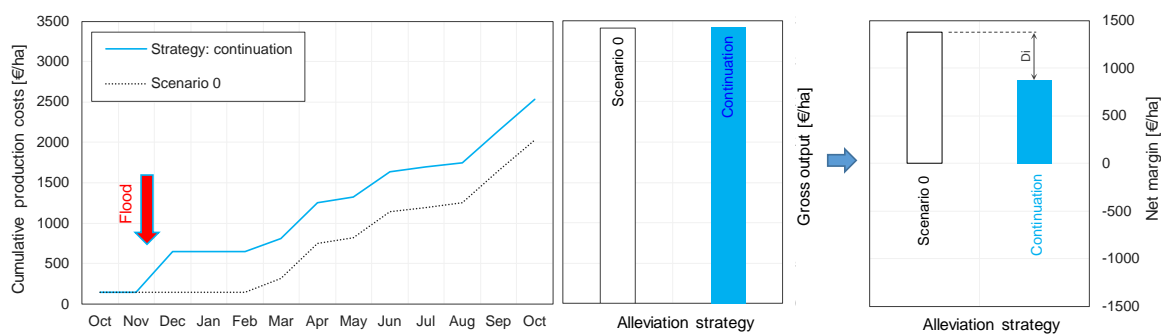
a) November flood (vegetative stage: break): any flood depth and duration
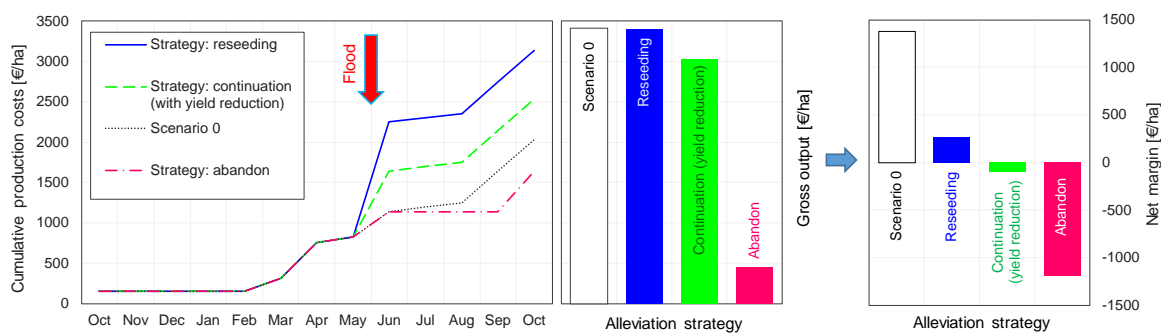
b) June flood (vegetative stage: growing): any flood depth and 5 days duration (yield loss 12.5%)

c) September flood (vegetative stage: maturation): flood depth > 1.30 m and 10 days duration (yield loss 50%)

Figure 5. Po Plain case: distribution of cumulative production costs for grain maize during the year and annual gross output and net margin in the 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 (Di) is obtained by the difference of the net margin in the Scenario 0 and in the investigated scenario, as exemplified in Figure 5a.

19

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 1980 €/ha. In case of abandoning, absolute damage equals 2677 €/ha, because of a yield reduction of 100% and saving of production costs of 283 €/ha.

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 case of no inundation, $d=D/NM_{noflood}$, 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 it is continuation 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, etc. 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 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 overcome the limitations of present CBAs, by providing a more comprehensive estimation of flood damages, 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, as it is typically the case of river restoration actions, included in "integrated river basin management" projects (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 in 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) is also useful to orient the behaviour of farmers towards more resilient practices, 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 flooded, 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, Figure 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, obtained by the farmer also without any yield) and of 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%;

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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-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

5 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 high-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.

10 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 few parameters (see Section 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 Section 2); this uncertainty can be even amplified by the inherent

15 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. 2019).

20 Likewise, a sensitivity analysis of input variables should always be performed, to get a flavour of 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 the 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

25 considered or production costs increase more than 10%. The "new" damage scenarios change the relative convenience associated to the different mitigation strategies; in particular, continuation may be more convenient that reseeding for short duration floods. Sensitivity analysis allows also investigating 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:

30 physical productivity is spatially non-uniform within the sub-regions of the Po Plain; prices and costs are highly variable in time and specific locations; only few farmers apply for EU contributions for the minimum tillage.

Water depth < 130 cm

Phase	Month	Strategy	<5	5	6	7	8	9	10	11	>11
Bare field	Jan	c					36%				
		r					-				
		a					-				
	Feb	c					36%				
		r					-				
		a					-				
	Mar	c					36%				
		r					-				
		a					-				
Initial phase	Apr	c					-				
		r					80%				
		a					158%				
	May	c					-				
		r					80%				
		a					158%				
Growing	Jun	c	36%	63%	90%	117%	144%	171%	198%	225%	-
		r					80%				
		a	-				187%				
Flowering	Jul	c	36%	90%	144%	198%			-		
		r					-				
		a	-				191%				
	Aug	c	36%	90%	144%	198%			-		
		r					-				
		a	-				191%				
Maturation	Sep	c					36%				
		r					-				
		a					-				
	Oct	c					36%				
		r					-				
		a					-				
Bare field	Nov	c					36%				
		r					-				
		a					-				
	Dec	c					36%				
		r					-				
		a					-				

Water depth ≥ 130 cm

Phase	Month	Strategy	<5	5	6	7	8	9	10	11	>11
Bare field	Jan	c					36%				
		r					-				
		a					-				
	Feb	c					36%				
		r					-				
		a					-				
	Mar	c					36%				
		r					-				
		a					-				
Initial phase	Apr	c					-				
		r					80%				
		a					158%				
	May	c					-				
		r					80%				
		a					158%				
Growing	Jun	c	36%	63%	90%	117%	144%	171%	198%	225%	-
		r					80%				
		a	-				187%				
Flowering	Jul	c					-				
		r					-				
		a					191%				
	Aug	c					-				
		r					-				
		a					191%				
Maturation	Sep	c				36%			90%	144%	198%	-
		r					-				
		a				-				195%	
	Oct	c				36%			90%	144%	198%	-
		r					-				
		a				-				195%	
Bare field	Nov	c					36%				
		r					-				
		a					-				
	Dec	c					36%				
		r					-				
		a					-				

Figure 6. Po Plain case: relative damage (Eq. 2) to maize crops (in case of minimum tillage) for the different combinations times 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"=abandoning. Results shown for the "r" option are obtained by assuming a null yield penalty for late (re-)plating.

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 damages, 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.

5 Finally, comprehensiveness of damage assessment is limited by the lack of consideration of other farm components which may be damaged in case of flood like damage to perennial plants, livestock, stock, equipment and machineries, 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.

10 The development of AGRIDE-c highlighted some challenges for the hydrology and the 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 1D steady hydraulic models to 2D 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, both for technical and economic constraints. Thus, rapid approximate methods

15 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 affects

20 also 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

25 model has been exemplified in the Po Plain – North of Italy, for which a spreadsheet (partly customizable by users) for the calculation of damage has been also 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,

30 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 on 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.

Author Contributions

Conceptualization, D.M., A.R.S. and F.B.; Methodology, D.M., A.R.S., F.B. and A.G.; Data Management, D.M., A.R.S. and A.G.; Analysis, D.M., A.R.S. and A.G.; Investigation of the results, D.M., A.R.S. and F.B.; Development of the spreadsheet, A.G., Writing – Original Draft, D.M.; Writing - Review, D.M., A.R.S., and F.B.

Competing interests

The authors declare that they have no conflict of interest

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

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10   **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. All aAvailable 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 with the evaluation of its economic consequences on the income of the farmersfarmers' gross product. This allows AGRIDE-c to be used to guide the flood damage assessment process in different geographical and economic

15   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 damage mechanisms to crops allows for comprehensive cost-benefit analyses of risk mitigation actions, and is a powerful tool to orient farmers' behaviour towardssupport more resilient effective damage alleviation practicesmitigation strategies, both at public and at private (i.e. farmers) level.

1 Introduction

20

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 damages 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

25   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 andbased on the assessment of welfare change associated with public investments. In fact, CBAs would require a

30   comprehensive estimation of the benefits produced by the adoption of different strategies (Jonkman et al., 2004; Mechler,

1

2016), consisting in the avoided losses to all exposed sectors and at different temporal scales (i.e. direct and indirect/long term damages). ~~define and select mitigation actions to be included in Flood Risk Management Plans, on the basis of reliable and inclusive cost benefit analyses (CBAs). The latter would require a comprehensive estimation of the benefits associated with the adoption of different strategies (Jonkman et al., 2004; Mechler, 2016), consisting in the avoided losses to all exposed sectors and at different temporal scales (i.e. direct and indirect/long term damages).~~

5 ~~However,~~ Ppresent damage modelling capacity is mainly focused on direct damage to people and 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 opposite, the importance of developing new and reliable models for more

10 ~~comprehensive~~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 weigh 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 sector, by presenting a new conceptual model for the estimation of flood damage to crops. ~~Therefore, the inclusion of damage to agriculture in CBAs is critically needed, especially when risk mitigation measures involve floodplains~~

15 ~~devoted to agricultural activities: this is typically the case of river restoration actions, as usually included in "integrated river basin management" projects (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). The latter should consider all the direct and indirect costs and benefits that a specific measure brings to the society (Jonkman et al., 2004; Mechler, 2016), with benefits consisting in the avoided damage with respect to a null action.~~

20 ~~In this framework, this paper deals with the estimation of flood damage to the agricultural sector. Indeed, the inclusion of damage to agriculture in CBAs is critically needed, especially when risk mitigation measures involve floodplains devoted to agricultural activities: this is typically the case of river restoration actions, as usually included in "integrated river basin management" projects (Morris and Hess, 1988; Brémond et al., 2013; Massaruto and De Carli, 2014; Guida et al., 2016). Moreover, a thorough understanding of flood damage mechanisms may increase farmers' resilience to floods, by supporting~~

25 ~~them in identifying the most proper damage alleviation and coping strategies~~

In the literature on flood damage modelling, agriculture has received so far less attention than other exposed sectors, 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

30 empirical data for understanding damage mechanisms and deriving prediction models, and finally, (~~iii~~iiiv) ~~the insurance coverage for damage to farms, strongly incentivised at national level in many countries since the late nineties,~~ a policy shift, especially in Europe post 1980s, when the subsides to agriculture were being challenged by the increase of agricultural surpluses under the Common Agricultural Policy, along with the incentivisation of insurance coverage for damage to farms, that led most of 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 middle 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 et al. 2008; Morris 1992). 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 the grey literature (see e.g. Hallett et al. 2016). Nonetheless, Aavailable damage models for agriculture are not only few in number, but are also affected by many limitations, the major 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), and limited which limit their transferability to different contexts more than other exposed sectors, as the residential and commercial ones as wells as the lack of information/data for their validation; a. Accordingly, the first requirement for a new damage models is their its possible application in a wide variety of geographical and economic contexts. Experience gained in flood damage assessment for other sectors (typically residences) highlighted that a broad generalisation is often not possible, as damage models must be able to capture the specificities of the investigated area, both in terms of hazard and vulnerability features (Cammerer et al., 2013). Still, a general conceptualisation of the problem at stake 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 is aims to be generally valid, the analytical expression of its components is 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 at https://tinyurl.com/yyj2arhp) for the calculation of damage to crops, which can be adapted to other contexts.

The paper is organised in four parts as follows. Section 2 reviews the state of art on flood damage modelling to crops, as the starting point of the research. Section 3 presents the AGRIDE-c model, while Section 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 Section 6.

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

Keyword search	Number of papers
"Flood damage"	4036

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"Flood damage" AND "crop"	81
"Flood damage" AND "agriculture"	71
"Flood damage" AND "building"	284
"Flood damage" AND "infrastructure"	122

2 State of art on flood damage modelling for crops

~~The main available~~Prominent examples of damage models for crops are reported in Table 2. ~~As an overall consideration arising from the analysis of the literature, it can be first underlined that assumptions at the base of many models are not adequately~~

5 ~~described, leaving uncertainties in the interpretation of the approach and possibly leading to incorrect implementation of the procedure for damage assessment.~~

The analysis of ~~Table 2~~the table ~~shows~~ indicates that 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

10 duration, sediment and contaminant load), for crops a key role is played by the period of the year, generally the month~~h,~~ of the flood event, as damage is strongly dependent on crop calendars (USACE, 1985; Morris and Hess, 1988; Hussain, 1996; RAM, 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 which makes damage models for crops strongly context specific. Indeed, crop calendars delineate the vegetative stage of the plants at the time of the flood

15 (which strongly affects the damage suffered by the plants) for any crop type, the latter being the only vulnerability parameter often considered by the models. In the case of meso-scale models (Kok et al., 2005; Hoes and Schuurmans, 2006), this parameter is replaced by the agricultural land-use. No model in Table 2 considers instead the behaviour of farmers after the occurrence of the flood (e.g. the decision of abandoning 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).

20 With respect to the approach, only few literature models are directly derived from field observations of flood consequences on crops: this is mainly due to the scarcity of ~~ex post~~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

25 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 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 ~~gross profit~~net margin (USACE, 1985; RAM, 2000; Agenais et al., 2013; Shrestha et al., 2013) or of the ~~turnover~~ 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 in relative terms, as a percentage of a maximum exposed value. Finally, 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).
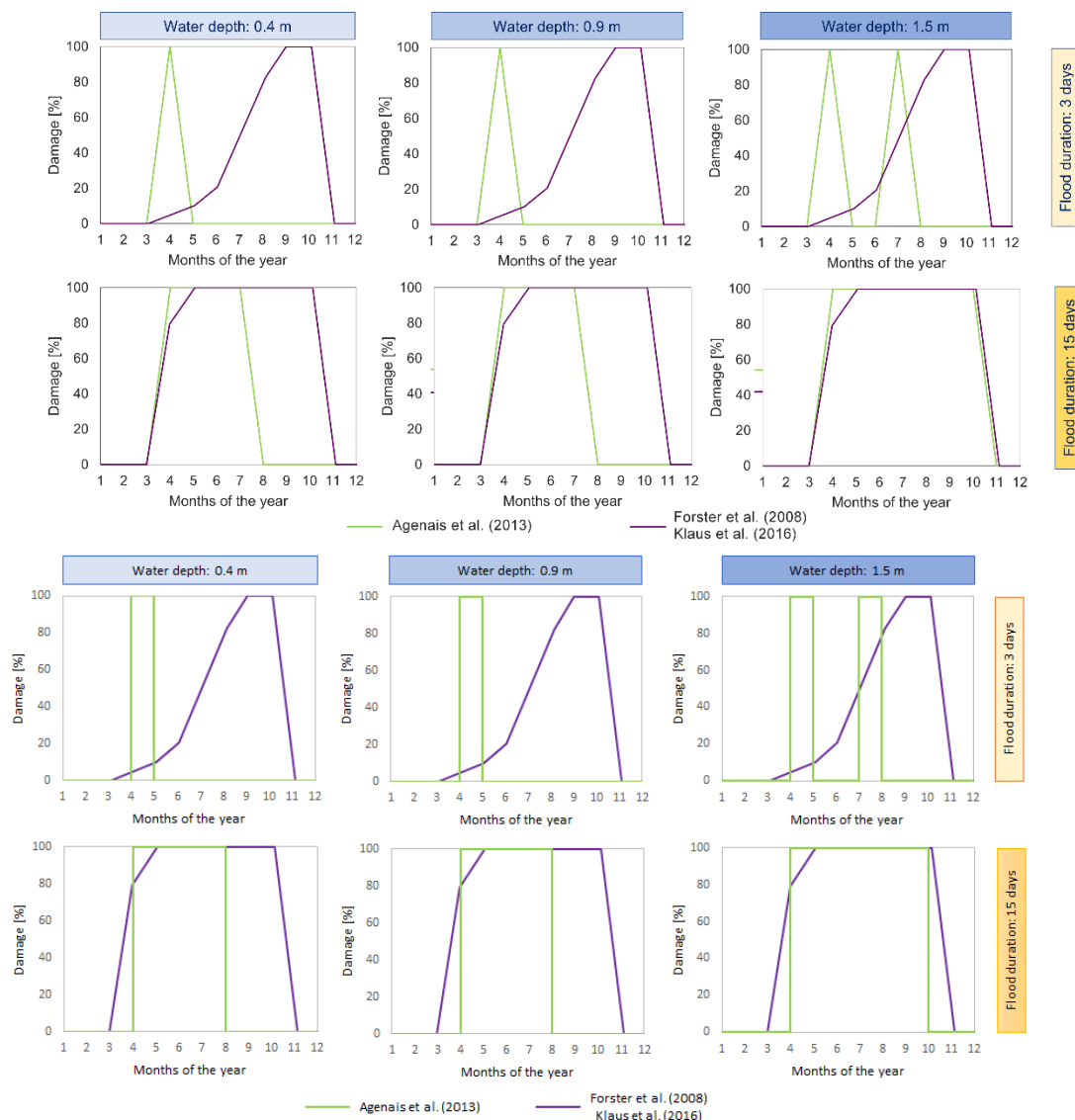
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Study and country	Crop types	Hazard parameters	Vulnerability aspects	Modelling approach		Monetary evaluation approach	Validation
				Empirical vs. expert based	Cost vs. physically based		
AGDAM/ Hazus (USACE 1985) - USA	Generic crop	Duration, time of occurrence (month)	Crop type	Not specified	Cost based (supposed)	Relative - Damage as a percentage of the ~~gross profit~~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 ~~gross profit~~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~~turnover~~	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~~turnover~~	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~~turnover~~	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)	~~Relative Damage as reduction of the gross profit~~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~~turnover~~	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~~turnover~~	No

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

Overall, the state of art depicts a fragmented scenario, characterised by the existence of 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

5 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, e.g., 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 to be applied 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

10 ~~ex post~~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

15 calendars (for maize, seeding in April and harvest in September/October), they produced significantly different results, as reported in Figure 1, where the models are applied for three different values of the water depth and two different flood durations.

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

For example, for short duration floods (d=3 days), Agenais et al. 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. estimate the maximum damage in September-October, whatever is the value of the water depth.

The main reason for this inconsistency lays in the different modelling approach adopted by the two models: physically-based in the case of Agenais et al. and cost-based in the case of Förster et al.. Coherently, Agenais et al. estimate the maximum

damage in correspondence of the most fragile vegetative phases of the crop, i.e. the growth (~~March~~April-May) and the flowering (Ju~~ly~~ne-August), while Förster et al. well reproduce increasing costs sustained by farmers during the vegetative cycle, 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. consider water depth as a control parameter,

5   while Föster et al. do not, thus leading to different damage estimation 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. is derived by referring to the ~~gross profit~~net margin, the relative model by Förster et al. refers to the ~~turnover~~gross output. Given that conventions do not exist on how translating relative damage into absolute terms, the choice of the wrong reference value could amplify inconsistency between the two approaches.

10   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

15   AGRIDE-c has been developed by adopting an expert-based approach, encapsulating and systematising ~~all~~ 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 ~~model~~framework, which identifies the different aspects to be modelled for the assessment of flood damage to crops, their (inter)connections as well as 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)

20   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 ~~in~~for the Po Plain is supplied in Section 4. ~~Information~~Knowledge at the base of AGRIDE-c has been derived by a thorough investigation of the literature (Section 2) and by consultation with experts. ~~(i.e. agronomists and representatives of the authorities responsible for agricultural damage management and compensation).~~

25   More specifically, experts were involved to support the definition of the conceptual model, by ~~means of~~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 judgment. 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.

30   Then, there was an iterative revision of improved versions of the model until an agreement on its final structure was reached. ~~T~~three kinds of experts were involved in the process: (i) ~~a~~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) t~~T~~wo agronomists of a local association of farmers (Coldiretti Lodi), with specific knowledge on the Po Plain context and with direct experience in managing floods in the last 20 years; the viewpoint of several individual local farmers who experienced flooding in the past years was also included in the analysis, as the two agronomists asked them for direct data and information to support their considerations; (iii) a~~A~~n academic economist, with specific expertise in agriculture.

~~The result of this process is a general, conceptual model, which identifies the different aspects to be modelled for the assessment of flood damage to crops, their (inter)connections as well as 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 is supplied in Section 4.~~

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 damages, in particular, loss reduction of soil productivity in the following cycles is not considered);

In addition, AGRIDE-c does not consider damage to other components/elements of the farm that, on turn, may induce additional damage to crops, as, for instance, damage to machineries and equipment (e.g. irrigation system) that may prevent cultivation for a while (Dunderdale and Morris, 1997; Posthumus et al., 2009; Agenais et al., 2013; Bremond et al., 2013; Morris and Brewin, 2014). Only short term impacts on soil are included, based on the evidence that, during a flood, damages to soil and crops are concurrent, differently from damages 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 structure of AGRIDE-c~~The m~~M~~odel structure is depicted in detail in Figure 2. Absolute damage (D) for an individual farmer is expressed as the difference between the reduction in the ~~turnover~~ gross output (Δ~~T~~GO) and the increase/decrease in production costs (ΔPC), as a consequence of the flood of a specific crop. This is equal to consider absolute damage as the change in the ~~gross profit~~net margin (~~GP~~NM = ~~T~~GO– PC, where ~~T~~GO = ~~turnover~~gross output and PC = production costs) due to the flood, compared to the case when no flood occurs (i.e., Scenario 0):

$$D = NM_{noflood} - NM_{flood} = (GO_{noflood}-GO_{flood}) - (PC_{noflood}-PC_{flood}) = \Delta GO - \Delta PC \qquad (1)$$

Accordingly, relative damage (d) can be obtained by dividing the absolute damage by the net margin in the Scenario 0 ($NM_{noflood}$)

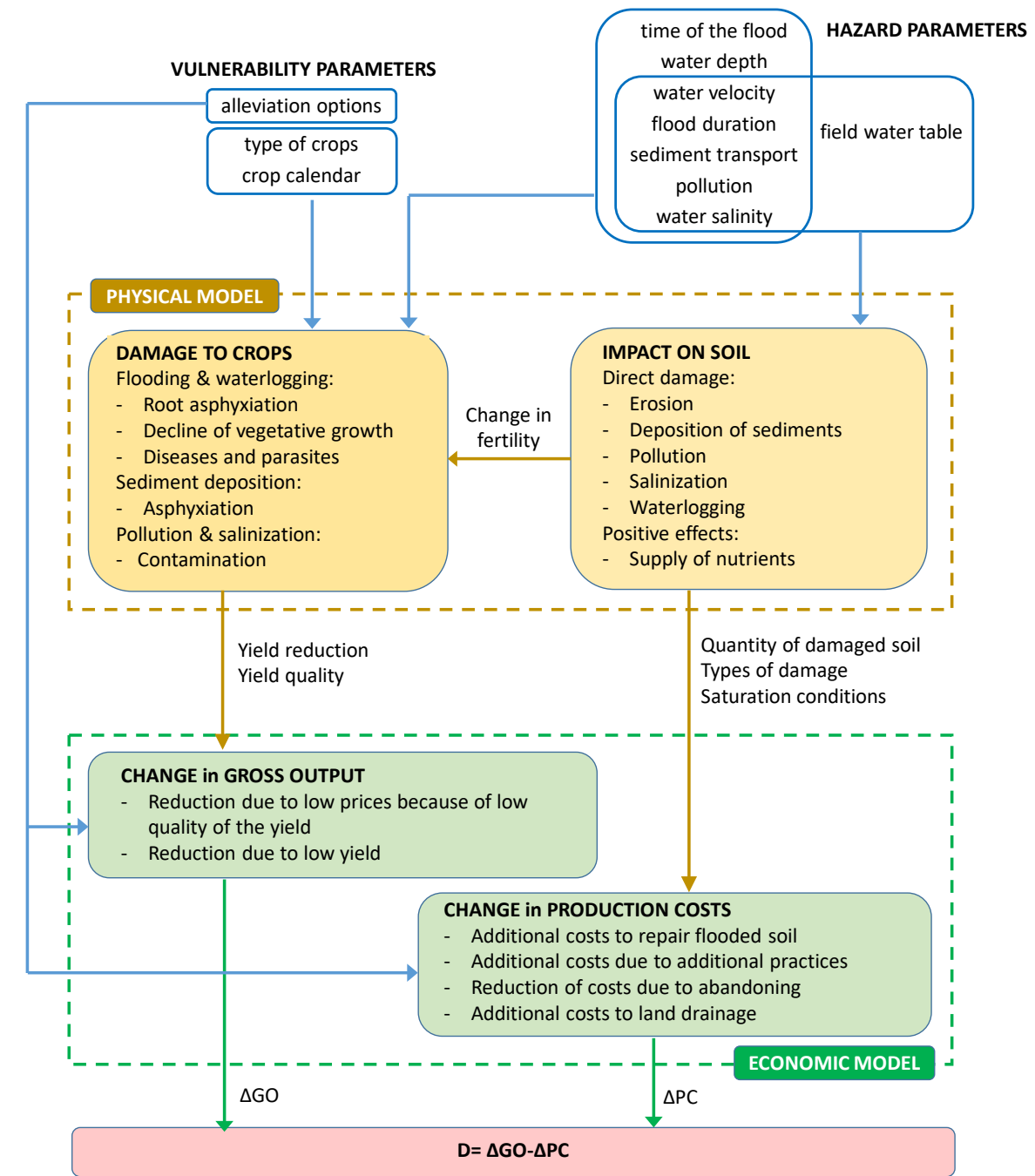$$d = D/NM_{noflood} = 1 - NM_{flood}/NM_{noflood} \qquad (2)$$
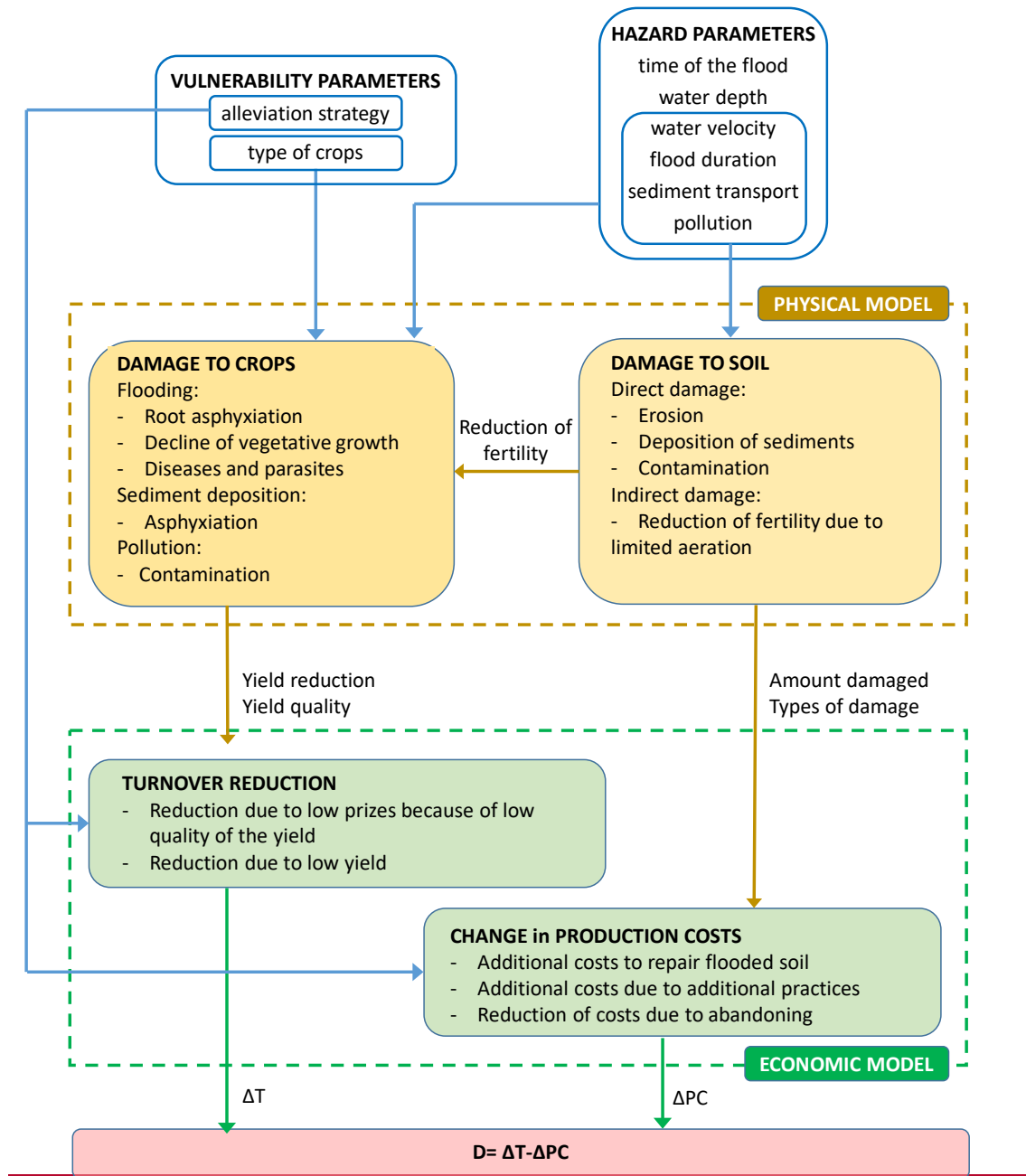
Figure 2. Conceptual model of AGRIDE-c

5   AGRIDE-c ~~includes~~ combines a physical and an economic model to evaluate the absolute damage~~; the first provides information on the physical damage, while the second converts the physical effects of the flood into monetary terms~~. In this way, the problems of consistency among physically-based and/or cost-based models discussed in Section 2 are overcome, being both aspects explicitly taken into account.

~~Physical damage to crops depends, on the one hand, on the direct contact of the flooding water with the plants~~crop; ~~on the~~
10   ~~other hand, damage to other components/elements of the farm may induce additional damage to crops, as, for instance, damage to soil that may imply a reduction in soil fertility, and damage to machineries and equipment (e.g. the irrigation plant), that may prevent cultivation for a while. A~~among these, AGRIDE-c considers only the damage to soil. ~~This choice derives from the evidence that, during a flood, damage to soil and plants occurs always at the same time differently from damage to the other components which can occur or not, independently from the damage to plants; as a consequence, damage to soil and~~
15   ~~plants is modelled together, while damage to the other components can be modelled as separated factors.~~ The physical model ~~of AGRIDE-c~~ (identified by the yellow dashed box in Figure 2) is ~~therefore~~ composed of two sub-models, for the evaluation of physical damage to crops (i.e. the plants) and impact ~~to~~ on soil, respectively. 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
20   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 case of coastal flooding) and the contaminants load. In particular, the model takes into account of processes like erosion, deposition of sediments and contamination (which affect the costs for soil restoration),as well as of 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
25   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 of soil fertility, explained by a (re-)distribution of river sediments and organic matter in the course of flooding that replenish carbon and nutrients in topsoil.

30   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

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duration, sediment~~,~~ salinity ~~-~~and contaminants 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 model for the assessment of physical damage impact on to soil calculates instead the amount of soil that is damaged and~~
5 ~~the kind(s) of damage suffered by the soil, i.e. erosion, deposition of sediments, contamination (on which costs for soil restoration depend), as well as the consequent reduction in soil fertility (which affects the quality and the quantity of the harvest), as a function of the duration of the flood, the water velocity, the sediment and the contaminants loads.~~

The economic model of AGRIDE-c (identified by the green dashed box in Figure 2) consists of two sub-models as well: one for the evaluation of the reduction in the ~~turnover~~ gross output and one for the assessment of the increase/decrease in production
10 costs~~,~~ compared to the ~~Scenario 0 (i.e.~~ no flood scenario), whereas production costs include direct-avoidable costs, like field operations costs, and direct fixed costs. ~~-~~The first model calculates Δ~~T~~GO as the reduction in the ~~turnover~~ 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.
15 Indeed, farmers can react in different ways to alleviate flood damage, according to the vegetative stage of the plant at the occurrence of the flood, and of the physical damage suffered by the plant (Agenais et al., 2013; Pivot, et. al 2002). The 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 ~~under investigation~~. Finally, when the yield loss is severe, farmers can decide to abandon the production. ΔPC strongly depends on
20 the strategy adopted by the farmer ~~as well as~~which, on 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 in the saving of part of the production costs.

25 **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.
30 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 ~~gross profit~~ for the farmer in the Scenario 0, by considering the amount of production (yield), selling prices of the crops, time

and costs of cultivation practices in the absence of any flood. Third, analytical expressions for all the processes shown in Figure 2 are derived and then, starting from the 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 / information used in the application for the Po Plain (example of maize). Data sources are clarified in the following ~~paragraphs~~sub-sections.

The implementation of the conceptual model to Po Plain was ~~also~~ supported by specific knowledge of local experts. In particular, several individual meetings were organised with the aim of obtaining context-specific information related on 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 occurred in the province, i.e. the flood of the Adda River in November 2002 (AdBPo, 2003; AdBPo, 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) and low sediment and pollution loads in the flooded areas as typical of the region; accordingly, 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 those related to other crops are reported in the supplement.

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 experts consultation
Impact on soil	As shown in Fig.2	Soil restoration considered as a fixed cost (500€/ha)	APIMA (2013-2017) and experts consultation
Economic Model			
Gross output	Crop yield	175 q/ha	Regione Lombardia (2013-2017)
	Unit price for crop	16.9 €/q	Borsa Granaria di Milano (2013-2017)
	Other (e.g. EU contributions)	150 €/ha for crop rotation; 300€/ha for minimum tillage	PSR Regione Lombardia
Production costs			
Variable costs		As shown in Fig.3 and Tab. 4	APIMA (2013-2017) and experts consultation

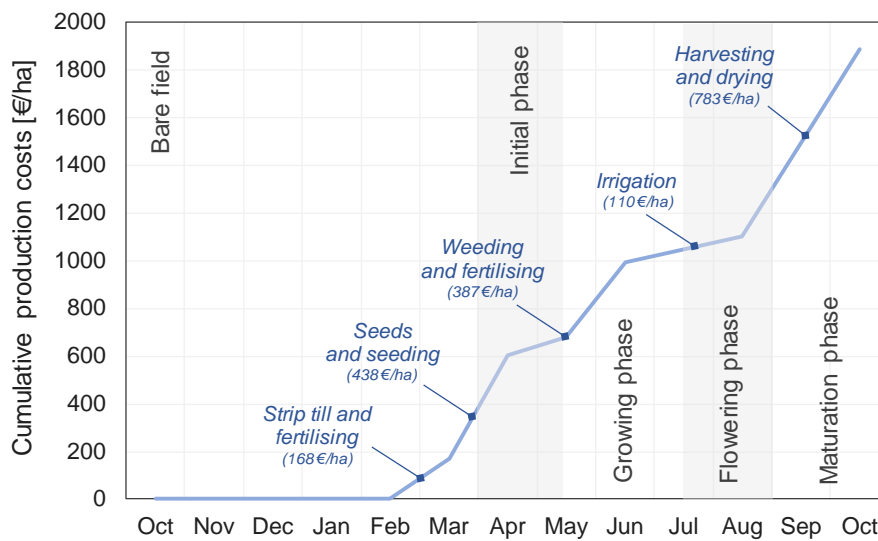| Fixed costs	Depend on crop type and cultivations practises / strategies	Assumed equal to 5% of the gross output	Experts consultation

4.2 Characterisation of the Scenario 0

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

Given that ~~only one~~the vegetative cycle of grain maize ~~is possible~~ in the Po Plain covers ~~in~~ one year, the ~~turnover~~gross output is estimated as the product between the average yield and price for grain maize over the ~~last five years~~period 2013-2017 (data sources: Regione Lombardia and Borsa Granaria di Milano (Milan Crops Stock Market)), equal to 175 q/ha and 16.92 €/q, respectively. In addition, we also consider the annual EU contributions for agriculture as a further 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 150 €/ha (data source: PSR - Programma di Sviluppo Rurale, Regione Lombardia: http://www.psr.regione.lombardia.it).

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 as direct, avoidable costs, as interviewed local experts indicated that in Lodi province most of 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.

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

Finally, fixed costs sustained by farmers (like management costs) are assumed to be a portion (5%) of the ~~turnover~~gross output.

5 Based on these data, the analysis results in a ~~gross profit~~net margin for the famer in case of no flood equal to 1376 €/ha per year.

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

10 and flood duration) are coherent with the typical flooding characteristics identified for the Po Plain (Section 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.

15 An example of the physical damage model for maize is depicted in Figure 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 the 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 days the model gives a null yield loss, independently from the water depth; on the opposite, a flood lasting more than 12 days results in a total loss. For floods

20 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 days, adapting the model to the context under investigation. The use of this model implies that, at present, we do not take into account ~~nor~~ neither the reduction in the quality

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of the yield due to the flood nor 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 Section 4.4).
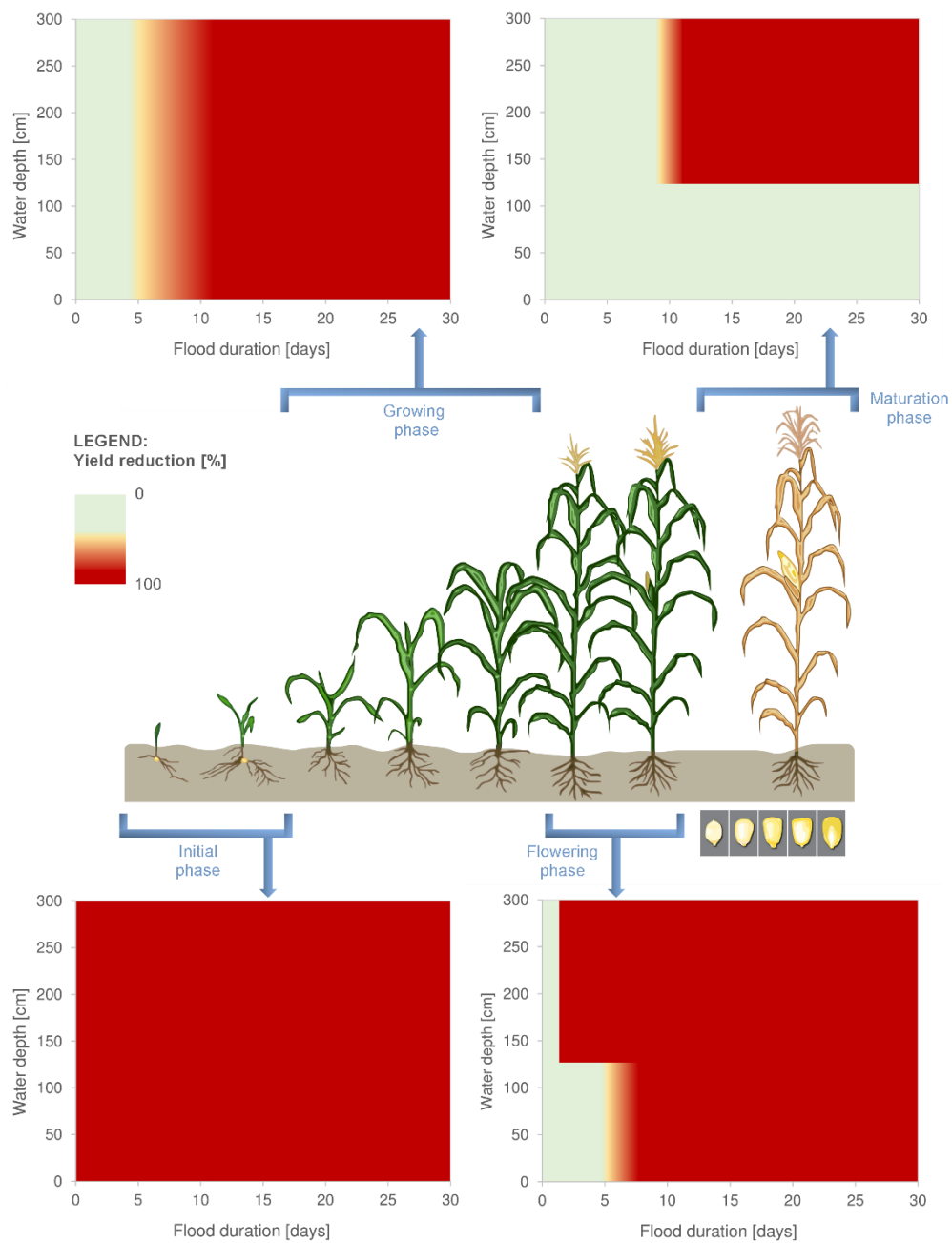
4.4 ~~Damage~~ Impact ~~to~~ on soil

Concerning the ~~physical damage~~physical impact ~~onto~~ soil, only the negative effects of floods were computed as, according to
5 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 ~~we are, therefore,~~were not able to parametrise the possible types of damage, the amount of damaged soil and the
10 reduction in soil fertility as a function of hazard features. For these reasons, ~~aA~~t present, the model is based on the simplified assumption that soil always requires restoration in case 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 Section 4.2).
15 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 sub-component 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 damages 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
20 source: APIMA), restoration costs have been considered here, in a first instance, as fixed costs equal to 500 €/ha.

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
25 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 the continuation or the abandon 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~~3~~).

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

5

Table 43. 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	€/ha	Avoided costs	€/ha
November - March	Bare field	Continuation	0	Soil restoring	500		
April - May	Initial phase	Abandoning	100	Soil restoring	500	Weeding and fertilising	387
						Irrigation	110
						Harvesting and drying	783
		Reseeding	0	Soil restoring (	500		
				Strip till and fertilising	168		
				Seeds and reseeding	438		
June	Growing phase	Continuation	see Fig. 4	Soil restoring	500		
		Abandoning	100	Soil restoring	500	Irrigation	110
						Harvesting and drying	783
		Reseeding	0	Soil restoring	500		
				Strip till and fertilising	168		
				Seeds and reseeding	438		
July - August	Flowering phase	Continuation	see Fig. 4	Soil restoring	500		
		Abandoning	100	Soil restoring	500	Irrigation	55
						Harvesting and drying	783
September - October	Maturation phase	Continuation	see Fig. 4	Soil restoring	500		
		Abandoning	100	Soil restoring	500	Harvesting and drying	783

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 Figure 4 as a function of hazard features, while additional costs are only due to soil restoring (see Section 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 obtainedAt present, our model adopts by adopting the simplified assumption that late reseeding does not imply a yield reduction, neither in quantity nor in 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 neither 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 still, analysts can set the right value for the context under investigation, in the spreadsheet supplied as supplementary material (https://tinyurl.com/yyj2arhp). 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 Section 3 and assumptions described in the previous sub-sections, 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 Δ~~T~~GO and ΔPC:

5   D = D (month, water depth, flood duration, alleviation strategy) = Δ~~T~~GO - ΔPC _____(3)

In detail, Δ~~T~~GO and ΔPC are calculated on the basis of yield reduction and additional and avoided costs, as reported in Table 4~~3~~. 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, Figure 5 shows changes in production costs and ~~turnover~~ gross output for maize
10   cultivation, for three different flood scenarios. Values of the annual gross output ~~turnover~~ 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 calculating the damage D for the farmer.

15   The first scenario (Figure 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 3~~4~~). Farmers will then continue the production with additional costs limited to those required to restore the flooded soil for a total of 500 €/ha (Table 3~~4~~), which is the absolute damage sustained by farmers.

The second scenario (Figure 5b) refers to a flood in June, when the plant is in the growing stage. According to the physical model described in Figure 4, in this phase damage depends only on flood duration, while water depth has no effect on it. Figure
20   5b refers to a 5 days 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 ~~turnover~~ 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 870 €/ha. In the second case (blue line), no reduction in the gross output ~~turnover~~ occurs because reseeding would allow 100% of the yield, while additional production costs include both soil
25   restoration and reseeding costs, resulting in an absolute damage of 1106 €/ha. Figure 5b shows that, although possible in theory, abandoning the production is not a reasonable choice as absolute damage equals 2568 €/ha, due to a yield reduction of 100% (the only income for the farmer consists in the EU contributions for cultivation) against a saving of production costs of about 389 €/ha.

~~At last~~Finally, Figure 5c refers to a flood occurring in September; in this period (i.e. maturation phase of the plant), damage
30   depends on both water depth and flood duration. Figure 5c refers in particular to a 10 days flood with a water depth above 1.30 m. According to the physical model (Figure 4), this flood scenario leads to a 50% yield loss. Farmers have then two choices.
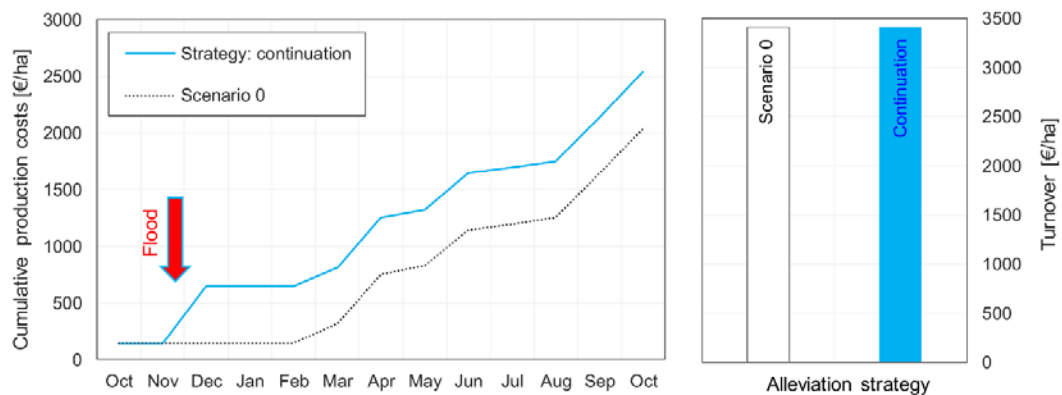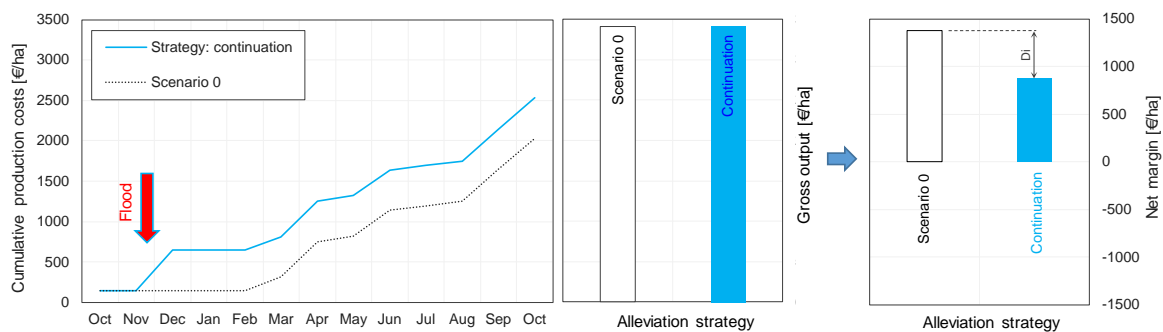
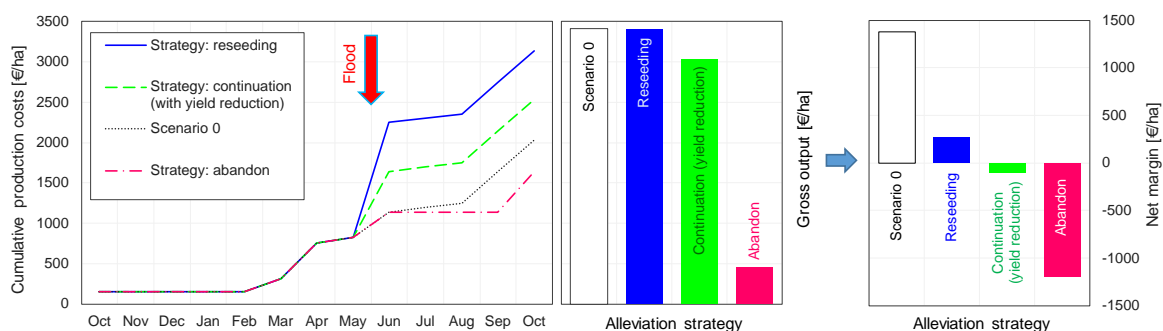a) November flood (break): any flood depth and duration
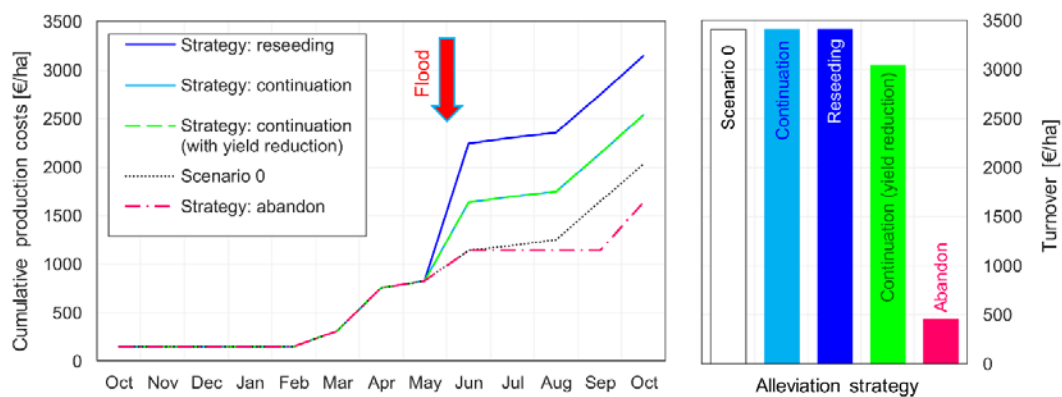
b) June flood (growing): any flood depth and 5 days duration (yield loss 12.5%)
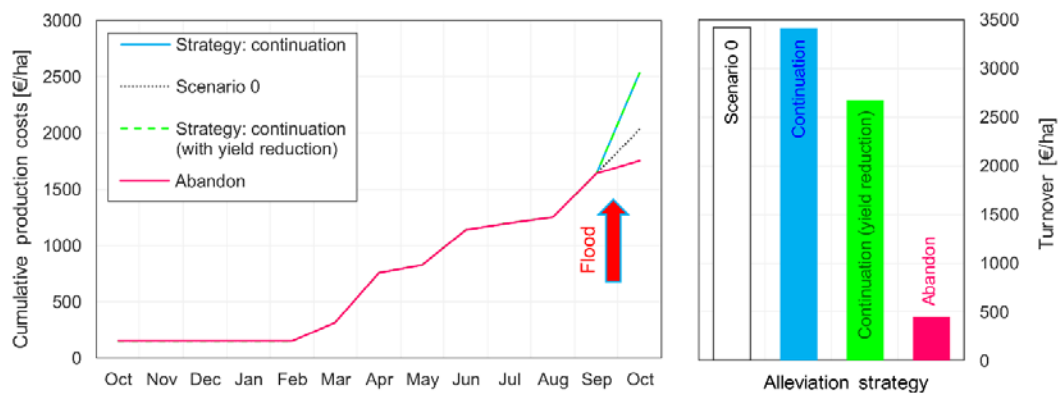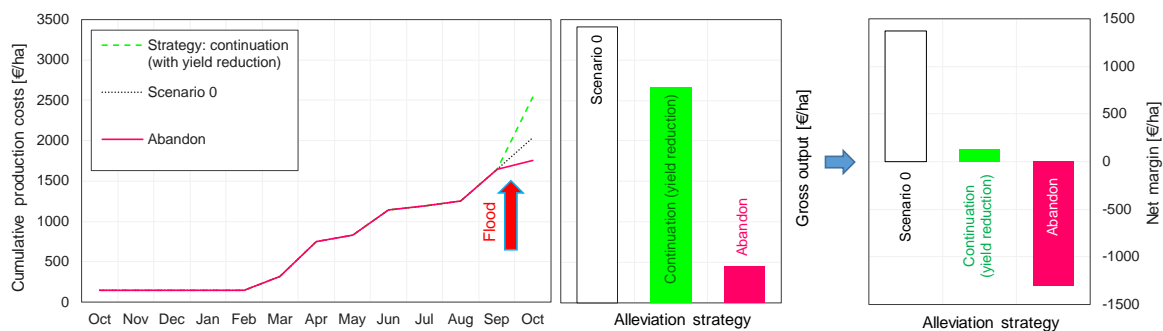

c) September flood (maturation): flood depth > 1.30 m and 10 days duration (yield loss 50%)

a) November flood (vegetative stage: break): any flood depth and duration

b) June flood (vegetative stage: growing): any flood depth and 5 days duration (yield loss 12.5%)

c) September flood (vegetative stage: maturation): flood depth > 1.30 m and 10 days duration (yield loss 50%)

Figure 5. Po Plain case: dDistribution of cumulative production costs for grain maize during the year and annual ~~turnover~~ gross output and net margin in the 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 (Di) is obtained by the difference of the net margin in the Scenario 0 and in the investigated scenario, as exemplified in Figure 5a.

5

If production is continued the ~~turnover~~ gross output decreases by 50% and additional costs are required to restore the flooded soil, resulting in an absolute damage equal to 1980 €/ha. In case of abandoning, absolute damage equals 2677 €/ha, because of a yield reduction of 100% and saving of production costs of 283 €/ha.

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 ~~gross profit~~net margin in case of no inundation, $d=D/$~~$GP_{noflood}$~~$NM_{noflood}$, 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 it is continuation 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, etc. 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 case of flood, represents a powerful tool to support more informed decisions on flood risk management for both public and private stakeholders. ~~Indeed, on the hand,~~, ~~both regarding public investments and from an owners' perspective. In fact, b~~By enabling the estimation of the ~~expected direct damage to crops in case of flood,~~ AGRIDE-c ~~is~~contributes to ~~fill the gap~~overcome the limitations of present CBA~~'~~s, by providing ~~t~~~~in favour of~~ ~~mo~~a more comprehensive estimation of ~~a powerful tool to increase the comprehensiveness of present CBAs of risk mitigation strategies. Indeed, while costs estimation is based on quite consolidated practices, available flood damage models do not allow for a comprehensive estimation of avoided~~flood damage~~s, in case of flood~~ ~~and then~~, thus supporting a better definition and choice of public actions for risk mitigation~~ measures, including both direct and indirect damage to all exposed sectors (Meyer et al., 2013); as a consequence, CBAs currently consider~~ are presently limited to the~~only~~ direct avoided damage to people and some exposed items~~ sectors~~ as benefit of a flood mitigation measure ~~(~~. In addition, the inclusion of damage to agriculture in CBAs is fundamental, especially when the interventions involve floodplains devoted to agricultural activities, as it is typically the case of river restoration actions, included in "integrated river basin management" projects (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~~, to meet such an objective~~, the tool must be critically used, e.g. by considering possible transfers of losses/gains between farmers in an economic perspective, according to the temporal and spatial scales of the analysis. ~~Even so, it must be stressed that the inclusion of damage to agriculture in CBAs of (public) risk mitigation measures is critically needed, especially when such measures~~

involve floodplains devoted to agricultural activities as it is typically the case of river restoration actions, included in "integrated river basin management" projects (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). On the opposite, the importance of developing new and reliable models for comprehensive 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 weigh differently according to the type of the event and the affected territory.

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) is also useful to orient the~~farmers'~~ behaviour of farmers towards more resilient practices, as the ~~choice~~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 flooded, 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, Figure 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 ~~turnover~~ (if excluding the EU contributions, obtained by the farmer also without any yield ~~apart from EU contributions~~) and of 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%; 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-c spreadsheet indicate a relative damage of 102% and 145% for a yield reduction of 10% and 30%, respectively.

~~Still,~~ 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 ~~one~~ is related to data requirements: ~~regards t~~the number and typology of input parameters ~~required by the model which~~ may prevent its ~~implementation~~use in ~~contexts characterised by low availability of data~~data-scarce ~~or extensive~~ areas. ~~As regards the first~~Regarding~~data availability~~However, ~~point,~~ it must be stressed that high-detailed tools like ~~the~~ AGRIDE-c ~~model~~ should be adopted only at an advanced stage of the analysis, when the costs of collecting ~~the~~site-specific data ~~collection of case-specific data is~~may be justified by the expected results (i.e. the choice of the best mitigation strategy); ~~. I~~in other cases, like ~~in~~ preliminary damage ~~assessments~~analyses ~~to~~for the identification of~~y~~ priority intervention areas or ~~in post event rapid~~post-event assessments, rapid ~~assessment~~ tools ~~like those~~(e.g. based on standardised damage/costs) should be preferred.

A second limitation concerns the high uncertainty ~~of~~characterising the input data required by AGRIDE-c, even in a specific context~~.~~ ~~An~~for example ~~is~~, the estimation, based on few parameters (see Section 4.5), of the expected yield reduction due to late (re)seeding, which may be problematic as it is ~~is~~very variable and depend~~e~~~~ant~~s on many factors (among others, type of late hybrids used) ~~that make difficult its estimation based on few parameters (see Section 4.5)~~. 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 Section 2); this uncertainty ~~that~~can ~~even~~ be even amplified by the inherent uncertainty of the sub-models

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implemented in AGRIDE-c, like , for example, the economic or the physical models for the estimation of flood damage to soil and crops, or the economic mode.

This suggests, as for other damage models, as for other damage models, the variability of parameters required by AGRIDE-c together with the limited availability of data for its validation (see Section 2) suggest the use of the modelAGRIDE-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. 2019).

Likewise, a sensitivity analysis of input variables should always be performed, to get a flavour of 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 the 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 to the different mitigation strategies; in particular, continuation may be more convenient that reseeding for short duration floods. Sensitivity analysis allows also investigating 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 sub-regions of the Po Plain; prices and costs are highly variable in time and specific locations; only few farmers apply for EU contributions for the minimum tillage.

Water depth < 130 cm

Water depth < 130 cm		Strategy	Flood duration [days]								
			<5	5	6	7	8	9	10	11	>11
Bare field	Jan	c					36%				
		r					-				
		a					-				
	Feb	c					36%				
		r					-				
		a					-				
	Mar	c					36%				
		r					-				
		a					-				
Initial phase	Apr	c					-				
		r					80%				
		a					158%				
	May	c					-				
		r					80%				
		a					158%				
Growing	Jun	c	36%	63%	90%	117%	144%	171%	198%	225%	-
		r					80%				
		a	-				187%				
Flowering	Jul	c	36%	90%	144%	198%			-		
		r					-				
		a	-				191%				
	Aug	c	36%	90%	144%	198%			-		
		r					-				
		a	-				191%				
Maturation	Sep	c					36%				
		r					-				
		a					-				
	Oct	c					36%				
		r					-				
		a					-				
Bare field	Nov	c					36%				
		r					-				
		a					-				
	Dec	c					36%				
		r					-				
		a					-				

Water depth ≥ 130 cm

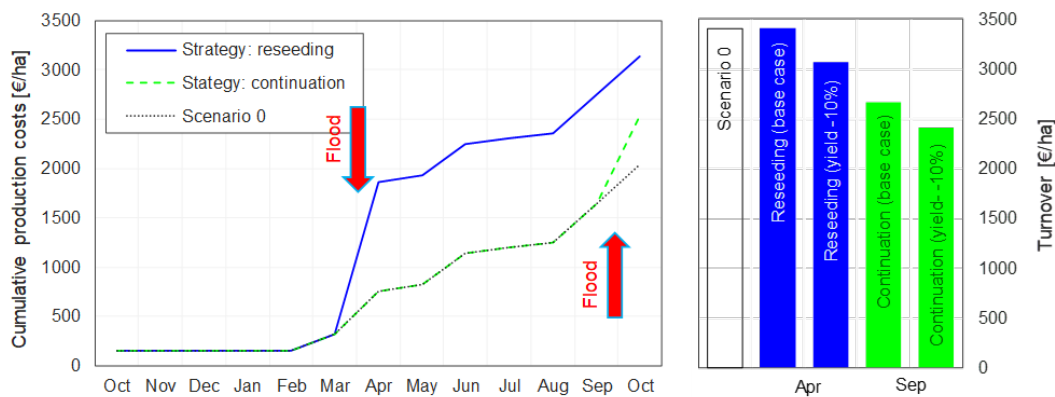| Water depth ≥ 130 cm		Strategy	Flood duration [days]								
			<5	5	6	7	8	9	10	11	>11
Bare field	Jan	c					36%				
		r					-				
		a					-				
	Feb	c					36%				
		r					-				
		a					-				
	Mar	c					36%				
		r					-				
		a					-				
Initial phase	Apr	c					-				
		r					80%				
		a					158%				
	May	c					-				
		r					80%				
		a					158%				
Growing	Jun	c	36%	63%	90%	117%	144%	171%	198%	225%	-
		r					80%				
		a	-				187%				
Flowering	Jul	c					-				
		r					-				
		a					191%				
	Aug	c					-				
		r					-				
		a					191%				
Maturation	Sep	c				36%		90%	144%	198%	-
		r					-				
		a			-				195%		
	Oct	c				36%		90%	144%	198%	-
		r					-				
		a			-				195%		
Bare field	Nov	c					36%				
		r					-				
		a					-				
	Dec	c					36%				
		r					-				
		a					-				

Figure 6. Po Plain case: ~~Relative~~ relative damage (Eq. 2) to maize crops (in case of minimum tillage) for the different combinations times 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"=abandoning. **Results shown for the "r" option are obtained by assuming a null yield penalty for late (re-)plating.**

~~beAnother strength of the implemented approach is the possibility of investigating the effect on damage of possible changes in the physical and economic context in which the farm is located (or, in another termswords, to perform a sensitivity analysis of input variables). For example, for maize, the model reveals that even a reduction of 10% of the yield in the 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 (Figure 7) and continuation in July and September (when yield loss is expected). The same occurs (not shown here) 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%; all of these scenarios are realistic in the context under investigation, but they may change in time and space (i.e. lower yields have been observed in other sub-regions of the Po Plain, prices and costs are highly variable, while only few farmers apply for EU contributions for the minimum tillage) highlighting, in particular, the importance of EU contributions for damage alleviation.~~ 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 damages, 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~~s~~ components which ~~can~~may be damaged in case of flood like damage to perennial plants, livestock, stock, equipment and machineries, 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~~.; in fact, most of available data and models limit the attention on damage to crops (Brémond et al., 2013).~~.

The development of AGRIDE-c highlighted some challenges for the hydrology and the 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 1D steady hydraulic models to 2D 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, both for 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 no~~t only~~ ~~more~~ on annual probabilities, but also on seasonal probabilities (Förster et al., 2008; Klaus et al., 2016; Morris and Hess, ~~1999~~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 affects also 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 customizable by users) for the calculation of damage has been also developed.

~~According to authors' knowledge,~~ 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. ~~represents the first attempt to organise all the available knowledge on flood damage to crops in a usable and consistent tool (i.e. the model integrates physical and economic approaches) that can be implemented to guide the flood damage assessment process, in 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.

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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 on 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.

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10 **Author Contributions**

Conceptualization, D.M., A.R.S. and F.B.; Methodology, D.M., A.R.S., F.B. and A.G.; Data Management, D.M., A.R.S. and A.G.; Analysis, D.M., A.R.S. and A.G.; Investigation of the results, D.M., A.R.S. and F.B.; Development of the spreadsheet, A.G., Writing – Original Draft, D.M.; Writing - Review, D.M., A.R.S., and F.B.

15 **Competing interests**

The authors declare that they have no conflict of interest

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