IWA-IDB INNOVATION CONFERENCE
ON SUSTAINABLE USE OF WATER:
Cities, Industry and Agriculture

Bayesian Belief Network model as a trade-off tool to estimate ecosystem services: case study of the Guayas River Basin, Ecuador

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GUAYAQUIL, ECUADOR
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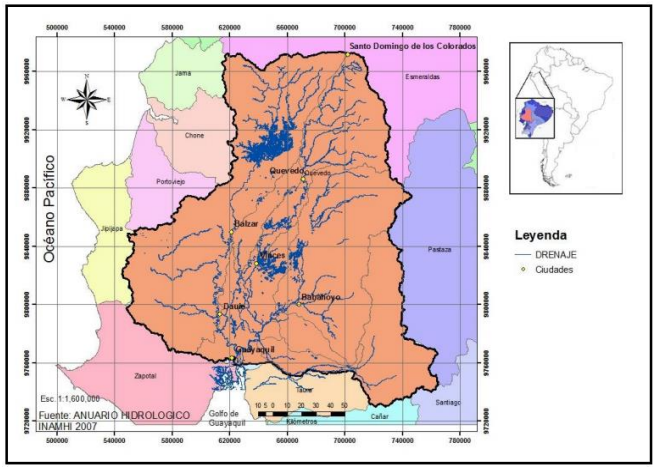
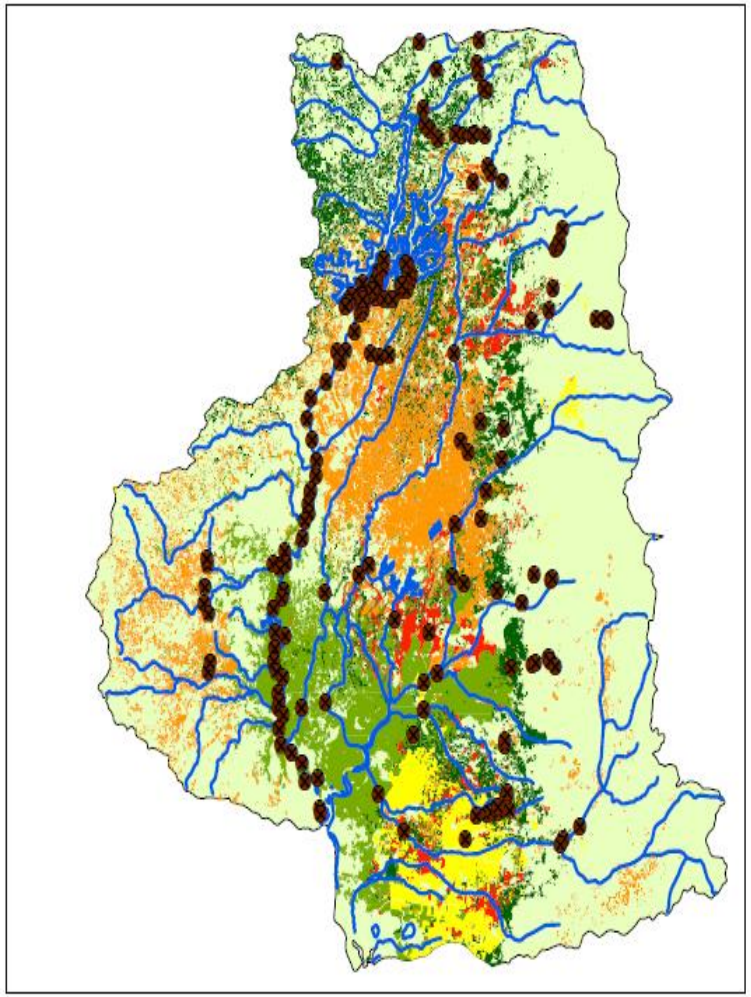
COORDINATED BY:

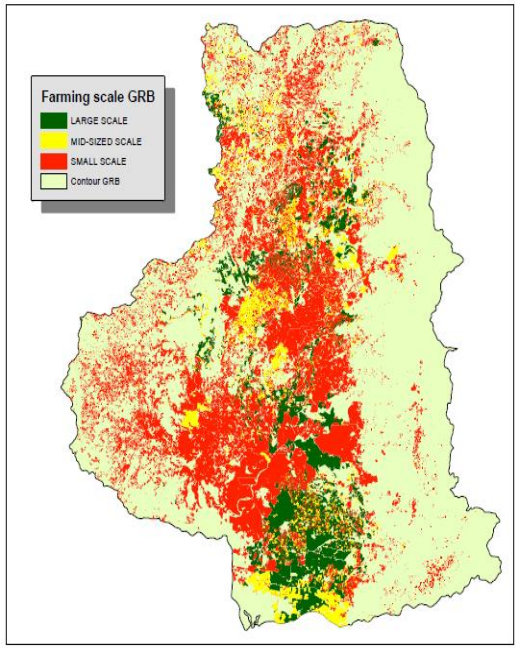
THE GUAYAS RIVER BASIN (GRB)

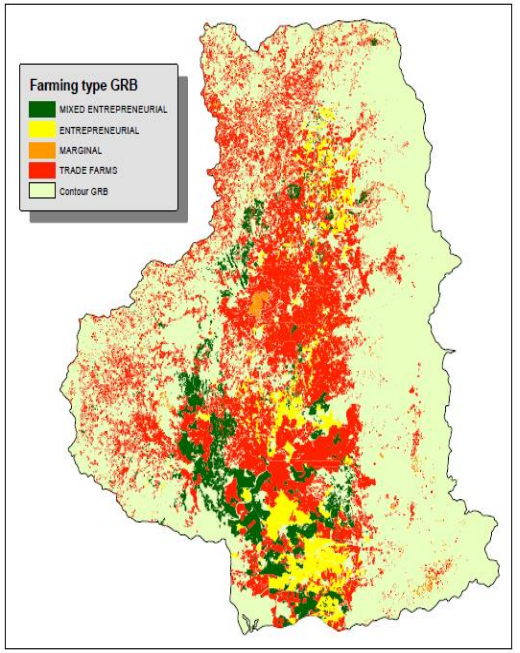




FARMING & AGRICULTURE

- The GRB is dominated by small scale farming (max. 10 Ha) approx. 63.83% LUC.
- Large scale farming (>50 Ha) covering 23.02% LUC.
- Production of rice and maize dominated by small scale farming.
- Cacao plantations mostly belong to small and mid-scale farms.
- Large scale farming is concentrated in the southern-central region of the GRB, where primarily sugar cane and banana are cultivated.



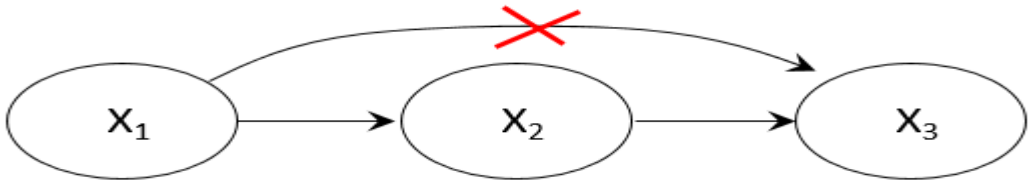


ECOSYSTEM SERVICES: WATER QUALITY

- Deknock et al. (2019):
  - Detected pesticide residues near cultivated areas.
  - Banana and rice industries (presumably large scale entrepreneurial farm-holders) are major pesticide sources.
  - Ammonium concentrations were associated with pesticide residues.
- Damanik-Ambarita et al., 2018; Damanik-Ambarita et al., (2016):
  - Water quality fluctuates throughout the GRB with good quality observed at (upstream) forested locations.
  - Moderate and bad water quality sites are closer to arable land and residential areas, respectively.

WHAT IS A BAYESIAN BELIEF NETWORK (BBN)?

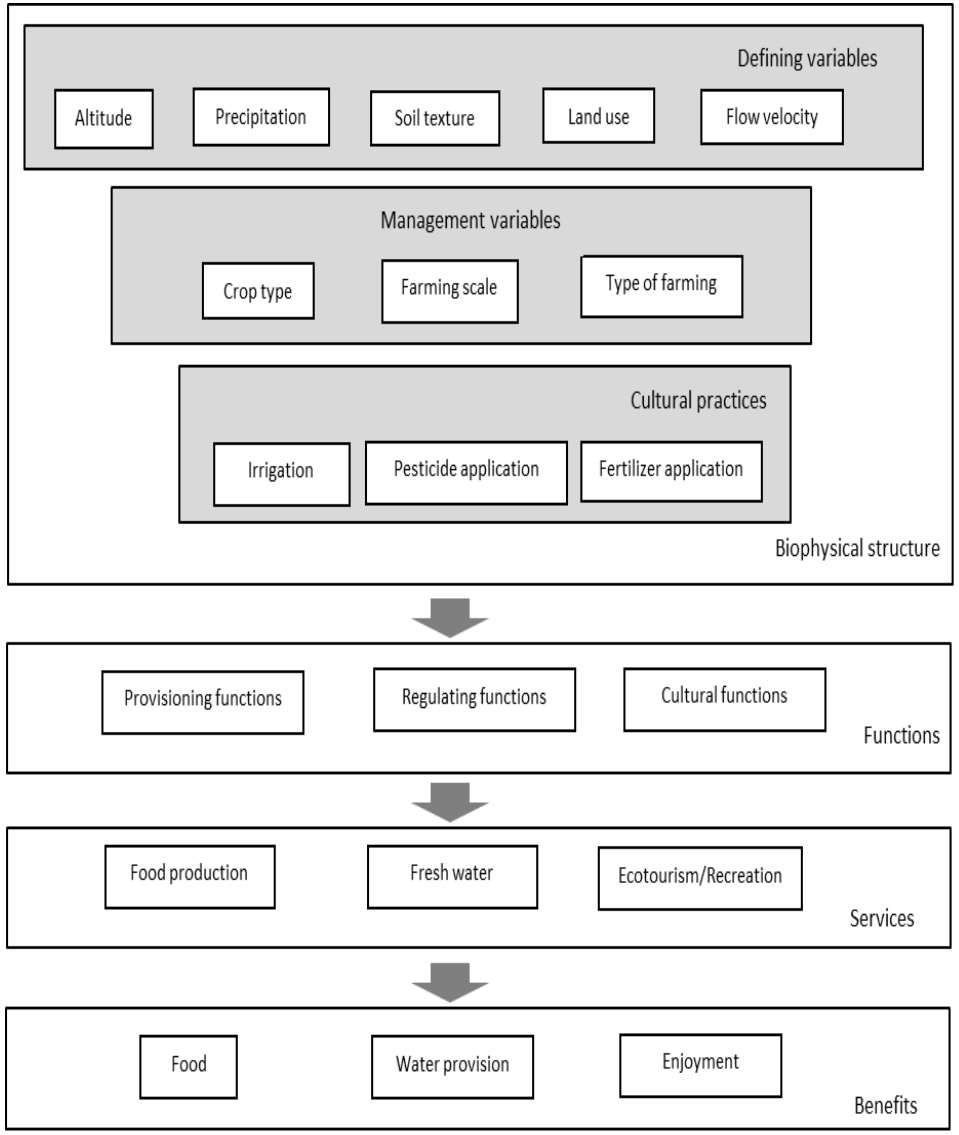
- A way to represent knowledge in an uncertain domain and a way to reason about this knowledge.
- Directed acyclic graph:
  - Nodes are variables (discrete or continuous) and represent measured or qualitative data.
  - Arcs indicate dependency.
  - Conditional Probabilities (local distributions).
- Missing arcs imply conditional independence.
- Independencies + local distributions => modular specification of a joint distribution



$$p(x_1)\ p(x_2 \mid x_1)\ p(x_3 \mid x_1, x_2) = p(x_1, x_2, x_3)$$

CONCEPTUAL FRAMEWORK

- The diagram presents a chain of ecosystem functions and processes that ultimately deliver a set of Ecosystem Services (ES).
- Conceptual simplification of ecosystem services production process.
- The model was kept as simple as possible, as the availability of data and information for the GRB case study are limited.
- The model was constructed in Netica (Norsys Software Corporation, 2017).



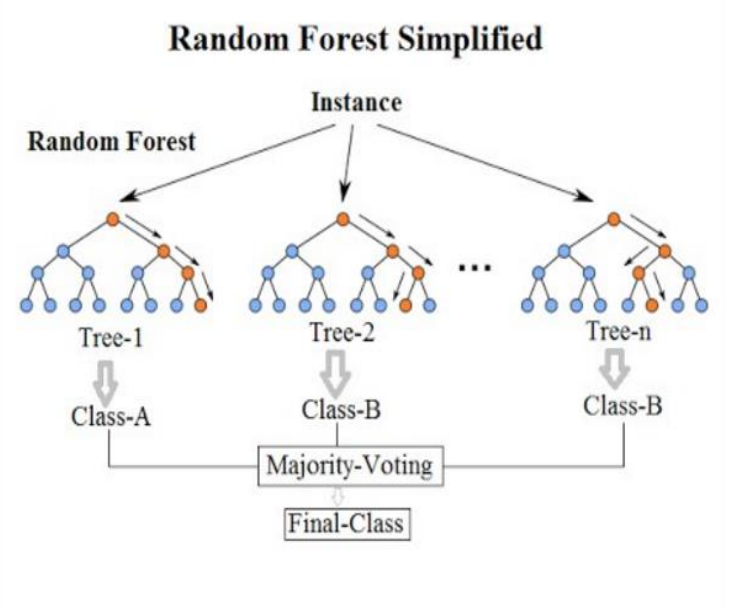
NETWORK DEVELOPMENT

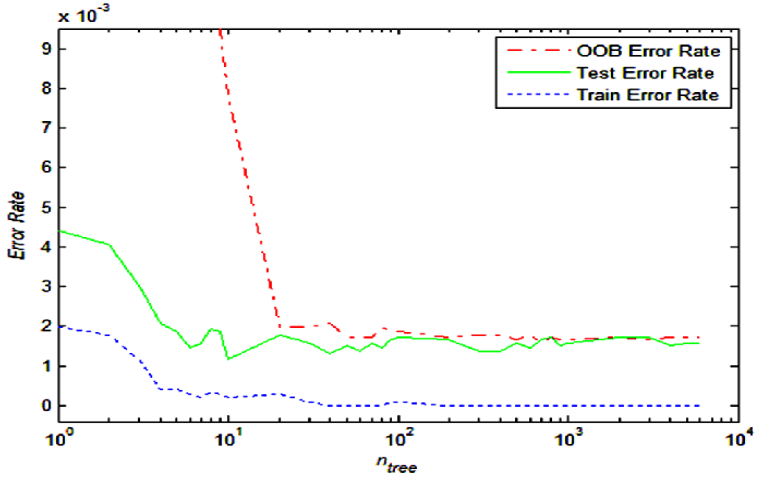
- 16 nodes were identified, and data were collected.
- The different source spatial layers were processed with ArcGIS 10.5:
  - Downscaled spatial resolution to 1:25000 if necessary.
  - Spatial vector/raster layers clipped to the GRB contour.
  - Spatial intersection with topcrops_grb polygon which corresponds to the LUC of the main five crops in the GRB.
- Next, additional processes were required for some data sources to produce the states for each node and the relevant CPTs according to model design.

Nodes	Source spatial layer name	Sources of data
Altitude	altitude_grb	Digital elevation map
Precipitation	annual_rainfall_grb	World Clim Global Database (Satellite raster map)
Soil texture	soiltexture_reclass_grb	Processed geodatabase
Land use	-	Raster map
Flow velocity	flow_chem_bio_quality	Sampling campaign
Crop type	topcrops_grb	Processed geodatabase
Scale of farming	topcrops_grb	Processed geodatabase
Type of farming	topcrops_grb	Processed geodatabase
Irrigation	topcrops_grb	Processed geodatabase
Fertilizer	trainresult_practices_grb	Predictive imputed map from various data sources
Pesticide	trainresult_practices_grb	Predictive imputed map from various data sources
Yield	trainresult_practices_grb	Predictive imputed map from various data sources
Chemical water quality	flow_chem_bio_quality	Expert knowledge validated by data obtained from sampling campaign
Biological water quality	flow_chem_bio_quality	Sampling campaign
Water provision	-	Expert knowledge
Ecotourism	-	Expert knowledge

NETWORK DEVELOPMENT

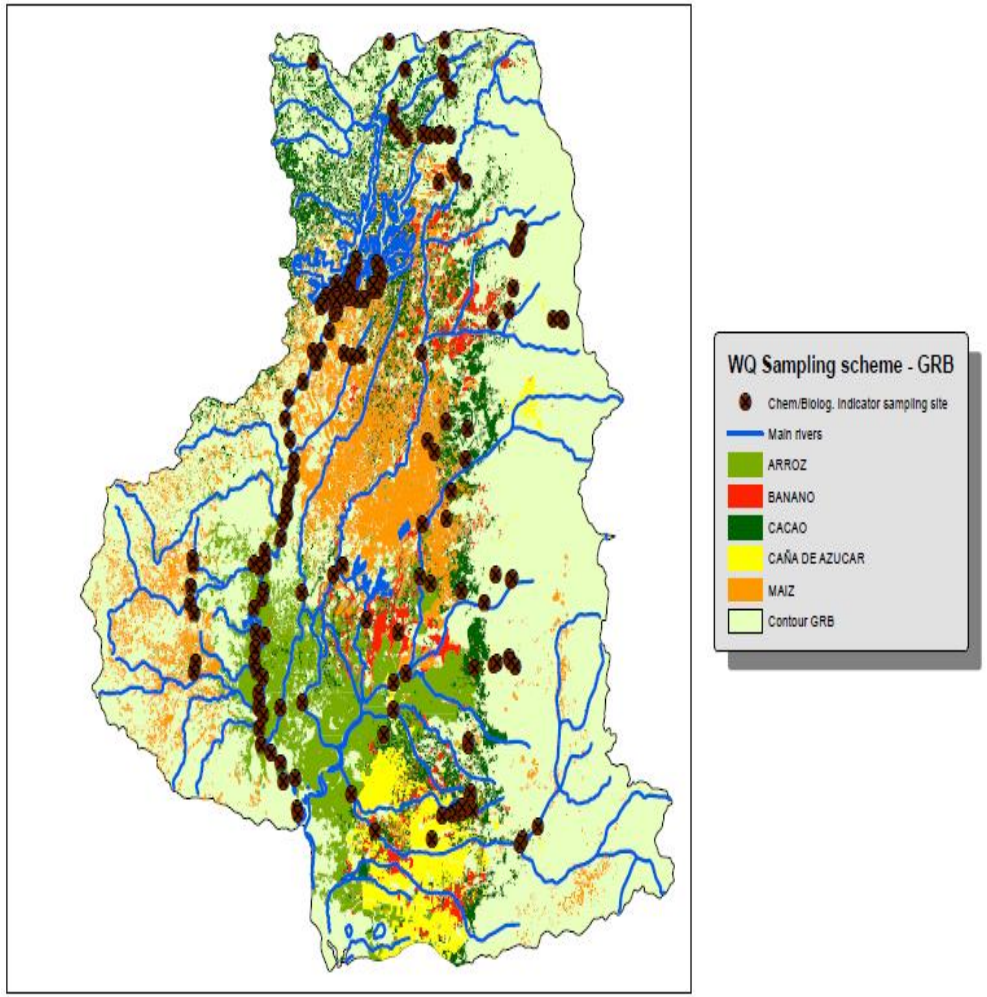
- Only available data on fertilizer, pesticide, irrigation and yield is the National Land Use Cover and Agricultural Production (NLUCAP) survey.
- Despite a lack of geo-references, it is still possible to use this survey to impute this data to the specific LUC layers, since it includes data about the farmhold and farmer socioeconomic status and agricultural/cultural practices (systematically matched with the typologies).
- Imputation process using Random Forest (RF) models
  - K-fold cross-validation (considering survey structure).
  - Model performance was generally very good **except for** the prediction for the intensive use of pesticide.
- The resulting layer contains LUC and farmer typology data for the five main crops, as well as the imputed predictions from the training process.





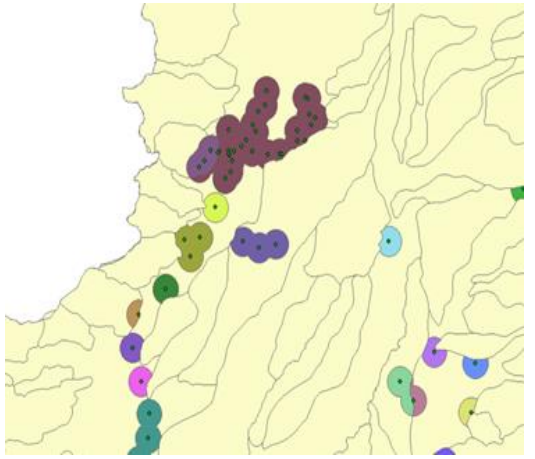
NETWORK DEVELOPMENT

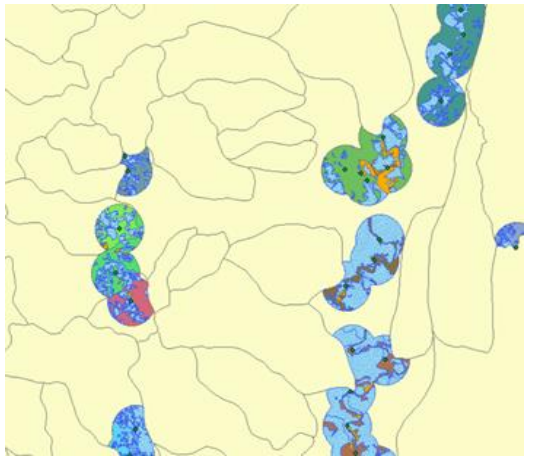
- Data on flow velocity, chemical and biological quality at 167 sampling sites (Deknock et al., 2019).
- Chemical water quality was derived from water parameters such as pH, biological oxygen demand, chemical oxygen demand, ammonium and nitrate concentrations, electrical conductivity and pesticide concentrations.
- Biological water quality derived from the Biological Monitoring Working Party-Colombia (BMWP/Col).
- Flow velocity and biological water quality nodes were populated based on the collected field data using Netica's expectation-maximization (EM) algorithm (Gupta and Chen, 2011).



NETWORK DEVELOPMENT

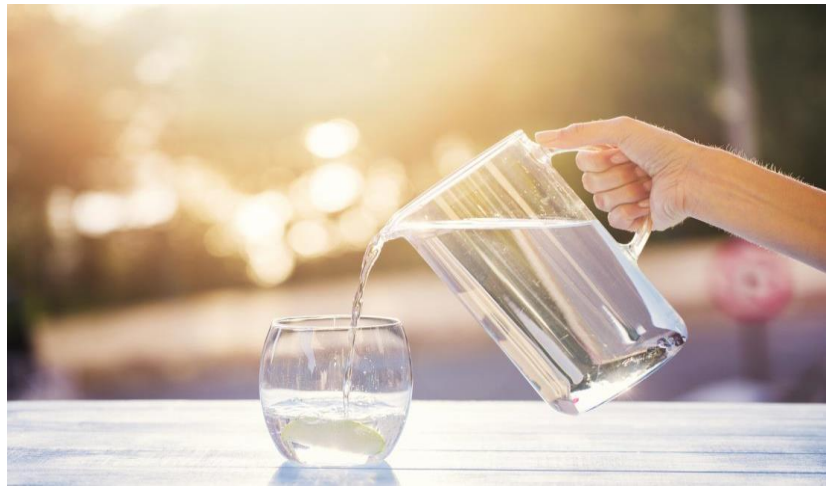
- For trade-off quantification via the CPTs for the effects of fertilizer and pesticide use and irrigation:
  - An influence area was defined by a circular buffer with 2.5 km radius.
  - Intersect result to define each influence area according to the hydrological flow (micro-basins of the GRB).
  - Intersection with *trainsresult_practices_grb* layer to obtain the LUC that exclusively belongs to each influence area.
  - The proportion of the total LUC area was calculated for each practice and use/non-use value.
  - The intersected spatial data were spatially joined to the *flow_chem_bio_quality* layer to match the prevalence of each practice use/non-use value.
  - CPTs were compiled from these imputed spatial datasets.



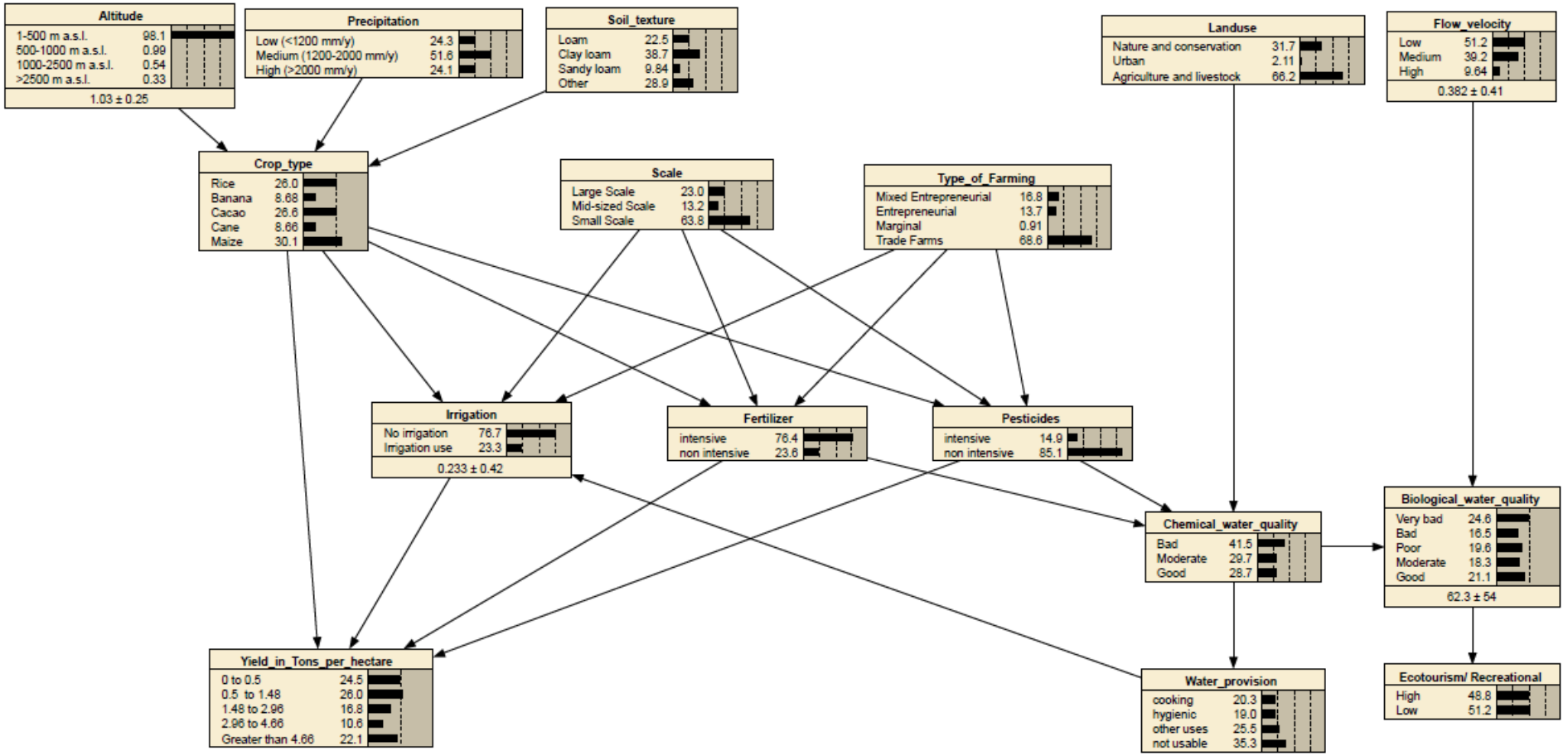


NETWORK DEVELOPMENT

- Water Provision and Ecotuourism nodes (and their CPTs) were populated using expert knowledge via a careful set of assumptions.
- E.g. for water provision:
  - Pristine waters can be used for cooking or drinking without/after minor water treatment (e.g. removal of pathogens, iron and suspended solids).
  - Slightly polluted water can be used for other uses (i.e. acceptable based on WHO water standard for irrigation) (e.g. irrigation, industrial water supply).
  - Polluted water is not usable unless severe water treatment is implemented (i.e. removal of pesticide residues and other persistent pollutants, removal of excessive nutrient and organic pollutants, etc.).



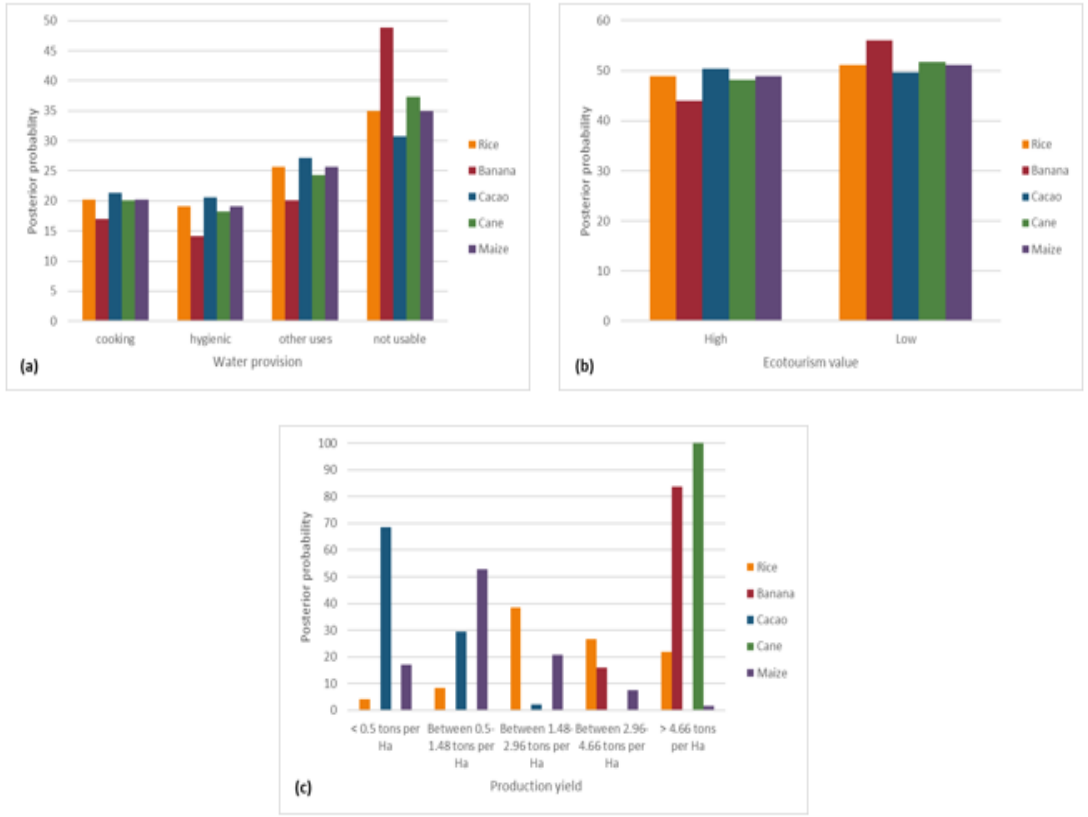
THE BBN


Altitude
1-500 m a.s.l. 98.1
500-1000 m a.s.l. 0.99
1000-2500 m a.s.l. 0.54
>2500 m a.s.l. 0.33
1.03 ± 0.25
Precipitation
Low (<1200 mm/y) 24.3
Medium (1200-2000 mm/y) 51.6
High (>2000 mm/y) 24.1
Soil_texture
Loam 22.5
Clay loam 38.7
Sandy loam 9.84
Other 28.9
Landuse
Nature and conservation 31.7
Urban 2.11
Agriculture and livestock 66.2
Flow_velocity
Low 51.2
Medium 39.2
High 9.64
0.382 ± 0.41
Crop_type
Rice 26.0
Banana 8.68
Cacao 26.6
Cane 8.66
Maize 30.1
Scale
Large Scale 23.0
Mid-sized Scale 13.2
Small Scale 63.8
Type_of_Farming
Mixed Entrepreneurial 16.8
Entrepreneurial 13.7
Marginal 0.91
Trade Farms 68.6
Irrigation
No irrigation 76.7
Irrigation use 23.3
0.233 ± 0.42
Fertilizer
intensive 76.4
non intensive 23.6
Pesticides
intensive 14.9
non intensive 85.1
Chemical_water_quality
Bad 41.5
Moderate 29.7
Good 28.7
Biological_water_quality
Very bad 24.6
Bad 16.5
Poor 19.6
Moderate 18.3
Good 21.1
62.3 ± 54
Yield_in_Tons_per_hectare
0 to 0.5 24.5
0.5 to 1.48 26.0
1.48 to 2.96 16.8
2.96 to 4.66 10.6
Greater than 4.66 22.1
Water_provision
cooking 20.3
hygienic 19.0
other uses 25.5
not usable 35.3
Ecotourism/ Recreational
High 48.8
Low 51.2

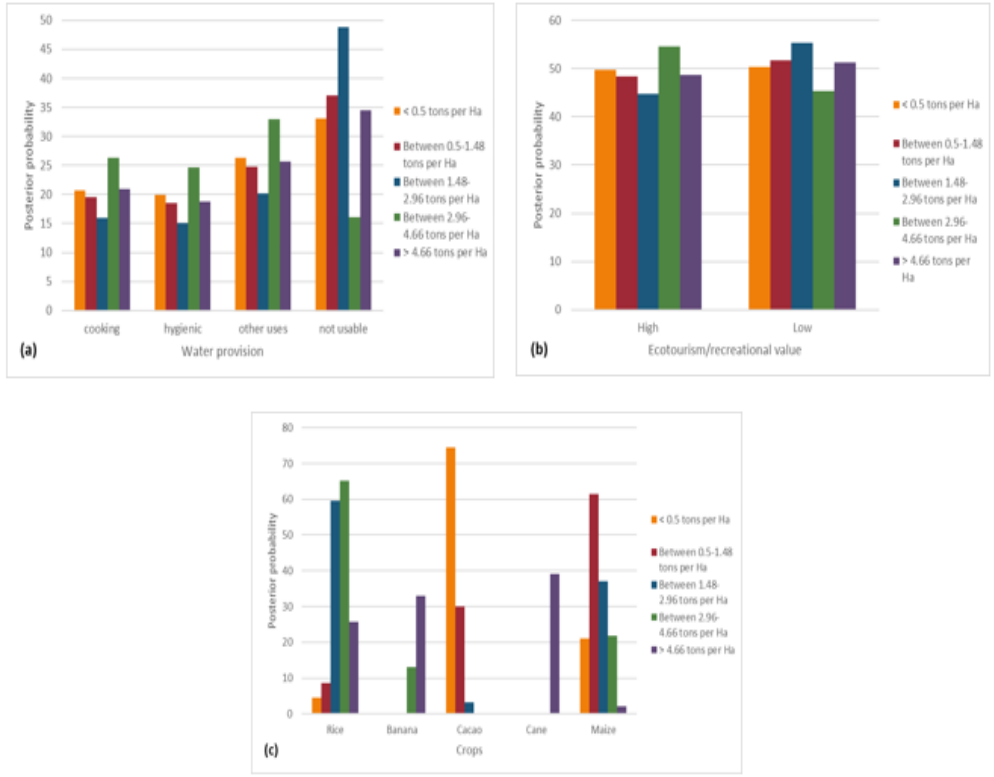
SCENARIOS FOR POLICY IMPLICATIONS

Scenarios	Description	Settings in the BBN model
Scenario 1	Intensification of the current agricultural situation	The 'Large scale' state's probability was to 100% in the *Scale* node. For the *Type_of_Farming* node, the probability of the states 'Mixed entrepreneurial' and 'Entrepreneurial' was set to 50%, while for the 'Marginal' and 'Trade farms' states, this value was set to 0%.
Scenario 2	Conversion of crop cover based on the official crop suitability map developed by a series of experts in the Ecuadorian Ministry of Agriculture[4]	In the *Crop_type* node, the probabilities for the states 'Rice', 'Banana', 'Cacao', 'Cane' and 'Maize' were set to 20.7%, 15.5%, 25.3%, 6.0% and 32.4%, respectively.
Scenario 3	Intensification of the agricultural situation in Scenario 2	Same settings as Scenario 2. The 'Large scale' state's probability was set to 100% in the *Scale* node. For the *Type_of_Farming* node, both 'Mixed entrepreneurial' and 'Entrepreneurial'" states were set to 50% probability, while the rest was set to 0%.

BAU SCENARIO: RESULTS

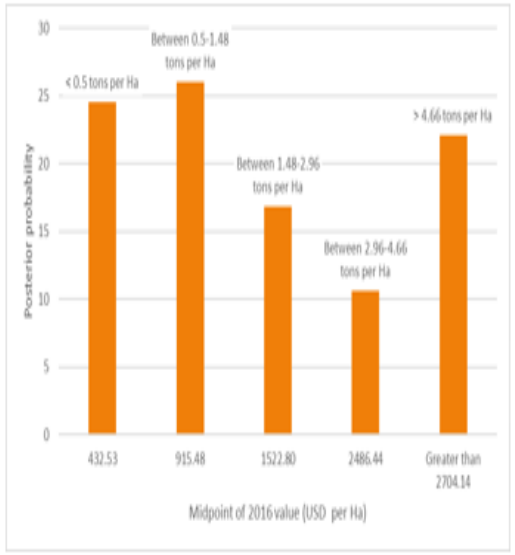


Predicted posterior probability of the water provision (a), ecotourism/recreational (b) and yield (tons per hectare) (c) nodes when the probability of each crop in the *Crop_type* node is set to 100%.

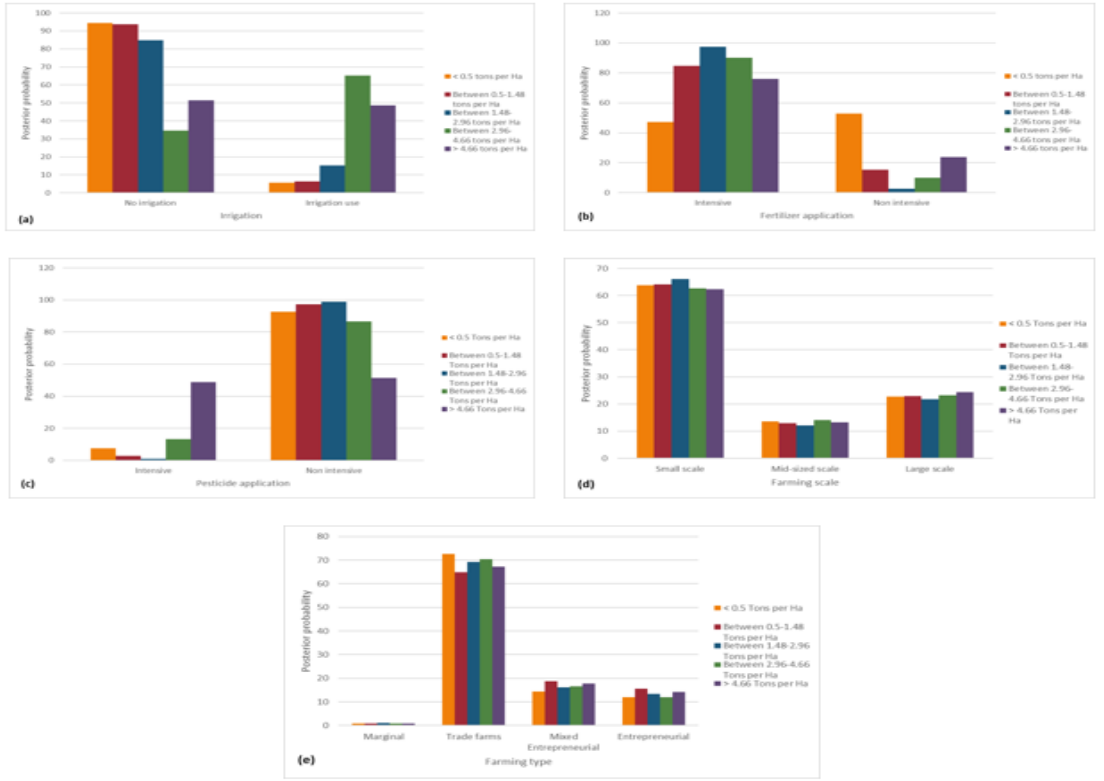


Probability distributions of the water provision (a), ecotourism/recreational (b), and land use cover (crop type) (c) nodes when the probability of each state in the production yield is set to 100%.

BAU SCENARIO: RESULTS

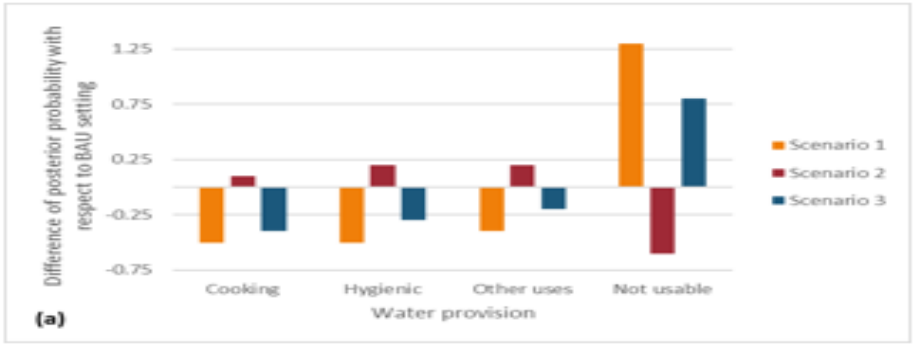


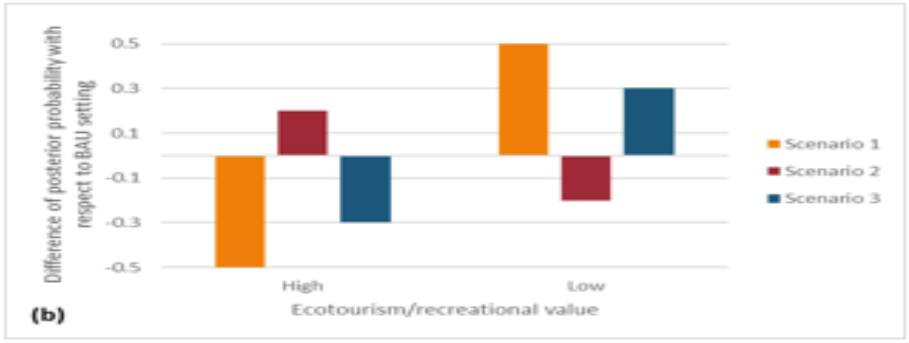
Probability distribution of the economic value per Ha (in 2016 USD) across different yield targets in the Guayas River Basin.

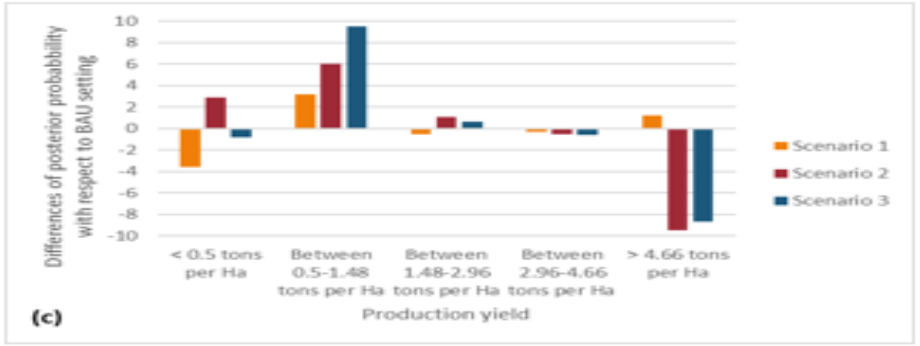


Probability distributions of the water provision for irrigation (a), fertilizer application (b) and for pesticides application (c), farming scale (d), farming type (e) nodes when the probability of each state in the production yield is set to 100%.

RESULTS: OTHER SCENARIOS







Difference of predicted posterior probability of the nodes yield (tons per hectare) (a) water provision (b) and ecotourism (c) between the current situation (BAU) and the following scenarios were applied: Scenario 1 (large scaling/changing type of farming in BAU situation), Scenario 2 (crop suitability map generated by local experts), Scenario 3 (large scaling/scoping of agricultural situation crop suitability map).

CONCLUSIONS & REMARKS

- The BBN was able to portray implications of different model settings on crop productivity (yield), water provisioning and eco-tourism/recreation, providing a trade-off analysis and insights among the three services at a large spatial scale (i.e. the whole Guayas River basin).

- Model outcome suggests that both banana and cane generated the highest yields but contributed to low ecotourism value and generated a higher percentage of unusable water.

- Cacao produced the lowest yield but generated better water quality. However, the higher price of cacao (when compared to the rest of the crops), clearly offsets the notion that higher yields are economically favorable under the current situation.

CONCLUSIONS & REMARKS

- Crops with higher yields such as sugar cane and banana create more damage to the aquatic ecosystems.

- Intensifying agriculture (i.e. scaling up and entrepreneurial agriculture) slightly improves yield and it is slightly disadvantageous for both water usability and ecotourism.

- Agricultural intensification has limited potential and is not the best management alternative for the basin given the apparent limited capability of the GRB agro-ecosystem to respond to changes in farming scale and type.

CONCLUSIONS & REMARKS

- Model analysis suggests crop types and cultural practices (i.e. irrigation, fertilizer and pesticide application) and not farming scale and type are main drivers for economic returns.

- Environmental gains are also possible by optimizing the environmental disposition of the LUC in the basin by means of adequate consideration of soil and climate conditions that suit the edaphoclimatic requirements of crops.

- Combining both strategies of LUC optimization and up-scaling and intensifying farming activities can allow the system to reach some of these gains in water provision and ecotourism/recreation, while mitigating some productivity losses.

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