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Annex 1

Overall logic for assessing development, adaptation and mitigation options in agricultural water management and irrigation, in response to climate change

The pressure and rationale for economic development to benefit the world's poor will remain a major goal for mankind as populations continue to rise. The provision of adequate food, water and sanitation is one of the most basic aspects of continued economic development. Coupled with changing dietary preferences, it is estimated that world food production will have to double by 2050 to meet likely future demands (FAO, 2007; CA, 2007 (Ch. 2); Nelson *et al*., 2009).

This calculus does not factor in climate change, which introduces further pressures and constraints. The satisfaction of future needs, even without consideration of climate change impacts, has major implications of its own for land use, water use, expansion of irrigated and rainfed crop areas, and their corollary impacts on forest and rangeland areas (MA, 2005; CA, 2007):

1. Sustainable use of increasingly pressured natural resources (land and water) requires careful consideration of competing socio-economic uses and values, and of the trade-offs (short- and long-term benefits: financial costs; and environmental costs) between different mixes of land and water development and the intensification of production on existing lands.
2. Agricultural development that relies on intensification through the use of fossil energy (transport, traction, production of fertilizers (N) and agricultural chemicals) will, in turn, contribute further to climate change forcing through emissions of CO_2, CH_4 and N_2O.
3. Further expansion and intensification of agricultural production has the potential to continue existing trends in the degradation of soils and their long-term productivity (increase of salinity and acidity; loss of nutrients; and loss of soil carbon).
4. In contrast, there are significant hopes that soil carbon storage can be enhanced to minimize net agricultural emissions and possibly to mitigate emissions from other sources (industry, transport and energy for the built environment) (Smith *et al*., 2008; USGS, 2002; USDA, 2008).

Climate change impacts on agriculture will include:

1. Rising **temperatures** that will result in higher evaporation rates; shorter crop seasons in mid and low latitudes, but longer crop seasons in the higher latitudes. There will be potential to increase the number of cropped seasons per year at all latitudes, where sufficient rainfall or water resources permit, although yield

potentials for most crops in the mid and low latitudes will decline due to shorter seasons, higher respiration rates, and increased evaporative demand. There will be corresponding declines in potential water productivity, with and without CO_2 fertilization, for which the prospects of mitigating loss of yield potential seem to be diminishing (Long *et al.*, 2005; USDA, 2008).

2. Less clearly understood and more spatially variable **changes in precipitation**: The general trends in precipitation predicted by AR4 modelling exercises are gradually being corroborated by analysis of trends in some areas (declines in northern Africa and southern Europe, for example (Allison *et al.*, 2009)). However, there remains strong disagreement in the directions, extents and spatial patterns of changes in precipitation. The fundamental reasons for this are that most GCMs used so far do not couple land use and land surface interactions that dominate weather at regional and local scales – topography, physiography, elevation and land cover (IPCC 2007; Allison *et al.*, 2009). GCM models predict intensification of the hydrologic cycle, with more extreme behaviour around the mean (more intense storms and longer dry periods in between) for both net reductions and increases in annual rainfall. Any meaningful assessment of the agricultural impacts of changed precipitation regimes requires more precise temporal and spatial prediction, which should be made with a higher level of certainty than is the norm at present.
3. Direct competition for land and water resources for the production of biofuels, in part related to GHG mitigation strategies (de Fraiture, 2008; FAO, 2008b; USDA, 2008).

Climate change **impacts on water resources** will reflect changes in water balance brought about by increased evaporation rates and changes in precipitation.

1. Where rainfalls decline there will be much larger corresponding reductions in surface runoff (CSIRO 2007; Milly *et al.*, 2005). In all cases where rainfall, runoff and groundwater recharge decline, current tensions between agricultural and environmental allocation of water will be magnified. It is becoming clear that allocation policy in the future will face considerably tougher dilemmas in balancing environmental flow allocations with those in agriculture (DSE, 2007). In general, it is likely that other high-value demands can be satisfied relatively easily, as the quantities demanded are small in relation to those for agriculture and natural ecosystems. The very definition of a natural eco-system under climate change will provoke much thought and discussion. Where surface runoff declines, groundwater recharge is also <u>likely</u> to decline.
2. Where rivers depend on glacier melt, shorter-term increases in runoff because of warming, and retreat of glaciers will be replaced by long-term declines in yield (Barnett *et al.*, 2005, Kulkarni *et al.,* 2007). Quantification of such changes is as yet poor, resulting from the variable contribution of snowmelt to total annual flow. It is likely that low flows (in summer) will fall, and the timing of seasonal flows will move from spring to winter flows. There is also an improving understanding of the complexity of mountain hydrology and the spatial extents of different runoff processes within large mountain areas (Fowler and Archer, 2005).
3. As rainfall regimes are expected to become more extreme, with more intense rainfalls and more frequent high-intensity rainfall, offset by longer periods of drought between rains, the following can be anticipated: reduction in base flows; increased frequency and severity of flooding, although where groundwater recharge is determined mostly by flood plain flows, then groundwater recharge may be stabilized or enhanced; increased frequency and severity of within-season, seasonal and annual droughts – and needs to adapt agricultural water management to those different time scales. Where rainfall increases, the frequency of flooding and high flow events is expected to increase.
4. The main implications for water resources for agriculture are:
    - Risks of within and across season water stress increase. This is particularly true for rainfed agriculture in low rainfall zones.

- Risks of flooding and erosion also increase.
- Water supplies for irrigation will become less reliable.
- Enhanced water storage will be required to enable supplies to meet deficits reliably within season, between seasons and across years. Overall, water supply security for agriculture will fall in all areas of declining rainfall, and may also do so in some cases with increasing rainfall.

Downscaling techniques (empirical, statistical and model based, using Regional Climate Models) offer considerable improvement in the prediction of likely impacts on agricultural production systems, and for irrigation in particular (USDA, 2008; Kumar *et al.*, 2006; Naylor *et al.*, 2007). However, they are still governed by potential errors and inconsistencies in the GCM output that drives them. This can be addressed through:

- ➢ Ensemble GCM modelling to develop probabilistic predictions.
- ➢ Improvement of GCM structure and processes to included land-surface interactions.
- ➢ Possible use of GCMs with higher spatial resolution.
- ➢ Ensemble modelling of RCM simulation to refine probabilistic outcomes at local and regional scales.

Although climate change will reduce and limit potential land and water productivities, current levels of productivity are, in many instances, considerably below their potential[2], limited by water, nutrients and management techniques. Selection of agricultural development and adaptation options will depend to a considerable extent on their potential to realize higher real-world yields and water productivities within the limits imposed by future climate. Clearly, where cropping systems can be 'transferred' from existing AEZs/conditions to other locations that experience similar conditions in the future, then adaptation may be relatively straightforward.

Achieving higher real world yields and water productivity requires better provision for and management of limiting factor inputs. At the margins, notably in the semi-arid and arid mid-latitudes, the challenges of moving to yet hotter and drier conditions are daunting. There is uncertain potential to breed crops that have drought resistance, improved yield potential (temperature tolerance) and even increased water use efficiency (Huntingford *et al.*, 2005; Porter and Semenov, 2005; and Rebetzke *et al.*, 2008). There is considerable interest and activity in conventional and enhanced crop breeding, as well as in transgenic manipulation (GM crops). Achieving these goals is highly desirable, but positive outcomes are not a foregone conclusion and the time frames could be lengthy (Padgham, 2009). A sober reading of recent crop physiology literature suggests that it would be unwise to expect a silver bullet in terms of a second green revolution.

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[2] This is broadly true in the semi-arid, arid and humid tropics and sub-tropics. In northern America and Europe, agricultural productivity is much closer to its full potential.

Annex 2

Evaluating and selecting options for climate sensitive development

Better analysis of climate change impacts on food production systems needs to be focused on precise regions and localities, where it is possible to predict with some certainty the combined effects of increased temperature, changed precipitation and water resources availability, and the nature and frequency of extreme events (droughts and floods).

The typology (Table 4.2) developed to this point, defines specific contexts where irrigation (and other forms of agricultural water management) are 1) important; 2) have a specific form (with likely limitations on adaptation options); and 3) are vulnerable to specific combinations of climate threats (sea-level rise, reduced runoff, loss of water resources, heat waves and droughts, cyclone activity). Most of the examples in the typology do not yet include detailed and specific local analysis that would be required – for example the contrasting conditions and solutions for the Red River and Mekong Deltas (Delta category) in Vietnam.

1. The existing level of water development is an important second level of the typology that has not thus far been explicitly stated. The literature on adaptation contains many references to the benefits of increasing irrigation efficiency (usually not defined) as a means of saving water, with no reference to basin level water use and the possibility of making real net water savings at basin level.
2. A third level of the typology could (in nearly all categories) be extended to groundwater resource characteristics and use. Groundwater becomes an increasingly attractive mode of storage under climate change scenarios – to minimize infrastructure costs, maximize flexibility, and manage both short- and long-term variability in surface water supplies.

A decision tree can be mapped to help define the climate change impacts on crop production; this will be based on better elaboration of specific changes in temperature, rainfall, water resources availability, to arrive at solutions that are properly tailored to context and risk. This sits across and within the typology presented in Table 4.2.

The decision tree considers additional contextual (current development) information that is summarized in Figure 4.5 and links it more specifically to crop focused impacts outlined in Figure 4.1.

It attempts to provide a guideline framework to elaborate the generalized approach outlined in Figure 7.1. It addresses a specific national or regional context, or category within the typology. There are strategic (policy, programme, institutional development and public goods research) elements to an effective adaptation strategy. There are also likely to be a wealth of local (farmer, agro-industry) innovations in response to climate change. It will be important for planners and programme managers to be aware of such innovation and initiative and to take positive steps to reinforce all promising options.

An associated set of steps are embedded in the decision tree, and could be listed as follows:

1. *Define climate change impacts on water resources availability.*
2. *Define (account for) current water resources use, and projected use for current development goals.*
3. *Determine climate change impacts on future water availability and implications for future allocations.*
4. *Define the production status and potential of current agricultural (cropping) systems under selected climate change scenarios.*
5. *Examine the water and land-use implications of alternative combinations of agricultural development activities, incorporating rainfed agriculture; irrigated agriculture; agroforestry; rangeland; and integrated mixed farming.*

a. *Match options to likely scale and nature of farming in the future in recognition of current and likely levels of urban migration and remaining rural population.*

b. *Evaluate mitigation options for synergy, practicality and cost effectiveness.*

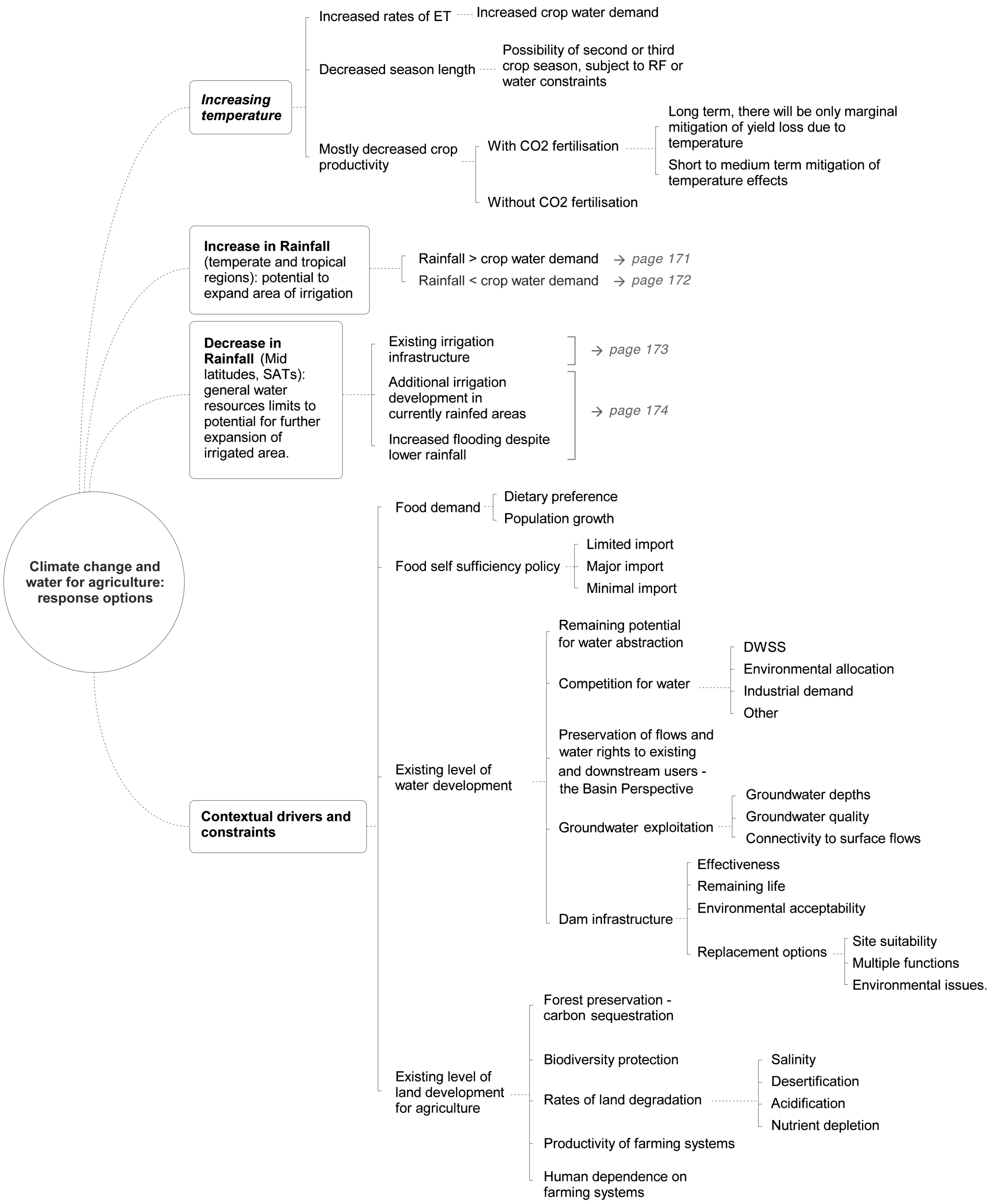
6. *Define resources and adaptations needed to maintain current levels of output and productivity.*
7. *Define resources and adaptations required to meet future demands.*
8. *Assess impacts on eco-systems and on the sustainability of the existing or proposed farming system.*
9. *Cost alternatives.*
10. *Prioritize options.*

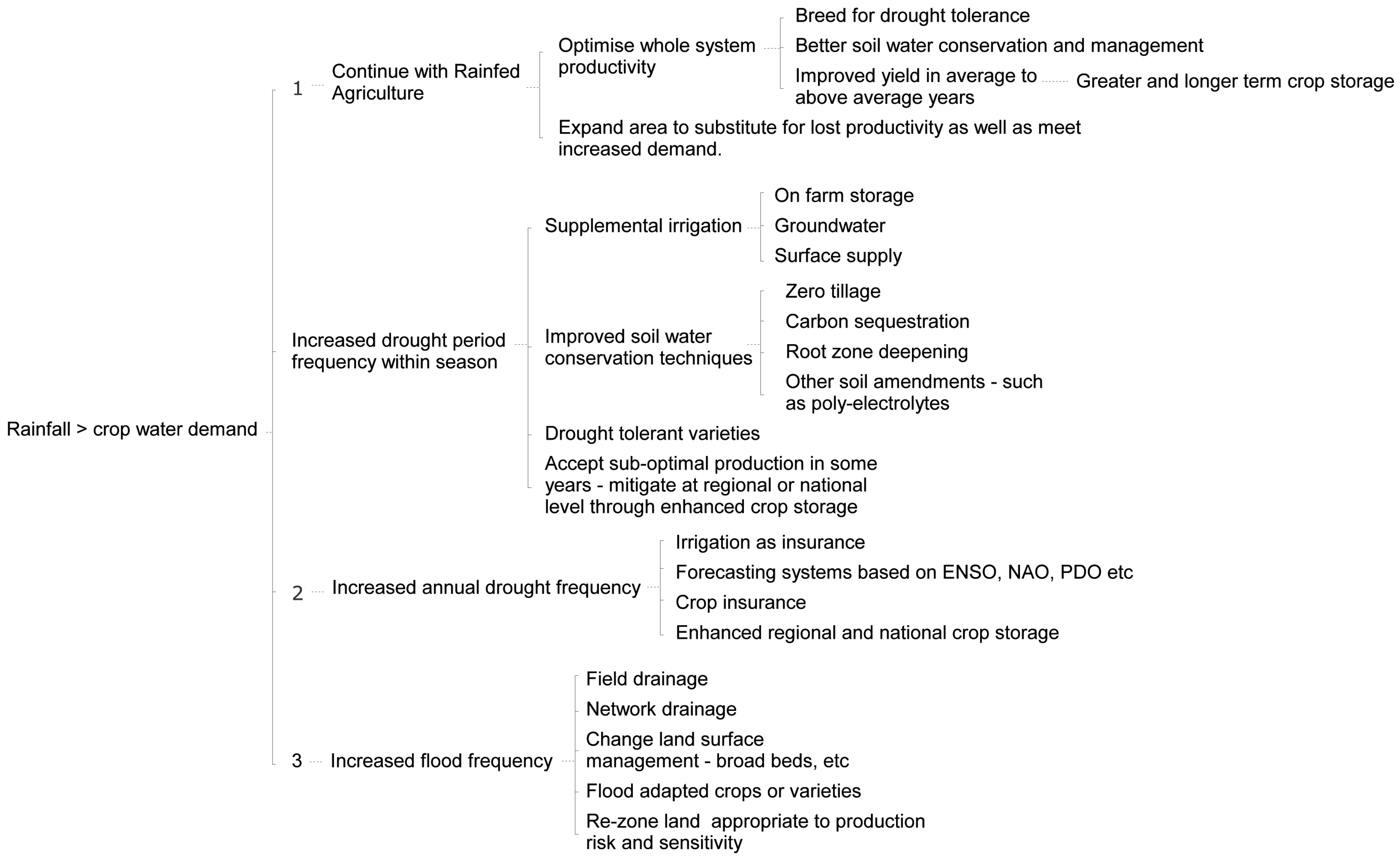
The continuing development of packages of adaptation options including adapted crops (breeding); soil water conservation techniques; nutrient management; improved irrigation modes (full, deficit, supplemental) and technology (water storage; agroforestry) can be based on:

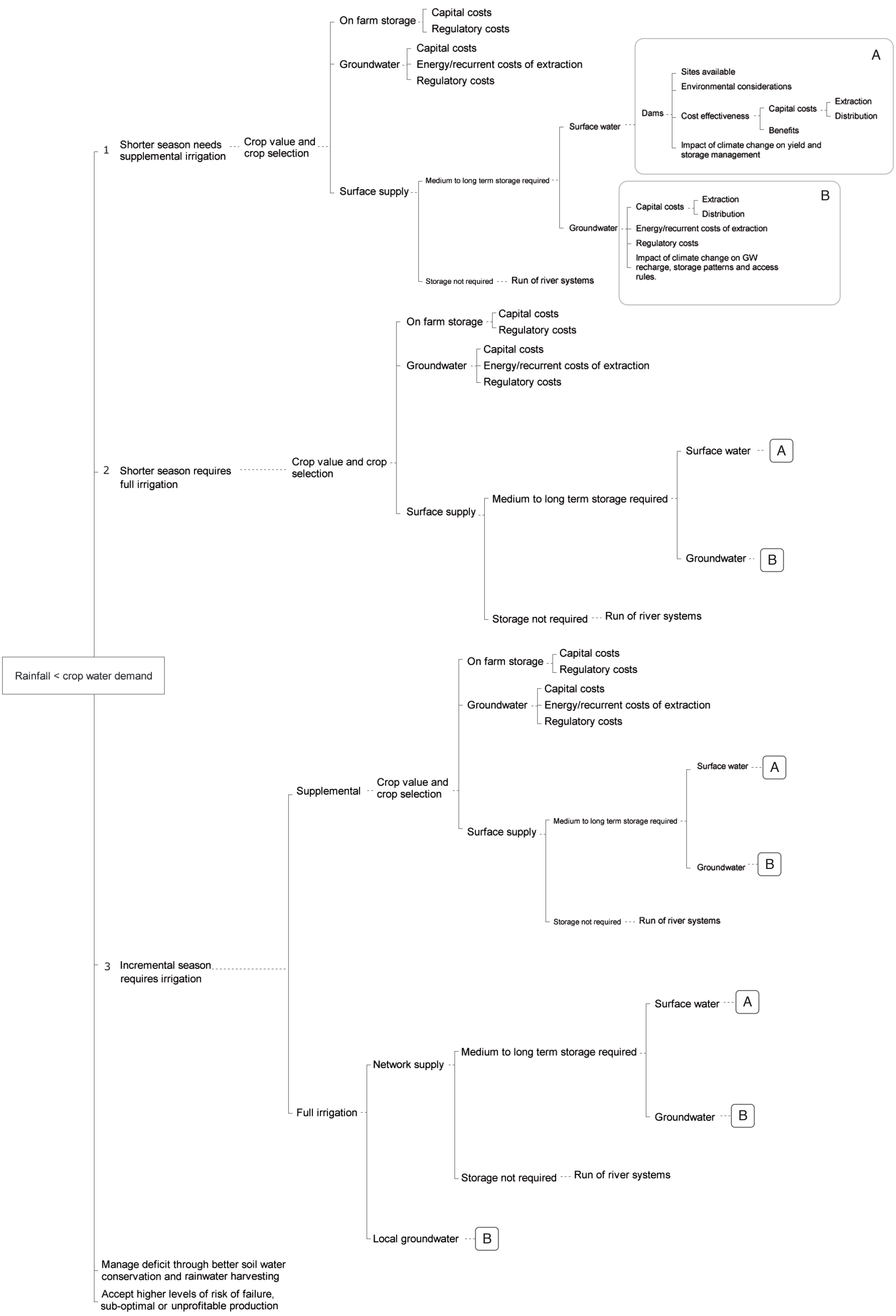
- Observation, assessment and promotion of appropriate and effective innovations developed by farmers at field level.
- Well-targeted research that addresses the specific climate change and socio-economic context (as defined through this process).
- Experience and knowledge transferred from similar contexts.

Examples of the overall decision tree, and the expansion up to 12 levels are given on the following five pages. The first page covers the broad range of response options to different sets of agricultural impacts. The other pages investigate more in details the cases related to increase or decrease of rainfall and implications for various type of agricultural water management.

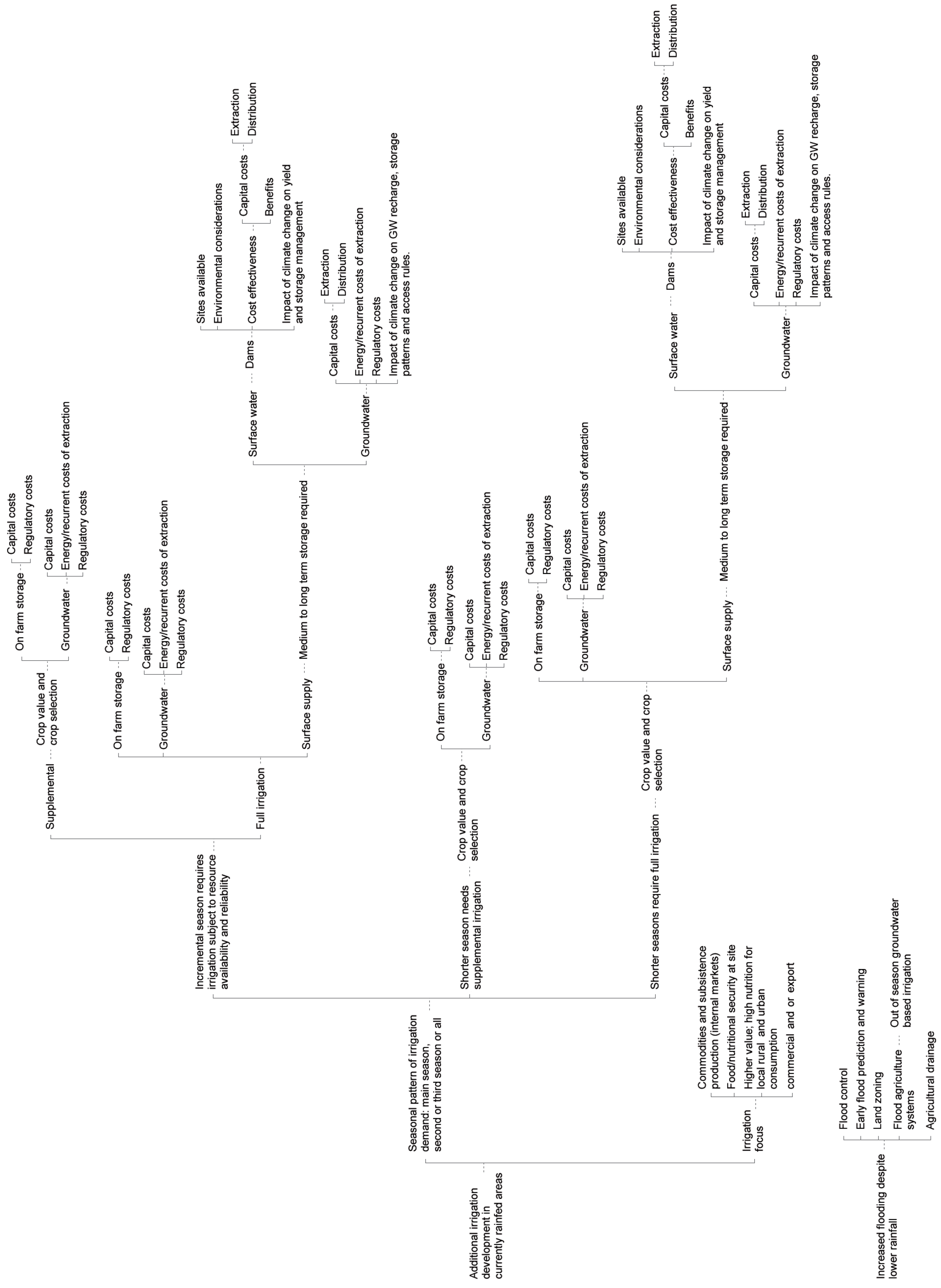
Example of decision tree




Rainfall > crop water demand
1
Continue with Rainfed Agriculture
Optimise whole system productivity
Breed for drought tolerance
Better soil water conservation and management
Improved yield in average to above average years
Greater and longer term crop storage
Expand area to substitute for lost productivity as well as meet increased demand.
Increased drought period frequency within season
Supplemental irrigation
On farm storage
Groundwater
Surface supply
Improved soil water conservation techniques
Zero tillage
Carbon sequestration
Root zone deepening
Other soil amendments - such as poly-electrolytes
Drought tolerant varieties
Accept sub-optimal production in some years - mitigate at regional or national level through enhanced crop storage
2
Increased annual drought frequency
Irrigation as insurance
Forecasting systems based on ENSO, NAO, PDO etc
Crop insurance
Enhanced regional and national crop storage
3
Increased flood frequency
Field drainage
Network drainage
Change land surface management - broad beds, etc
Flood adapted crops or varieties
Re-zone land appropriate to production risk and sensitivity


Rainfall < crop water demand
1 Shorter season needs supplemental irrigation
Crop value and crop selection
On farm storage
Capital costs
Regulatory costs
Groundwater
Capital costs
Energy/recurrent costs of extraction
Regulatory costs
Surface supply
Medium to long term storage required
Surface water
A
Dams
Sites available
Environmental considerations
Cost effectiveness
Capital costs
Extraction
Distribution
Benefits
Impact of climate change on yield and storage management
Groundwater
B
Capital costs
Extraction
Distribution
Energy/recurrent costs of extraction
Regulatory costs
Impact of climate change on GW recharge, storage patterns and access rules.
Storage not required
Run of river systems
2 Shorter season requires full irrigation
Crop value and crop selection
On farm storage
Capital costs
Regulatory costs
Groundwater
Capital costs
Energy/recurrent costs of extraction
Regulatory costs
Surface supply
Medium to long term storage required
Surface water
A
Groundwater
B
Storage not required
Run of river systems
3 Incremental season requires irrigation
Supplemental
Crop value and crop selection
On farm storage
Capital costs
Regulatory costs
Groundwater
Capital costs
Energy/recurrent costs of extraction
Regulatory costs
Surface supply
Medium to long term storage required
Surface water
A
Groundwater
B
Storage not required
Run of river systems
Full irrigation
Network supply
Medium to long term storage required
Surface water
A
Groundwater
B
Storage not required
Run of river systems
Local groundwater
B
Manage deficit through better soil water conservation and rainwater harvesting
Accept higher levels of risk of failure, sub-optimal or unprofitable production

- Existing irrigation infrastructure
  - Gravity/surface systems
    - Decreased runoff
      - 1 reduce service area
        - Maintain higher levels of unit area productivity (yield) at lower levels of water use efficiency
      - 2 ration water supplies across existing or reduced area
        - Accept lower yields, substituted by higher water use efficiency over a relatively larger area
        - Deficit irrigation
        - Crop insurance
      - 3 change demand pattern
        - improve or optimise use of rainfall
          - crop season dates
          - improved soil water management and conservation
        - change crop patterns to ones with lower demand
          - Crop choice
            - Policies and incentives
          - Crop breeding?
          - Deficit irrigation
        - Reduction of evaporative loading
          - Shade houses/protected agriculture
    - Changed pattern of runoff
      - 1 Snowmelt systems
        - reconfigure storage systems to match flow availability
          - groundwater
          - surface water
        - reconfigure and "control" abstraction patterns to match storage and flow availability
      - 2 Changed timing and duration of monsoons
        - adapt crop season timing and duration
          - seasonal forecasting
          - Annual forecasting, ENSO, NAO, etc
        - improved productive use of flood flows
          - local soil water conservation
          - groundwater recharge
          - surface water storage
      - 3 Increased proportion of storm/flood events
        - improved productive use of flood flows
          - local soil water conservation
          - groundwater recharge
          - surface water storage
        - adapt and zone farming system to maximise productivity and minimise risk in flood prone and flood managed areas.
  - Groundwater systems
    - Decreased recharge
      - reconfigure and "control" abstraction patterns to match storage and flow availability
      - enhance recharge (with reference to whole water balance and existing uses and users)
      - groundwater banking/preservation for drought periods
        - policy
          - Energy costs and technologies
        - monitoring
        - enforcement
    - Greater risk of over-pumping
      - policy
        - Energy costs and technologies
        - depth controls and preservation of high value urban, industrial supply
      - monitoring
      - enforcement
  - On-farm adaptation
    - On-farm storage
      - Hydrologic implications and limits
      - Capital costs
      - Regulatory costs
    - Improved soil water conservation
    - Crop selection and crop pattern
    - Change season dates for single and double cropping regimes
    - Improved husbandry
      - 'Precision Farming'
      - Better efficiency of use of factor inputs, such as fertiliser and pesticides: reduced use where possible
    - Organic farming (pros and cons)
    - Agroforestry systems
    - Integrated livestock and cropping systems
    - Managing and minimising salinity


Additional irrigation development in currently rainfed areas
Seasonal pattern of irrigation demand: main season, second or third season or all
Incremental season requires irrigation subject to resource availability and reliability
Supplemental
Crop value and crop selection
On farm storage
Capital costs
Regulatory costs
Groundwater
Capital costs
Energy/recurrent costs of extraction
Regulatory costs
Full irrigation
On farm storage
Capital costs
Regulatory costs
Groundwater
Capital costs
Energy/recurrent costs of extraction
Regulatory costs
Surface supply
Medium to long term storage required
Surface water
Dams
Sites available
Environmental considerations
Cost effectiveness
Capital costs
Extraction
Distribution
Benefits
Impact of climate change on yield and storage management
Groundwater
Capital costs
Extraction
Distribution
Energy/recurrent costs of extraction
Regulatory costs
Impact of climate change on GW recharge, storage patterns and access rules.
Shorter season needs supplemental irrigation
Crop value and crop selection
On farm storage
Capital costs
Regulatory costs
Groundwater
Capital costs
Energy/recurrent costs of extraction
Regulatory costs
Shorter seasons require full irrigation
Crop value and crop selection
On farm storage
Capital costs
Regulatory costs
Groundwater
Capital costs
Energy/recurrent costs of extraction
Regulatory costs
Surface supply
Medium to long term storage required
Surface water
Dams
Sites available
Environmental considerations
Cost effectiveness
Capital costs
Extraction
Distribution
Benefits
Impact of climate change on yield and storage management
Groundwater
Capital costs
Extraction
Distribution
Energy/recurrent costs of extraction
Regulatory costs
Impact of climate change on GW recharge, storage patterns and access rules.
Irrigation focus
Commodities and subsistence production (internal markets)
Food/nutritional security at site
Higher value; high nutrition for local rural and urban consumption
commercial and or export
Increased flooding despite lower rainfall
Flood control
Early flood prediction and warning
Land zoning
Flood agriculture systems
Out of season groundwater based irrigation
Agricultural drainage

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Climate change, water and food security

The impacts of climate change on the global hydrological cycle are expected to vary the patterns of demand and supply of water for agriculture – the dominant user of freshwater. The extent and productivity of both irrigated and rainfed agriculture can be expected to change. As a result, the livelihoods of rural communities and the food security of a predominantly urban population are at risk from water-related impacts linked primarily to climate variability. The rural poor, who are the most vulnerable, are likely to be disproportionately affected. Adaptation measures that build upon improved land and water management practices will be fundamental in boosting overall resilience to climate change. And this is not just to maintain food security: the continued integrity of land and water systems is essential for all economic uses of water.

This report summarizes current knowledge of the anticipated impacts of climate change on water availability for agriculture and examines the implications for local and national food security. It analyses expected impact of climate change on a set of major agricultural systems at risk and makes the case for immediate implementation of 'no-regrets' strategies which have both positive development outcomes and make agricultural systems resilient. It is hoped that policy makers and planners can use this report to frame their adaptation responses when considering both the water variable in agriculture and the competing demands from other users.

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