A methodology to assess damage and losses from natural hazard-induced disasters in agriculture

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DOI: 10.1481/icasVII.2016.f38d

INTRODUCTION

Over the last decades there has been an increase in the occurrence of natural hazard-induced disasters worldwide. Evidences show that extreme events such as droughts, floods and storms have occurred with high frequency and magnitude (CRED & UNISDR, 2015). These trends are particularly worrying for agriculture, considering the high dependence of the sector on climate and natural resources.

According to the Post Disaster Needs Assessment (PDNA) guidelines, the economic impact of disasters is measured as the sum of damage, i.e. monetary value of physical assets totally or partially destroyed, and losses, i.e. changes in economic flows arising from the disaster. Based on information obtained from PDNAs, the FAO study on *The Impact of Disasters on Agriculture and Food Security*showed that, between 2003 and 2013, 22 percent of the total economic impact of natural hazard induced disasters in developing countries was absorbed by agriculture, a figure much higher than previously reported. Yield trend analysis revealed that crop and livestock production losses after medium to large-scale disasters in developing countries averaged more than USD 7 billion per year over the same period (FAO, 2015).The study represented a first step towards filling the information and knowledge gap about the nature and magnitude of disaster impacts on agriculture, and highlighted the need for systematic monitoring and standardized assessment of damage and losses in crops, livestock, fisheries/aquaculture and forestry.

This paper describesa logical structure for linking the magnitude of the natural hazard to the corresponding damage and losses values, and proposes a standardized approach to measure damage and losses from natural hazard-induced disasters in agriculture.Overall, this paper fits in the FAO initiative for the development of an information system on damage and losses caused by disasters on the sector and its subsectors (crops, livestock, fisheries, aquaculture and forestry). As part of its commitment to enhancing the resilience of agriculture and rural livelihoods, FAO aims to support member countries to collect and report relevant data on the immediate physical damage caused by disasters on agricultural assets, as well as on the cascading negative effects of disasters on agricultural production, and value chains.

LOGICAL STEPS FOR MEASURING DISASTER IMPACT ON AGRICULTURE

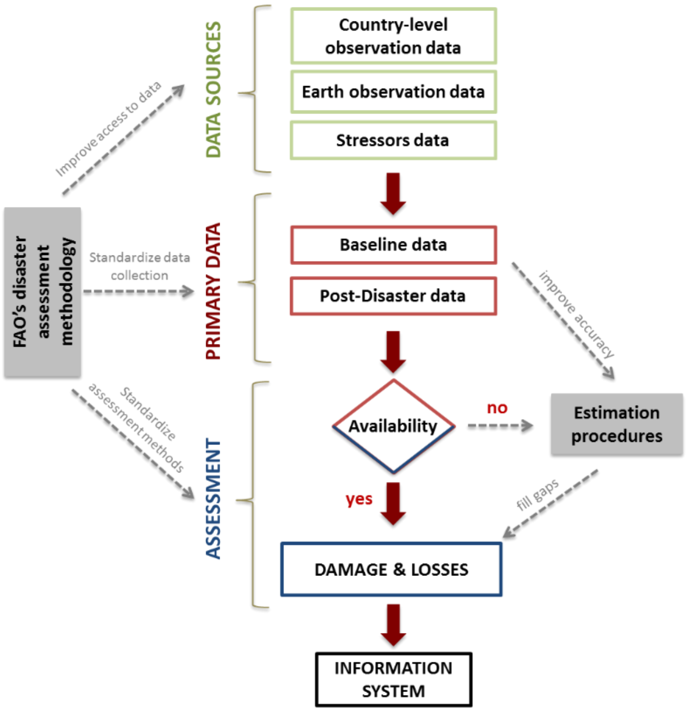
The logical structure behind a methodologyfor measuring the impact of disasters in agricultureinvolves three main steps:

1. The identification of the natural hazard and its magnitude.
2. The identification of the causal linkage between the hazard and damage and losses in agriculture.
3. The assessment of damage and losses causedby the hazard on agriculture, which constitute a measure of the disaster, i.e. the natural hazard impact on the primary sector.

The first step relies on the analysis of key indicators (e.g. climatic, environmental, geophysical, hydro-meteorological, biological indicators) in order to identify key characteristics of hazards, such as their location, area affected, intensity, speed of onset, duration and frequency. The second is the most delicate step: establishing a robustcausal relation between the hazard and the impact on agriculture may be complex, as the effects should be isolated from idiosyncratic shockssuch as civil conflicts, political instability or global macroeconomic shocks, whichmay play an important role in changing production dynamics. The third step involves the assessment of disaster impacts and the computation of the monetary value of damage and losses.

The definition of a standardized methodological framework ismeant to support theprocess that goes from the collection and sharing ofrelevant data at global, national and sub-national level to the calculation of disaster's damage and losses in agriculture (Figure 1). The collection of relevant data includes the selection and use of multiple sources at different levels, including country-level observation data (e.g. agricultural surveys), earth observation data (e.g. satellite, drone-based imagery), and stressors data (e.g. climatic and environmental indicators), among others. The primary data gathered should be organized in order to develop relevant information on post-disaster situation, and a reliable baseline for robust counterfactual analysis. Finally, the assessment stage implies the application of methods for the attribution of monetary values to damage and losses in each agricultural sub-sector.

Figure 1- Damage and Losses System Diagram: from data to D&L indicators



In cases when vital baseline or post-disaster data are only partially available, estimation and imputation procedures can be implemented through a procedural cascading structure in order to provide approximate figures on disaster impact. The use of a set of statistical tools allows to (1) fill data gaps and provide robust numbers for both the baseline and disaster impact values; and (2) forecast the impact of natural hazard-induced disasters based on country-specific characteristics. The forecasting capacity is strictly linked to theavailability of historical primary data on disaster impact collected through a standardized methodology, such as the one proposed in this paper. Damage and losses data are expected to support research on disaster impact trends in agriculture, as well as to enhance the resilience of rural livelihoods by informing evidence-based policies, strategies and action plans in disaster risk reduction and management.

Starting from the above considerations, this paperbuilds on the PDNA guidelines in order topropose a standardized methodology for calculating damage and losses caused by disasters in each agricultural sub-sector. In particular, the paper seeks to define uniform computation methods for translating primary data on disaster physical impact into monetary values of damage and losses.The adoption of standardized and systematic reporting mechanisms on damage and losses data at country levelare meant to provide policy-makers, and stakeholders at large, with a sound information base for decision-making. Ideally, the information should allow implementing ex-ante cost-benefit analysis of disaster risk reduction (DRR) as well as post-disaster resource allocation.

The analysis of damage and losses data on historical events, combined with information from early warning systems (e.g. GIEWS, EMPRES, IPC tool) could improve anticipation of disaster impact, and support actions to be taken before, during and in the immediate aftermath of an event. Accurate, up-to-date data on disaster impacts at the sector level would eventually inform the monitoring of progress towards sectoral resilience goals and targetsset under key international agendas, including the Sustainable Development Goals (SDGs) and the Sendai Framework for Disaster Risk Reduction (SFDRR).

DAMAGE AND LOSSES COMPUTATION METHODS

Disaster impact assessment methods largely vary depending on the sectors addressed, the goals of the assessment, and the organizations, governments and research institutes involved. For the purpose of the FAO information system on damage and losses in agriculture, the key reference methodology is the Post Disaster Needs Assessments (PDNAs), developed jointly by the World Bank, the United Nations and the European Commission (EC, UN, World Bank, 2013). A key element of the PDNA methodology is the distinction between damage, i.e. total or partial destruction of physical assets existing in the affected area, from losses, i.e. changes in economic flows arising from the disaster.

Following the logical structure of the PDNA methodology, Table 1 provides a standardized definition of damage and losses in the crops, livestock, fisheries, aquaculture, and forestry sub-sectors, including an indication of the items and economic flows that should be considered in the assessments, as well as the proposed calculation methods for assigning a monetary value to damage and losses. Each sub-sector has been sub-divided into two main sub-components, namely production and assets.

The *production* sub-component measures disaster impact on production inputs and outputs. Damages include, for instance, the value of stored inputs (e.g. seeds) and outputs (e.g. crops) that were fully or partially destroyed by the disaster. On the other hand, production losses refer to declines in the value of agricultural production resulting from the disaster. In the case of perennial crops, for example, production losses correspond to the sum of the monetary values of (1) fully destroyed standing crops; (2) decline in production in partially affected areas, as compared to pre-disaster expectations; and (3) the discounted value of lost production in fully damaged areas, until perennial crops become fully productive again.

The *assets* sub-component measures disaster impact on facilities, machinery, tools, and key infrastructure related to agricultural production. Crop-related assets include, among others, irrigation systems, machinery, equipment; livestock-related assets include sheds, storage buildings; fisheries assets include ponds, hatcheries, freezers and storage buildings, engines and boats, fisheries equipment; forestry assets include, among others, standing timber, firebreaks and watch towers, forestry equipment and machinery, fire management equipment. The monetary value of (fully or partially) damaged assets is calculated using the replacement or repair/rehabilitation cost, and accounted under damage (EC, UN, World Bank, 2013). The assumptions and formulas proposed for the computation of damage and losses are listed and described in the Technical Annexes 1 and 2, respectively.

A central component of theproposed methodology is resilience, intended asthe ability to prevent and mitigate disasters and crises as well as to anticipate, absorb, accommodate or recover and adapt from them in a timely, efficient and sustainable manner(FAO, 2013). The prevention and response components of resilience are embeddedin the computation methods. A set of resilience parameters are linked to the ‘Vulnerability’ and ‘Lack of coping capacity’ dimensions of the Index for Risk Management- INFORM, an open-source methodology for quantitatively assessing crisis and disaster risk(De Groeve, Poljansek, & Vernaccini, 2015). The higher is the risk defined by INFORM at national level, *ceteris paribus*, the higher is the cost attached to the disaster in a specific area. In other words, given the same intensity of the natural hazard, the estimation of damage and losses will be higher in those areas where the level of risk defined by INFORM is higher.

The proposed methodology is based on a set of assumptions and exogenous knowledge-based parameters; hence, results might be biased for a variety of reasons. First, the lack of data and the impossibility to relax the assumptions implies the utilisation of estimation procedures according to a cascading structure defined within the methodology. Second, errors may occur due to noise for externalities or lack of sensitivity in the measurement. Third, the knowledge-based features of the methodology may modify the final output depending on the source of knowledge.

The damage and losses computation methods proposed in this paper focus uniquely on the impact of disasters on agricultural assets and production flows. Nevertheless, it is acknowledged that disasters have negative effects beyond agricultural production and along the entire food and non-food value chain. In medium- and large-scale disasters, high production losses can lead to increases in imports of food and agricultural commodities to compensate for lost production and meet domestic demand. They can also reduce exports and revenues, with negative consequences for the balance of payment. When post-disaster production losses are significant and in countries where the sector makes an important contribution to economic growth, agriculture value-added or sector growth falls, as does national GDP(FAO, 2015). At the community level, disasters may undermine rural livelihoods and challenge food security.While further research is needed to develop and standardize the assessment of the cascading effects of disasters on the agriculture sectors, these elements fall outside the scope of this paper.

Table 1 - Damage and Lossessassesment methodology

Sub-sector	Component	Damage: Item(s)	Damage: Measurement	Losses: Economic flow(s)	Losses: Measurement
Fisheries	Production	Fish catch stored or ready for sale.	Pre-disaster market value of destroyed fish stored or ready for sale.	Value of fish catch.	(1) Difference between expected and actual value of annual fish catch in affected area in disaster year.
	Assets	Boats, ice and fish storage facilities, fishing gear	Total destruction: replacement cost of fully destroyed assets at pre-disaster prices. Partial destruction: repair/rehabilitation cost of partially destroyed assets at pre-disaster prices.		
	Community			Value of the labor force	Changes in value of labor force (tbd)
Crop	Production	Stored crops (annual and perennial); perennial trees; inputs stored (seeds, fertilizer, pesticide etc.); additional inputs bought for replanting (seeds, fertilizer, pesticide, labor etc.).	(2) Cost of additional inputs (including labor costs) bought for replanting in fully damaged hectares, when replanting is possible within the same season. Perennial crops: (1) Pre-disaster value of destroyed stored perennial crops (e.g. fruits), and inputs (e.g. seedlings). (2) Cost of additional inputs (including labor costs and value of trees) bought for replanting fully destroyed trees.	Value of crop production (excluding stored crops).	within the same season (2) Difference between expected and actual value of crop production in non-fully damaged harvested area in disaster year. Perennial crops: (1) Pre-disaster value of fully destroyed standing crops (e.g. fruits). (2) Difference between expected and actual value of crop production in non-fully damaged harvested area in disaster year. (3)) Discounted expected value of crop production in fully damaged harvested area until full recovery.
	Assets	Machinery, siloes, irrigation systems, equipment, tools.	Total destruction: replacement cost of fully destroyed assets at pre-disaster price. Partial destruction: repair/rehabilitation cost of partially destroyed assets at pre-disaster price.		
	Community			Value of the labor force	Changes in value of labor force (tbd)
Aquaculture	Production	Fish stock; fish stored or ready for sale	(1) Pre-disaster value of dead fish minus value of dead fish sold. (2) Pre-disaster value of destroyed fish stored or ready for sale.	Value of aquaculture production	(1) Difference between expected and actual value of aquaculture production in affected area in disaster year.
	Assets	Fishponds, ice and fish storage facilities, tools, machinery	Total destruction: replacement cost of fully destroyed assets at pre-disaster prices. Partial destruction: repair/rehabilitation cost of partially destroyed assets at pre-disaster prices.		
	Community			Value of the labor force	Changes in value of labor force (tbd)
Livestock	Production	Livestock units and livestock products (primary and secondary) stored or ready for sale.	Animals: Pre-disaster value of dead animals minus value of dead animals sold. Livestock products: Pre-disaster value of destroyed stored livestock products (primary and secondary).	Production value of livestock products (primary and secondary)	Livestock products: (1) Difference between expected and actual value of livestock products (primary and secondary) from survived animals in disaster year. (2) Discounted expected value of livestock products (primary and secondary) from dead animals until full recovery of livestock.
	Assets	Machinery, siloes, equipment, tools, and other buildings e.g., cattle fattening and rearing pens, milking stalls, sheds, stables, pigsties etc.	Total destruction: replacement cost of fully destroyed assets at pre-disaster price. Partial destruction: repair/rehabilitation cost of partially destroyed assets at pre-disaster price.		
	Community			Value of the labor force	Changes in value of labor force (tbd)
Forestry	Production	Log stored or ready for sale.	(1) Pre-disaster value of destroyed log stored or ready for sale.	Value of log production.	(1) Pre-disaster value of log from destroyed production forests. (2) Difference between expected and actual value of log production in non-fully damaged harvested area in disaster year. (3) Discounted expected value of log production in fully damaged forest area until full recovery.
	Assets	Machinery, siloes, equipment, tools etc.	Total destruction: replacement cost of fully destroyed assets at pre-disaster prices. Partial destruction: repair/rehabilitation cost of partially destroyed assets at pre-disaster prices.		
	Community			Value of the labor force	Changes in value of labor force (tbd)

CONCLUSIONS AND WAY FORWARD

This paper proposes a standardized methodological approach to assess damage and losses from natural hazard-induced disasters in agriculture, building on existing methodologies that are already implemented in several countries, such as Post Disaster Needs Assessment (PDNA). The systematic implementation of the methodology at national level would help refining and standardizing national methodologies for data collection, eventually leading tothe establishment of an FAO global information system that supports resilient and sustainable sectoral development planning, implementation and funding.

The adoption of the methodology for regular damage and losses monitoring and reportingat national level will require strengthening the capacity of relevant national authorities involved in disaster impact assessment in agriculture. Furthermore, the development and use of mobile data collection tools would be an essential step to improve the efficacy and reduce costs of post-disaster impact assessments.The methodology will be tested through the development of a series of case studies on previous disasters, in order to further refine and fine-tune the logical steps, calculation methods and estimation procedures. The results of case studies, together with the data regularly collected at national level, will be analysed and disseminated in the FAO'speriodic reportson *The Impact of Disasters on Agriculture and Food Security*.

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TECHNICAL ANNEXES

1. ASSUMPTIONS

The overall assumptions of the methodology for damage and losses assessment from natural disaster in agriculture, fisheries, aquaculture and forestry are:

1. Single disaster assessment. It is assumed that shocks to the agricultural sector are independent and their effects are not cumulative. Way forward: note that the complexity of linkages between different disasters must be further explored.
2. Prices used in the damage and losses assessment are always farm gate prices.
3. Annual crop are not affect the years that follow the disaster.
4. Changes in yields and changes in the size of the area harvested are assumed to be independent.
5. For perennial crops, yields are assumed to have a constant linear behaviour through time in the years before the disaster (e.g. 5 years' time series).
6. For perennial crop losses, all fully damaged hectares are replanted the same year of the disaster and no production is available until full recovery.
7. Replanting of the annual crops is feasible in the same season only if the natural hazard strikes before or during the sowing season. If replanting is still possible, the productivity is considered a linear function of the time available for replanting (e.g. if the planting is possible 5 months per year and the natural hazard strikes at the 4th of the 5 months, then 20% of the of total expected production for the same year can be retrieved. A more flexible functional form would allow to relax the linearity assumption and to have room for more accurate calibration.
8. It is assumed there is no mixed use of assets (infrastructure, machinery, tools) in order to avoid double counting. A relaxed version of this hypothesis is also proposed in the methodology.
9. The repair and rehabilitation cost of assets is linearly correlated with the level of damage.
10. Changes of area harvested are calculated as the difference of the first data available for hectares before the disaster and the first available after the disaster, in order to avoid accounting for changes in area harvested not strictly related to the shock(s) of the same year. Multiple shocks in the same year are still a source of bias in themethodology.
11. The area harvested after the disaster is assumed to be remain constant at pre-disaster levels in the counterfactual scenario of no disaster.
12. If the immediate substitution of assets destroyed or the repair of the damaged assets is not possible, an average rental cost of the assets is taken into account as a (linear) function of a specific resilience indicator (e.g. INFORM). The fit of the functional form deserves to be further explored.
13. It is assumed that no additional investments in assets are done except for investments needed to restore pre-disaster production.
14. The physical weight of each type of livestock is assumed to be constant across time but livestock-specific.
15. It is assumed that restoring the size of the livestock happens in bulk after a livestock-specific amount of time, if immediate intervention is not possible.
16. Following existing disaster assessment approaches, this methodology focuses on damage and losses. Potential benefits from natural disasters are not considered.
17. All projections are based on pre-disaster information.

2. MATHEMATICS BEHIND THE METHODOLOGY

Consider the following sets and subsets:

$$\forall\, i \in I = \{I_{AC}, I_{PC}, I_{L}, I_{FI}, I_{AQ}, I_{FO}$$

where i is the agricultural output considered and subscripts flag the sub-sectors (AC=Annual Crops; PC=Perennial Crops; L=Livestock; FI=fisheries; AQ=Aquaculture; FO=Forestry). Hence I_{AC} is the list of agricultural outputs of sub-sector. Note that $I_C = I_{AC} \cup I_{PC}$, where C= Crop

$$\forall\, j \in J = \{\text{set of most granular geographical units available}$$

where the granularity of the geographical unit depends on data availability. For instance it can be regions, provinces, villages, households);

$$\forall\, k \in K = \{K_{AC}, K_{PC}, K_{L}, K_{FI}, K_{AQ}, K_{FO}$$

where k is the is the asset (infrastructure, machinery, tool) used in order to produce an agricultural output. The subsets structure is depending on the agricultural output i category. If the asset characterization is strictly dependent on i, then it is represented as K_i. Note that $K_C = K_{AC} \cup K_{PC}$, where C= Crop. If asset k can not be exclusively associate to one item i, then the share of value of the asset attached to item i is proportionate to the share of the value production of item i over the total production value of all items that use that precise asset k;

$$x \in X = \{X_{AC}, X_{PC}, X_{L}, X_{FI}, X_{AQ}, X_{FO}\}$$

where x is the input of agricultural output production. Note that x can be item specific (X_{ij}), as the asset k_{ij}. Note that $X_C = X_{AC} \cup X_{PC}$, where C= Crop.

Also, consider t as the first time unit when post-disaster data are available; and $t-1$ as the first time unit when pre-disaster data are available. For instance, if data of year 2013, when typhoon Haiyan stroke the Philippines, have been collected after the natural hazard stroke, then we consider $t = 2014$ and $t - 1 = 2013$. If data for that year have been collected before the disaster then $t = 2013$ and $t - 1 = 2012$. Note that pre-disaster prices and labour force cost are used. Integrating price volatility is out of the scope of the methodological effort done so far. In order to discount values through time it is used$\rho = \frac{1}{1+r} is the time\ discount factor and r is the interest rate\ (e.g. 10\%)$

Finally, $y_{ij,t}$ is defined as the yield of item i in zone j at time t per spatial unit (i.e. hectare) and $1(s < m_{iN}) = \begin{cases} 1 \text{ if } s < m_{iN} \\ 0 \text{ otherwise} \end{cases}$ is an indicator function in which s corresponds to the moment when the disaster hits and m_{iN} is the moment when the sowing season of item i ends.

The methodology is presented by sub-sector, distinguishing damage from losses per component (production and assets) and considering further decompositions, for example in the case of crops sub-sector where annual and perennial crops are treated separately (sub-components).

The methodology also takes into account both prevention and response components of resilience. Note that resilience is both endogenously defined (e.g. variation in yields due to disasters) and exogenously parametrized (e.g. the capacity to sell the meat of animals dead because of the disaster).

Consider the following definitions, which rely on different subsets of the afore-mentioned sets according to the sub-sector:

$q_{x,ij}$ *is the quantity of input x in zone j needed for producing i in one hectare*;
$\bar{q}_{ij,k,t}$ *is the stored average quantity of item i in zone j per unit of infrastructure k*;
$\bar{q}_{x,ij,t}$ *is the stored average quantity of input x for item i in zone j per unit of infrastructure k*;
$\Delta q_{kj,t} = E_{t-1}[q_{kj,t}|\{q_{kj,t-1},\dots,q_{kj,t-n}\}] - q_{kj,t}$
is the unexpected change of the number of assets fully damaged at time t in zone j;
$\Delta q_{ij,k,t}$ *is theunexpectedchangeinquantitystoredofitemiinzonejineachassetk*;
$\Delta q_{x,ij,t}$ *istheunexpectedchangeinquantitystoredofinputxin zonejforitemiineachassetk*;
$q_{kj,t}$ *is the number of assets k in zone j at time t*;

$$\Delta q_{zj,t} = E_{t-1}[q_{zj,t}|\{q_{zj,t-1},\dots,q_{zj,t-n}\}] - q_{ij,k,t}$$

istheunexpectedchangeinquantityofstoredproductzinzonejattimet;
$p_{x,ij,t-1}$ *is the price of input x for item i in zone j at time* $t-1$;
$\bar{c}_{kj,t-1}$ *istherepair (rental) averagecostinzonejperunitofcapitalkthathasbeenonlypartially(fully)destroyed*;
that has been only partially (fullydestroyed) destroyed;
$p_{zj,t-1}$ *isthepriceofoneunitofproductz(primaryorsecondary)inzonejattimet* -1;
$p_{zj,t-1}$ *isthepriceofoneunitofweightofstoredproductzinsonejattimet* -1;
$p_{ij,t}$ *isthepriceofofoneunitofweightofitemiinzonejattimet*;
$l_{ij,t-1}$ *is the labour force cost per unit of time for one hectar of item i production in zone j*;
$T_i = T_{i,l} + T_{i,\$}$
is the number of time units needed for the production of item i in one hectare to be restored,
decomposable in the effective working time needed $(T_{i,l})$ *and the waiting time due to credit constraints* $(T_{i,\$})$;
$\bar{w}_i$ *istheaverageweightofitemi*;
T_k *isthetimeneededtoassetktobereconstructed ,expressingtheresponsecomponentofresilience*;
$ha_{ij,t}$ *is the number of hectares devoted at item i in zone j at time t*;
$\Delta ha_{ij,t} = E_{t-1}[ha_{ij,t}] - ha_{ij,t}$ *is the unexpected change in the quantity of hactares where i is produced*;
$k_{ij} \in K_{PC}$ *is the number of trees per hectare of item i in zone j*;
$\Delta y_{ij,t} = E_{t-1}[y_{ij,t}|\{y_{ij,t-1},\dots,y_{ij,t-n}\}] - y_{ij,t}$
istheunexpectedchangeinyieldsperunit(e.g. km or ha)ofgeographicalextention;
$\Delta y_{zj,t} = \mathrm{E}_{t-1}[y_{zj,t}|\{y_{zj,t-1},\dots,y_{zj,t-n}\}] - y_{zj,t}$ *and*
$y_{zj,t}$ *istheyieldofproductz(primaryorsecondary)peritemi(i.e.animal)inzonejattimet*;
1 $\Delta q_{kj,t} > 0)$ *impliesthatonlyassetskpartiallyorfullydestroyedaretakenintoaccount*;
sisthemonthwhenthedisasterhits;
m_{i0} *isthemonthwhenthesowingseasonofitemibegins*;
m_{iN} *isthe monthwhenthesowingseasonofitemiends*;
$\beta = f(R)$ *isafunctionofaspecificresilienceindexR(e.g.INFORM)s.t.* $\beta \in [0;1]$.
α *istheshareofthevaluedeadanimalthatcanbesold.*

CROP DAMAGE

1. *CROP PRODUCTION DAMAGE*

1.1. **ANNUAL CROP PRODUCTION INPUT DAMAGE.** $\forall\, i \in I_{AC} \wedge \forall\, j \in J$, given $x \in X = \{set\ of\ inputs\ for\ crop\ production\}$, the Damage to all Input x of Annual Crop i in zone j is

$$\mathrm{DIAC_{ij}} = \beta \cdot \sum_{x\in X} [\mathrm{p_{x,ij,t-1}} \cdot \mathrm{q_{x,ij}}] + \mathrm{l_{ij,t-1}} \cdot \mathrm{T_i}) \cdot \Delta ha_{ij,t} \cdot 1(s \in [m_{i0}; m_{iN}$$

1.2. **PERENNIAL CROP PRODUCTION INPUT DAMAGE.** $\forall i \in I_{PC} \wedge \forall j \in J$, given $x \in X = \{setofinputsforcropproduction\}$, the Damage to Inputs x of Perennial Crop i in zone j is

$$DIPC_{ij} = \sum_{x\in X} [p_{x,ij,t-1} \cdot q_{x,ij}] + l_{ij,t-1} \cdot T_i + p_{ij,t-1} \cdot k_{ij}) \cdot \Delta ha_{ij,t}$$

1.3. **STORED CROP DAMAGE (PRODUCTION AND INPUT).** $\forall i \in I_{PC} \wedge \forall j \in J$, given $x \in X_C$ and $k \in K_C$, the Damage to Stored Crops (inputs and production) is

$$DSC_{ij} = p_{ij,t-1} \cdot \sum_{k\in K_C} \Delta q_{ij,k,t} + p_{x,ij,t-1} \cdot \sum_{k\in K_C} \sum_{x\in X_C} \Delta q_{x,ij,t}$$

Note that $\Delta q_{ij,k,t} = E_{t-1}[q_{ij,k,t}] - q_{ij,k,t}$ and $\Delta q_{x,ij,t} = E_{t-1}[q_{x,ij,t}] - q_{x,ij,t}$ where $E_{t-1}[\cdot]$ is the expectation function of $[\cdot]$ at time $t-1$. Because of a systematic lack of these type of data, this methodology proposes the following estimation procedures:

$$\Delta q_{ij,k,t} = \sum_{k\in K_C} \bar{q}_{ij,k,t} \cdot \Delta q_{ij,t} \quad \text{and} \quad \Delta q_{x,ij,t} = \sum_{k\in K_C} \bar{q}_{x,ij,t} \cdot \Delta k_{ij,t}$$

2. CROP ASSETS DAMAGE

2.1. **CROP ASSETS TOTALLY DAMAGED.** $\forall i \in I_{PC} \wedge \forall j \in J$, given $k \in K_i \subset K_C$, the Damage of Assets Totally destroyed for Crops production is

$$DATC_{ij} = \sum_{k\in K_i} p_{kj,t-1} \cdot \Delta q_{kj,t}$$

Note that the estimation function $E_{t-1}[\cdot]$ is conditional on the time series of quantities of q_{kj} in the pre-disaster period for n units of time. This implies a direct relation with the size of investments in assets, which are assumed to be null except for investments needed to restore pre-disaster production.

2.2. **CROP ASSETS PARTIALLY DAMAGED.** $\forall i \in I_{PC} \wedge \forall j \in J$, given $k \in K_i \subset K_C$, Damage of Assets only Partially destroyed for Crops production is

$$DAPC_{ij} = \sum_{k\in K_i} \bar{c}_{kj,t-1} \cdot \Delta q_{kj,t}$$

CROP LOSSES

1. CROP PRODUCTION LOSSES

1.1. **ANNUAL CROP PRODUCTION LOSSES.** $\forall i \in I_{AC} \wedge \forall j \in J$, given $y_{ij,t}$, the Losses of Annual Crops Production component are

$$LACP_{ij} = p_{ij,t-1} \cdot \Delta y_{ij,t} \cdot ha_{ij,t} \cdot 1(\Delta y_{ij,t} > 0) +$$

$$+ \left(1 - \frac{m_{iN} - s}{m_{iN} - m_{i0}} \cdot 1(s \in [m_{i0}; m_{iN} \right. \cdot p_{ij,t-1} \cdot y_{ij,t-1} \cdot \Delta ha_{ij,t}$$

1.2. **PERENNIAL CROP PRODUCTION LOSSES.** $\forall i \in I_{PC} \wedge \forall j \in J$, given $y_{ij,t}$, the Losses of Perennial Crops Production component are

$$LPCP_{ij} = \sum_{g=0}^{T_i} \rho^g \cdot E_{t-1}[p_{ij,t-1} \cdot y_{ij,t-1}] \cdot \Delta ha_{ij,t} + p_{ij,t-1} \cdot \Delta y_{ij,t} \cdot ha_{ij,t}$$

2. ***CROP ASSETS LOSSES.*** $\forall i \in I_C \wedge \forall j \in J$, given $k \in K_i \subset K_C$, the Losses of Assets partially or fully destroyed used for Crops production are

$$LAC_{ij} = \sum_{g=0}^{T_k} \rho^g \cdot \sum_{k \in K_i} \bar{c}_{kj,t-1} \cdot \Delta q_{kj,t} \cdot 1(\Delta q_{kj,t} > 0$$

LIVESTOCK DAMAGE

1. ***LIVESTOCK PRODUCTION DAMAGE.*** $\forall i \in I_L \wedge \forall j \in J$, given $z \in Z_{stored}$ ={*set of livestock primary and secondary stored products*} $\subset Z_L = \{setoflivestockprimaryandsecondaryproducts\}$, the Damage to the Production component of Livestock is

$$DPL_{ij} = \sum_{z \in Z_{stored}} \{\Delta q_{zj,t} \cdot p_{zj,t-1}\} + \Delta q_{ij,t} \cdot \bar{w}_i) \cdot (p_{ij,t-1} - \alpha \cdot p_{ij,t}$$

2. ***LIVESTOCK ASSETS DAMAGE***
   2.1. **LIVESTOCK ASSETS TOTALLY DAMAGED.** $\forall i \in I_L \wedge \forall j \in J$, given $k \in K_i \subset K_L$, the Damage of Assets Totally destroyed for Livestock production is

$$DATL_{ij} = \sum_{k \in K_i} p_{kj,t-1} \cdot \Delta q_{kj,t}$$

   2.2. **LIVESTOCK ASSETS PARTIALLY DAMAGED.** $\forall i \in I_L \wedge \forall j \in J$, given $k \in K_i \subset K_L$, Damage of Assets only Partially destroyed for Livestock production is

$$DAPL_{ij} = \sum_{k \in K_i} \bar{c}_{kj,t-1} \cdot \Delta q_{kj,t}$$

LIVESTOCK LOSSES

1. ***LIVESTOCK PRODUCTION LOSSES.*** $\forall i \in I_L \wedge \forall j \in J$, given $z \in Z$ ={*set of livestock primary and secondary products*}, the Losses of Livestock production (primary and secondary) are

$$\sum_{g=0}^{T_i} \rho^g \cdot \sum_{z \in Z} \Delta q_{ij,t} \cdot p_{zj,t-1} \cdot y_{zj,t-1} + \sum_{z \in Z} q_{ij,t} \cdot p_{zj,t-1} \cdot \Delta y_{zj,t}$$

2. **LIVESTOCK ASSETS LOSSES.** $\forall i \in I_L \wedge \forall j \in J$, given $k \in K_i \subset K_L$, the Losses of Assets partially or fully destroyed used for Livestock production are

$$LAL_{ij} = \sum_{g=0}^{T_k} \rho^g \cdot \sum_{k \in K_i} \bar{c}_{kj,t-1} \cdot \Delta q_{kj,t} \cdot 1(\Delta q_{kj,t} > 0$$

FISHERIES

Consider the following additional definitions:

$$y_{ij,t} = \frac{\bar{w}_{ij} \cdot q_{ij,t}}{area_{ij,t}} where \bar{w}_{ij} \cdot q_{ij,t}$$
$$isquantityoffishicatch(e.g.intons)(averageweighttimesthenumberoffishes);$$
$$area_{ij,t} isthenumberofunitofareawhereitemi(i.e.typeoffish)inzonejattimetiscatched;$$

FISHERIES DAMAGE

1. ***FISHERIES PRODUCTION DAMAGE.*** $\forall i \in I_L \wedge \forall j \in J$, given $k \in K_i \subset K_{FI}$, the Damage of Fisheries Production component is

$$DFiP_{ij} = p_{ij,t-1} \cdot \Delta q_{ij,k,t} \cdot \bar{w}_i$$

Note that the estimation procedure is equivalent to the one proposed for stored crops.

2. ***FISHERIES ASSETS DAMAGE***

   2.1. **FISHERIES ASSETS TOTALLY DAMAGED.** $\forall i \in I_{FI} \wedge \forall j \in J$, given $k \in K_i \subset K_{FI}$, the Damage of Assets Totally destroyed for Fisheries production is

$$DATFi_{ij} = \sum_{k \in K_i} p_{kj,t-1} \cdot \Delta q_{kj,t}$$

   2.2. **FISHERIES ASSETS PARTIALLY DAMAGED.** $\forall i \in I_{FI} \wedge \forall j \in J$, given $k \in K_i \subset K_{FI}$, Damage of Assets only Partially destroyed for Fisheries production is

$$DAPFi_{ij} = \sum_{k \in K_i} \bar{c}_{kj,t-1} \cdot \Delta q_{kj,t}$$

FISHERIES LOSSES

1. ***FISHERIES PRODUCTION LOSSES.*** $\forall i \in I_{FI} \wedge \forall j \in J$, the Losses of Fisheries production are

$$LFP_{ij} = area_{ij,t} \cdot p_{ij,t-1} \cdot \Delta y_{ij,t}$$

2. ***FISHERIES ASSETS LOSSES.*** $\forall i \in \mathrm{I}_{FI} \wedge \forall j \in J$, given $k \in K_i \subset K_{FI}$, the Losses of Assets partially or fully destroyed used for Fisheries production are

$$LAF_{ij} = \sum_{g=0}^{T_k} \rho^g \cdot \sum_{k \in K_i} \bar{c}_{kj,t-1} \cdot \Delta q_{kj,t} \cdot 1(\Delta q_{kj,t} > 0$$

AQUACULTURE

Consider the following additional definitions:

$\Delta area_{ij,t} = E_{t-1}[\Delta area_{ij,t}] - \Delta area_{ij,t}$
$is the unexpected change in spatial unit\ quantity (e.g.\ cube metres) where item i is produced;$

AQUACULTURE DAMAGE

1. ***AQUACULTURE PRODUCTION DAMAGE.*** $\forall i \in I_{AQ} \wedge \forall j \in J$, given $k \in K_i \subset K_{AQ}$, the Damage of Aquaculture Production component is

$$DAQP_{ij} = (p_{ij,t-1} - \alpha \cdot p_{ij,t}) \cdot \bar{w}_i \cdot (\Delta \mathrm{q}_{ij,t} + \Delta q_{ij,k,t})$$

Note that the estimation procedure of $\Delta(\cdot)$is equivalent to the one proposed for stored crops.

2. ***AQUACULTURE ASSETS DAMAGED***

   2.1. **AQUACULTURE ASSETS TOTALLY DAMAGED.** $\forall i \in I_{AQ} \wedge \forall j \in J$, given $k \in K_i \subset K_{AQ}$, the Damage of Assets Totally destroyed for Aquaculture production is

$$DATAQ_{ij} = \sum_{k \in K_i} p_{kj,t-1} \cdot \Delta q_{kj,t}$$

   2.2. **AQUACULTURE ASSETS PARTIALLY DAMAGED.** $\forall i \in I_{AQ} \wedge \forall j \in J$, given $k \in K_i \subset K_{AQ}$, Damage of Assets only Partially destroyed for Aquaculture production is

$$DAPAQ_{ij} = \sum_{k \in K_i} \bar{c}_{kj,t-1} \cdot \Delta q_{kj,t}$$

AQUACULTURE LOSSES

1. ***AQUACULTURE PRODUCTION LOSSES.*** $\forall i \in I_{AQ} \wedge \forall j \in J$, the Losses of Aquaculture production are

$$LAQP_{ij} = \Delta area_{ij,t} \cdot p_{ij,t-1} \cdot y_{ij,t-1} + area_{ij,t} \cdot p_{ij,t-1} \cdot \Delta y_{ij,t-1}$$

2. ***AQUACULTURE ASSETS LOSSES.*** $\forall i \in I_{AQ} \wedge \forall j \in J$, given $k \in K_i \subset K_{AQ}$, the Losses of Assets partially or fully destroyed used for Aquaculture production are

$$LAAQ_{ij} = \sum_{g=0}^{T_k} \rho^g \cdot \sum_{k \in K_i} \bar{c}_{kj,t-1} \cdot \Delta q_{kj,t} \cdot 1\big(\Delta q_{kj,t} > 0$$

FORESTRY DAMAGE

1. ***FORESTRY PRODUCTION DAMAGE***

$\forall i \in I_{FO} \wedge \forall j \in J$, given $k \in K_i \subset K_{FO}$ and $z \in Z_{stored}$ = {set of forestry primary and secondary stored products} $\subset Z_{FO}$ = {set of forestry primary and secondary products} ,the Damage of Forestry Production component is

$$DFoP_{ij} = \Delta ha_{ij,t} \cdot \bar{y}_{ij,t-1} \cdot p_{ij,t-1} + \sum_{z \in Z_{stored}} \{\Delta q_{zj,t} \cdot p_{zj,t-1}\}$$

2. **FORESTRY ASSET DAMAGE**

   2.1. FORESTRY ASSETS TOTALLY DAMAGED. $\forall i \in I_{FI} \wedge \forall j \in J$, given $k \in K_i \subset K_{FI}$, the Damage of Assets Totally destroyed for Forestry production is

$$DATFi_{ij} = \sum_{k \in K_i} p_{kj,t-1} \cdot \Delta q_{kj,t}$$

   2.2. FORESTRY ASSETS PARTIALLY DAMAGED. $\forall i \in I_{FI} \wedge \forall j \in J$, given $k \in K_i \subset K_{FI}$, Damage of Assets only Partially destroyed for Forestry production is

$$DAPFi_{ij} = \sum_{k \in K_i} \bar{c}_{kj,t-1} \cdot \Delta q_{kj,t}$$

FORESTRY LOSSES

1. ***FORESTRY PRODUCTION LOSSES.*** $\forall i \in I_{FO} \wedge \forall j \in J$, given $z \in Z_{FO} = \{setofforestryprimaryandsecondaryproducts\}$, the Losses of Forestry production (primary and secondary) are

$$\sum_{g=0}^{T_i} \rho^g \cdot \sum_{z \in Z} \Delta ha_{ij,t} \cdot p_{zj,t-1} \cdot y_{zj,t-1} + \sum_{z \in Z} ha_{ij,t} \cdot p_{zj,t-1} \cdot \Delta y_{zj,t}$$

2. ***FORESTRY ASSETS LOSSES.*** $i \in I_{FO} \wedge \forall j \in J$, given $k \in K_i \subset K_{FO}$, the Losses of Assets partially or fully destroyed used for Forestry production are

$$LAAQ_{ij} = \sum_{g=0}^{T_k} \rho^g \cdot \sum_{k \in K_i} \bar{c}_{kj,t-1} \cdot \Delta q_{kj,t} \cdot 1\big(\Delta q_{kj,t} > 0$$

3. ERROR ANALYSIS - Calculations of error intervals in measurement.

In order to represent at least part of this variability in the outcome measurements, the following error interval procedure is proposed.

1. **Min-Max Interval.** The methodology presents a set of exogenous parameters per sub-component, distinctly for damage and for losses.

   1.1. For each parameter, it is defined an *average* value, a *minimum* and a *maximum*. All three values are primarily based on the existing concerned literature and on experts' judgment.

1.2. The outcome values for damage and for losses are calculated three times for each sub-component, using the *average* values of the exogenous parameters, the values that *minimize* the outcome, and the values that *maximize* the outcome.

Outcomes can also be aggregated per component, sub-sector, or totally as all sub-components are mutually exclusive and additive.

2. 90% Confidence Interval per level of geophysical stressor.

In order to identify the magnitude of a natural hazard, climatic and geophysical stressors information is collected at the most cost-efficient level of granularity.

2.1. Categories of intensity of the stressors are defined. For instance, in the case of Typhoons, wind speed (in accordance with the topography of the area) is a strong determinant of the magnitude of the natural hazard, and four categories are identified.
2.2. For each cluster (i.e. category of stressor's intensity), the mean of damage and mean of losses in zones j falling under that precise cluster are calculated.
2.3. Each mean of step 2.2. is provided with a 90% confidence interval.
2.4. Hypothesis test of difference between means is calculated. The T test tests the internal validity of step 2.