European Commission

A new R-SWAT Decision Making Framework for Efficient Allocation of Best Management Practices

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Allocating Best Management Practices

- Implementation of conservation programs is crucial for ***restoring and protecting the good ecological status of freshwater bodies***.

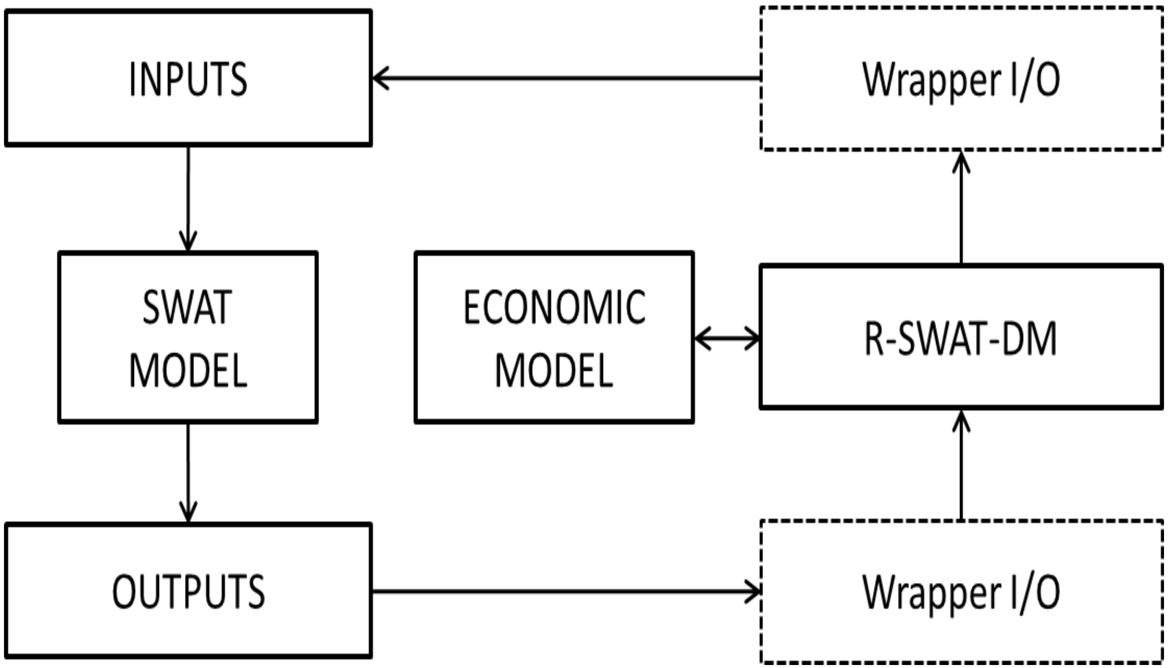
- The success of conservation programs depends to a great extent on the ***optimal allocation of management solutions (Best Management Practices – BMPs)*** with respect to envisaged environmental and economic objectives.

- BMPs allocation (“What BMP” & “Where”) is a ***complex task***, because BMPs costs and efficiencies can change ***depending on their location*** within a basin and in relation to the program objectives.

- The ***SWAT model*** was used to assess diffuse and point source pollution under current conditions (baseline) and for BMPs (fertilization, irrigation, and upgrading of Waste Water Treatment Plants – WWTP) scenarios

The R-SWAT-DM framework

- developed in R:
  - Open-source programming language
  - Built-in state-of-the-art mathematical & statistical algorithms
  - Libraries for data manipulation & visualization



- Builds on existing libraries for R to modify the SWAT input files or read output files [Zambrano and Rojas, 2013]

R Packages integrated in R-SWAT-DM

- **Input and Output communication with SWAT through ASCII files:**
  - ***SWAT2R package*** (Zambrano-Bigiarini, http://www.rforge.net/SWAT2R/)
  - ***hydroPSO (***Zambrano-Bigiarini, Rojas, http://cran.r-project.org/web/packages/hydroPSO

- **Optimization:**
  - ***Mco (***Mersmann, Trautmann, Steuer, Bischl, Deb, http://git.p-value.net/p/mco.git)
  - ***nsga2R (***Ching-Shih Tsou, 2013)

- **Visualization and Mapping:**
  - ***Ggplot2 (***Wickham, https://github.com/hadley/ggplot2)
  - ***Rgdal (*** Bivand, Keitt, Rowlingson, Pebesma, Sumner, Hijmans , Rouault***,*** https://r-forge.r-project.org/projects/rgdal/
  - ***Maptools (*** Bivand et al., http://r-forge.r-project.org/projects/maptools/)
  - ***Rgeos (***Bivand et al , https://r-forge.r-project.org/projects/rgeos/ http://trac.osgeo.org/geos/
  - ***gridExtra (***Auguie, http://code.google.com/p/gridextra/)

- ***……… and many more common libraries***

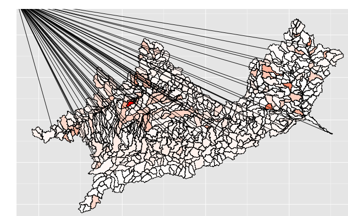
R-SWAT-DM Framework structure

Execution types:

- Individual Simulations
- Iterative Simulations
- Multi Criteria Optimization

Best Management Practices:

- Point Sources
- Fertilization
- Irrigation
- Combined: Fert. & PS. & Irr.



Base Line Scenario

.mgt files

```
Operation Schedule:
          0.150  1   12          1800.00000   0.00     0.00000 0.00   0.00  0.00
          0.160  3    4          1732.00000   0.00
          0.161  3   46          1735.00000   0.00
          0.162  3    1          1736.00000   0.00
          0.170 10    2   5        25.00000   0.70    50.00000 0.00
```

.dat files

```
2/18/2015 12:00:00 AM .dat file Constant Record Subbasin  11 in ArcSWAT 2012.10_1.14 interface

          FLOCNST          SEDCNST         ORGNCNST         ORGPCNST          NO3CNST          NH3CNST          N
 6.7500000000E+02 3.6000000000E+01 9.3280000000E-01 1.6324000000E-01 3.3712060000E+01 8.4280200000E+00 3.37120000
```

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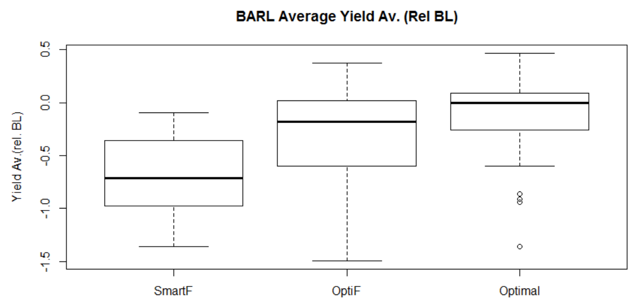
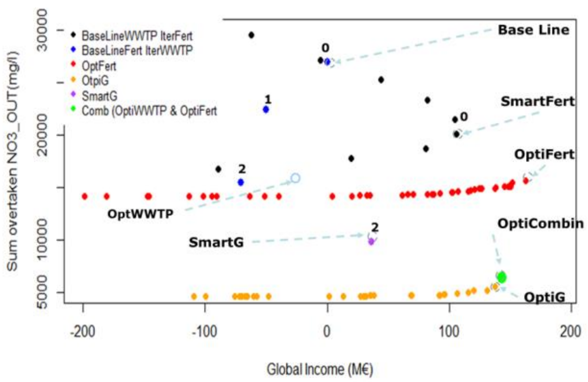
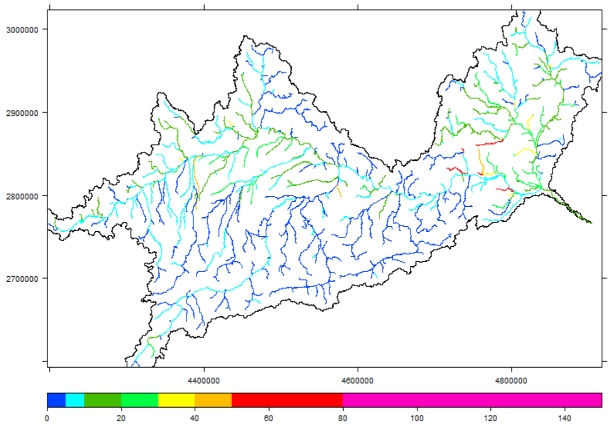
R-SWAT-DM Framework output analysis

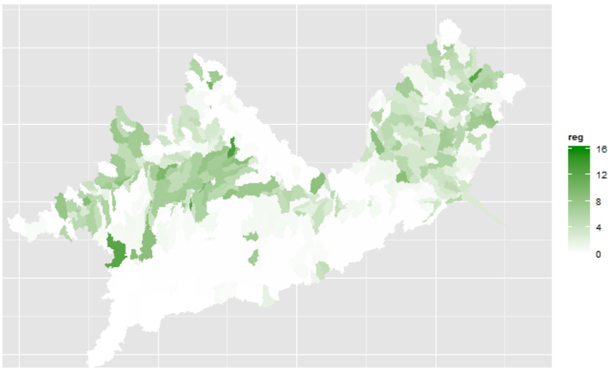
Scenario Analysis and comparisons:

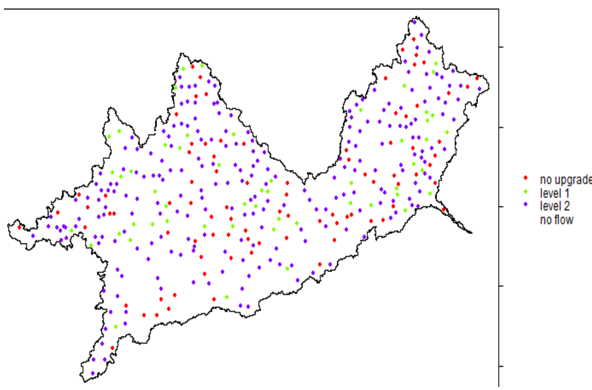




Scenario Visualization & Mapping:







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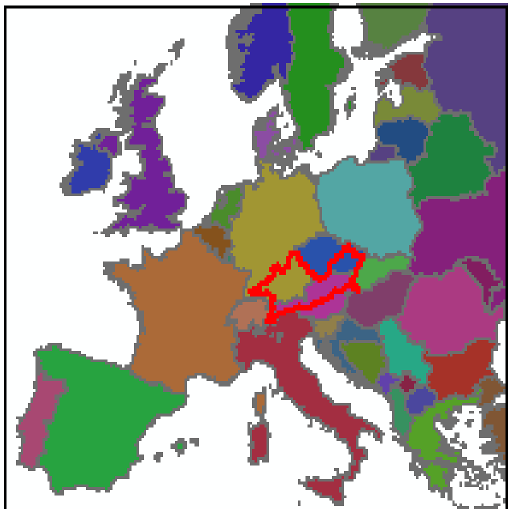
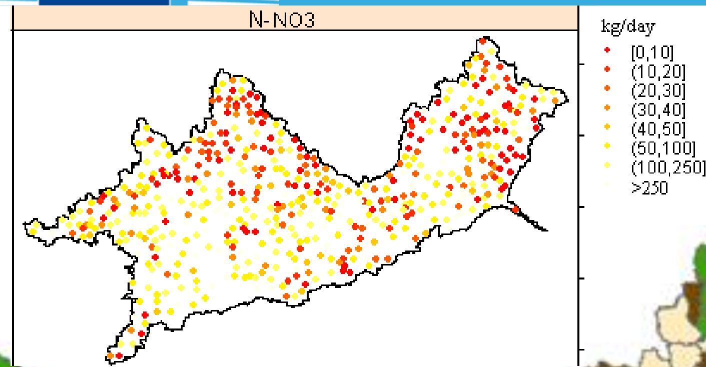
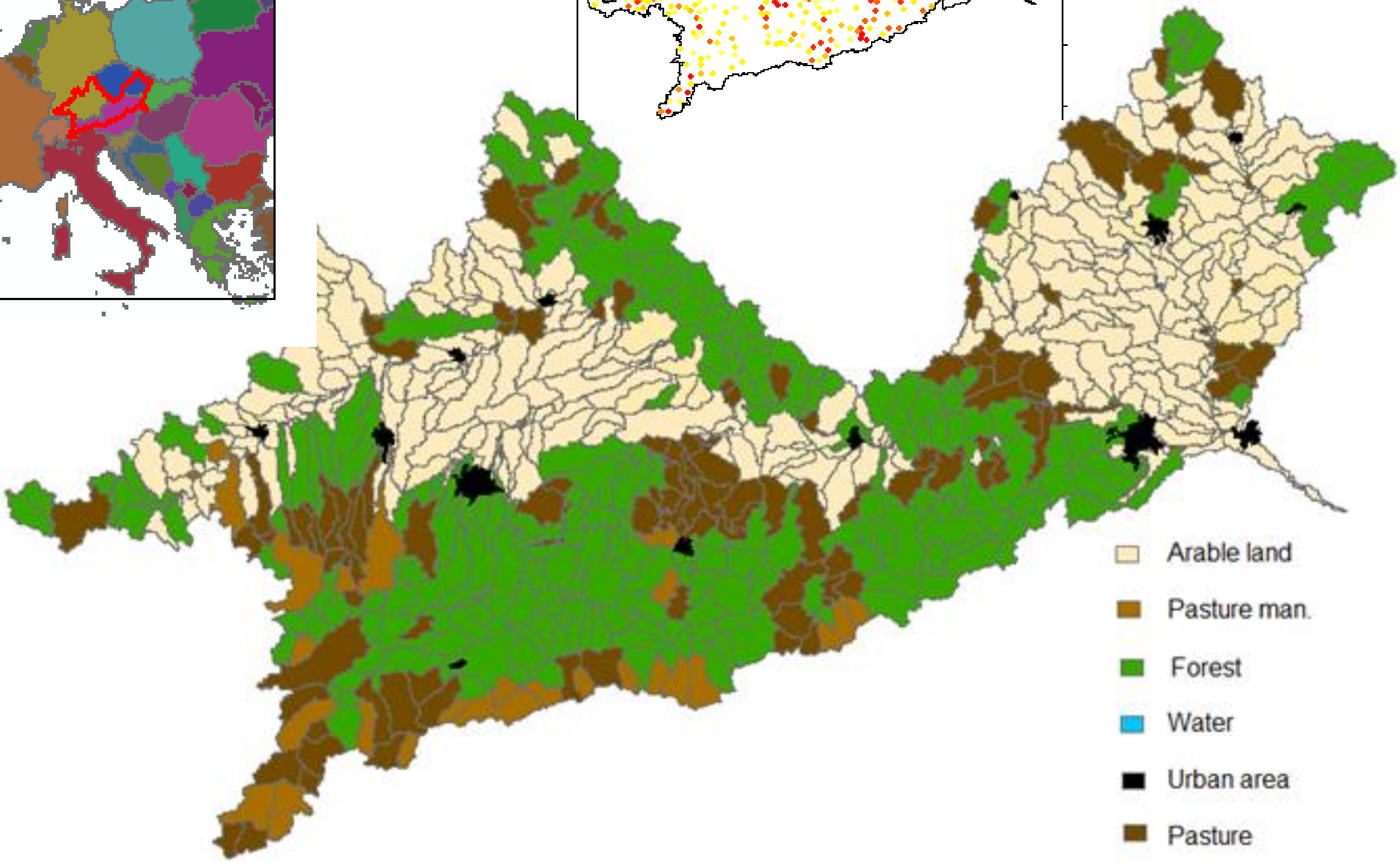
Case Study (Upper Danube)







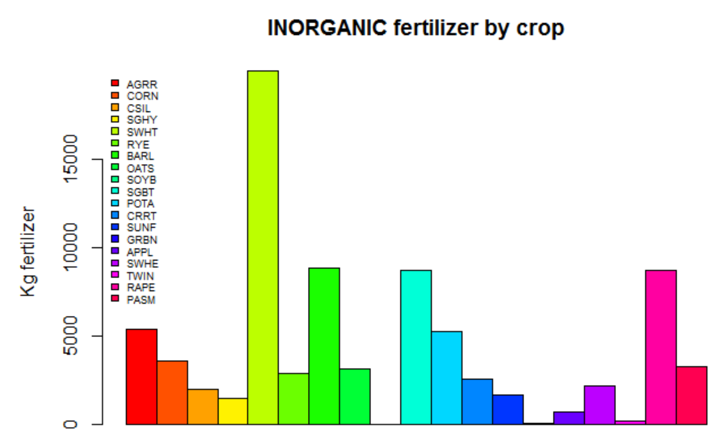
Diffuse Sources of Pollution

Mineral Fertilization (HRU level)

CrName	Id	num hru	hru tot fe	area(km2)	% area tot fert	Fertil
AGRR	2	31	10.7	8883.82	17.3	yes
APPL	93	6	2.1	61.55	0.1	yes
BARL	31	27	9.3	6747.98	13.2	yes
BERM	40	75		922.8		
CORN	19	21	7.2	3905.65	7.6	yes
CRRT	72	7	2.4	449.75	0.9	yes
CSIL	20	18	6.2	3968.8	7.7	yes
FRST	6	285		50300.64		no
GRBN	84	6	2.1	584.27	1.1	yes
OATS	32	11	3.8	845.16	1.6	yes
OTHR	119	41		5355.13		no
PASM	124	27	9.3	6715.04	13.1	yes
PAST	12	129		23678.98		no
POTA	70	11	3.8	1008.1	2.0	yes
RAPE	123	20	6.9	1839.45	3.6	yes
RYE	30	11	3.8	835.15	1.6	yes
SGBT	69	13	4.5	982.12	1.9	yes
SGHY	24	18	6.2	3058.22	6.0	yes
SOYB	56	1	0.3	43.46	0.1	yes
SUNF	74	6	2.1	398.12	0.8	yes
SWHE	120	11	3.8	1134.68	2.2	yes
SWHT	27	42	14.4	9533.18	18.6	yes
TWIN	121	4	1.4	229.51	0.4	yes
WATR	18	1		6.51		

# HRUs:	822
Forest HRUs:	285
Arable land HRUs:	537
Fertilized HRUs:	**291**

# crops:	**23**
# fertilized crop:	**19**



Agriculture Income Related to Fertilization

Economic Model:

$$g_1^{mp} = \sum_{i=1}^{HRU} \sum_{j=1}^{crop} \left(Y_{ij}^{mp} * A_{ij} * Up_j - Fc_{ij}^{mp} * Qf_{ij}^{mp} - Qw_{ij}^{mp} * Wc - Oc_j \right)$$

g_1^{mp} : *agricultural total gross margin for the mp management practice;*
Y_{ij}^{mp} : *yield of crop j in HRU i under a mp practice;*
Aij : area (ha) of crop j in HRU i.
Upj : unit price (income €/tm) of crop j. See Table 2.
Qf_{ij}^{mp} : *quantity of fertilizer applied (kg/ha) to crop j in HRU i under a mp management practice.*
Fc_{ij}^{mp} : *unit cost of fertilizer (€/kg) of crop j in HRU i under a mp management practice.*
Wc : the water irrigation unit cost (€/mm). This doesn't change across HRUs
Qw_{ij}^{mp} : irrigation quantity (mm/ha) for crop *j* in HRU *i* under a *mp* agricultural practice
Oc_j : operational management cost for the crop *j*.

Point Sources of Pollution

Upgrading the existing Waste Water Treatment Plants (WWTP)

PS (WWTP)	**533**

Two upgrading levels:

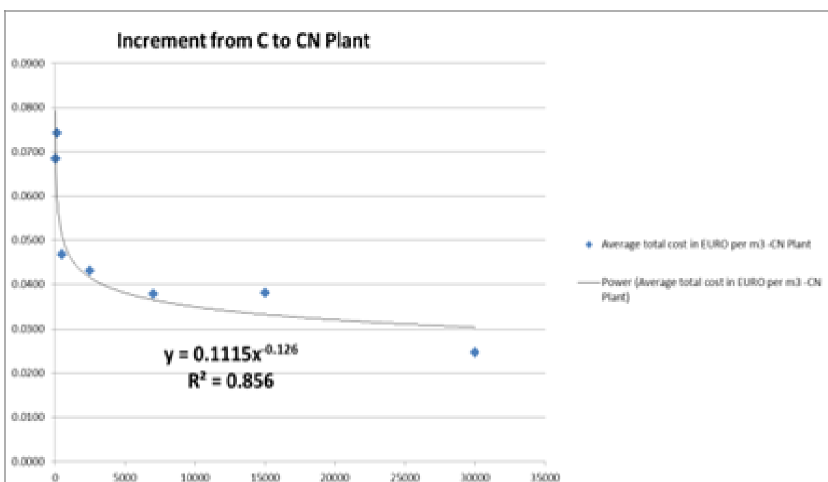
WWTP upgrade	**COST coef1**	**COST coef2**	**NO3 (%)**	**NH3 (%)**	**PO3 (%)**
C = Current (secondary)	0	0	0	0	0
CN = tertiary	0.1115	-0.126	20	20	0
CND = Tertiary + denitrification	0.1464	-0.119	55	55	5

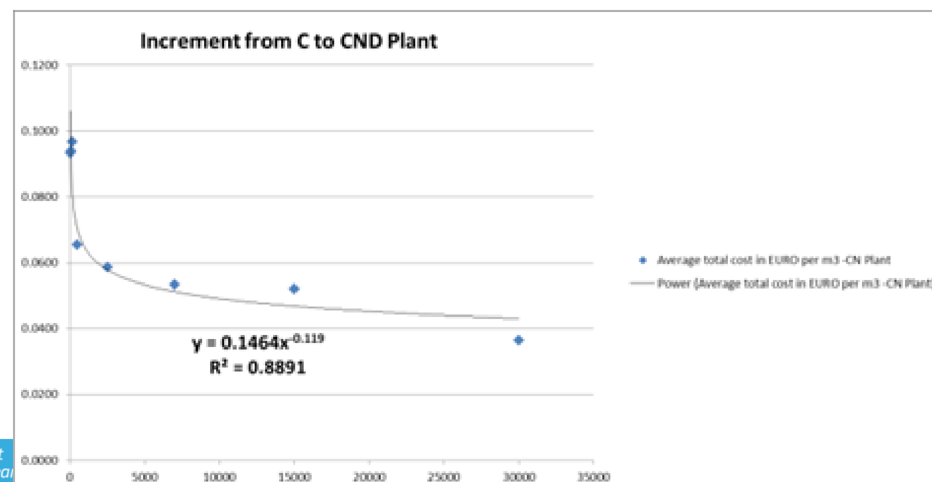
Cost coefficients and nutrients reduction for each type of WWTP upgrading

Cost of WWTP Upgrading

$$g_2^{mp} = \sum_{k=1}^{WWTP} \left(365 * Q_k * Coef_1[Y_k] * Q_k^{Coef_2[Y_k]}\right)$$

g_2^{mp} : WWTP upgrading anual cost for the mp water restoration management practices.
Qk : flow average (m3/day) in PS k.
Yk : type of upgrade of the k WWTP. 0: no upgrade ; 1: upgrade from C to CN; upgrade from C to CND
Coef1 [Yk]: coefficient 1 in table 2 for the Yk WWTP type of upgrade.





Environmental assessment and objective

SWAT outputs: .rch & .hru files provide temporal and spatial NO3, PO3, NH4 loads of each management scenario

Aggregation metrics (environmental objective):

$$\left[\frac{1}{ns}\left(\sum_{i=1}^{ns}\frac{1}{nt}\left(\sum_{j=1}^{nt}Q_{ij}\right)\right)\right]$$

p: represents pollutant load average
nt: number of simulation periods.
ns: number of stretches considered in the catchment model
Q_{ij}: the concentration (mg/l) of the considered pollutant in the stretch "*i*" and the simulation period "*j*"

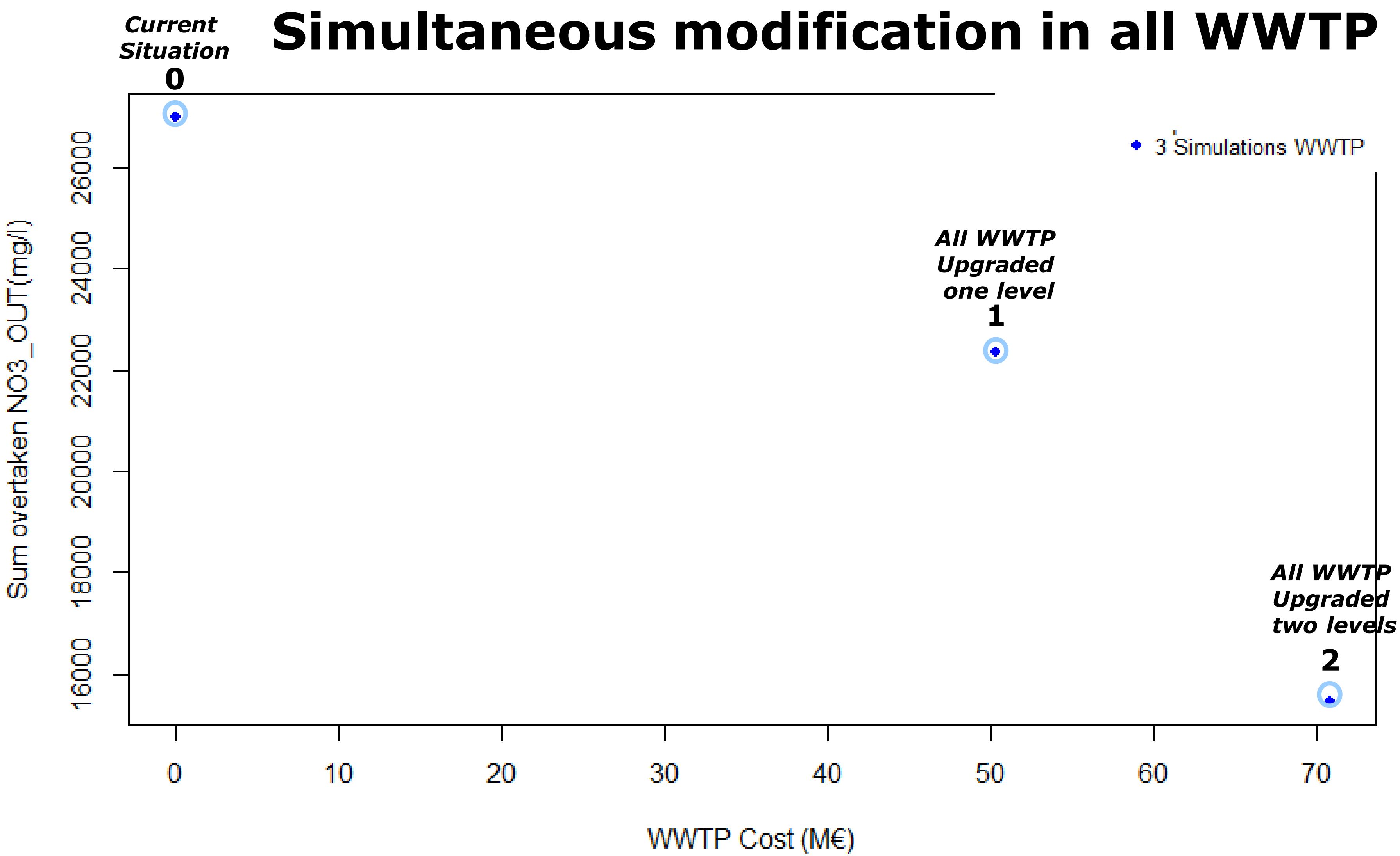
$$\sum_{i=1}^{ns}\sum_{j=1}^{nt}(Q_{ij}-Th) \ \ \forall\, i,j \mid Q_{ij} > Th$$

Th: represents the threshold considered acceptable (for example the water framework directive limit for the considered contaminant should be a logical value for the Danube case study).
In this case there should be divided by the number of sections and periods, since they are not a constant number

$$\frac{1}{nt}\sum_{j=1}^{nt}TL_j$$

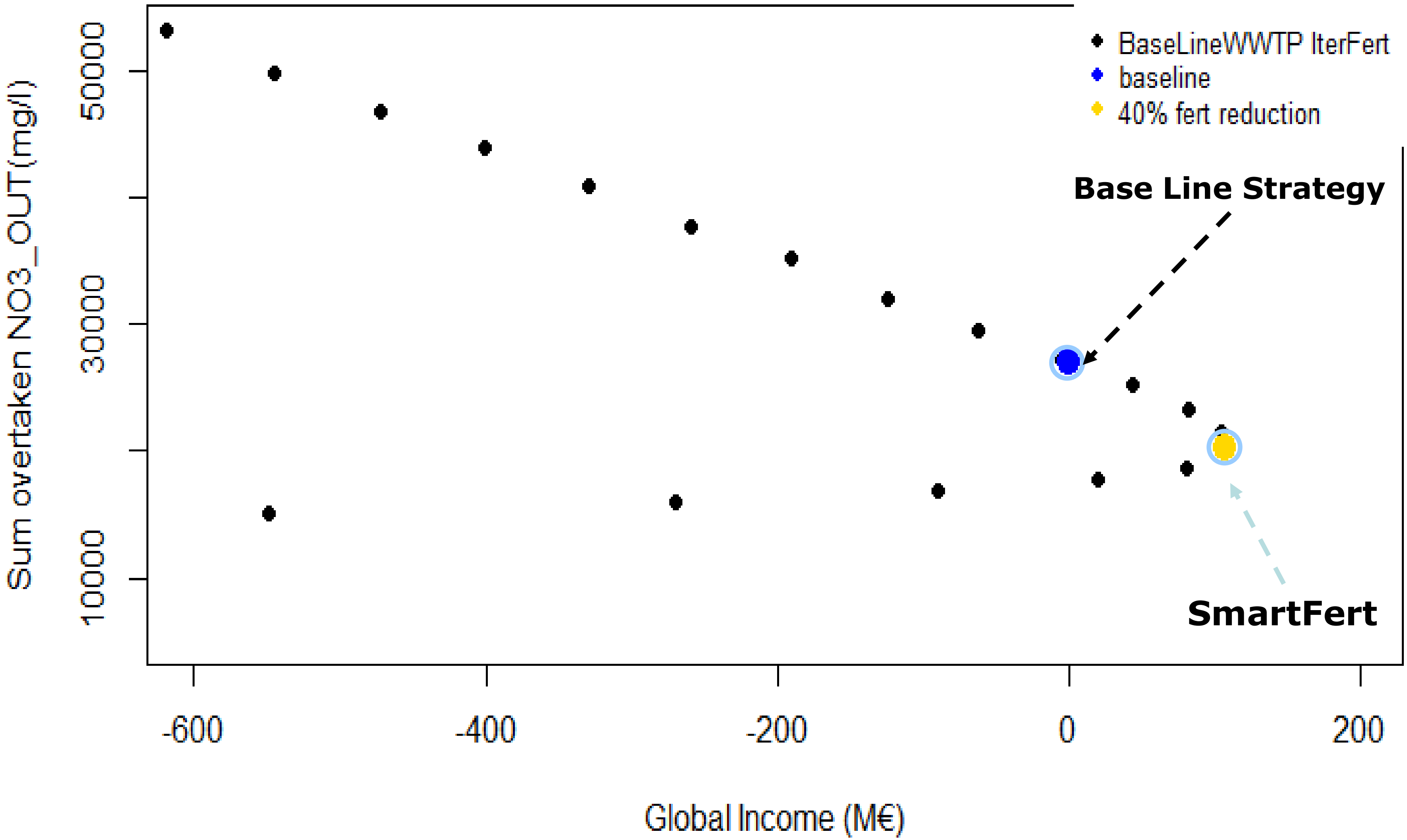
TL_j: the load (mg/l) of the considered pollutant in the catchment terminal stretch in the simulation period "*j*"

WWTP (Iterative Simulation)

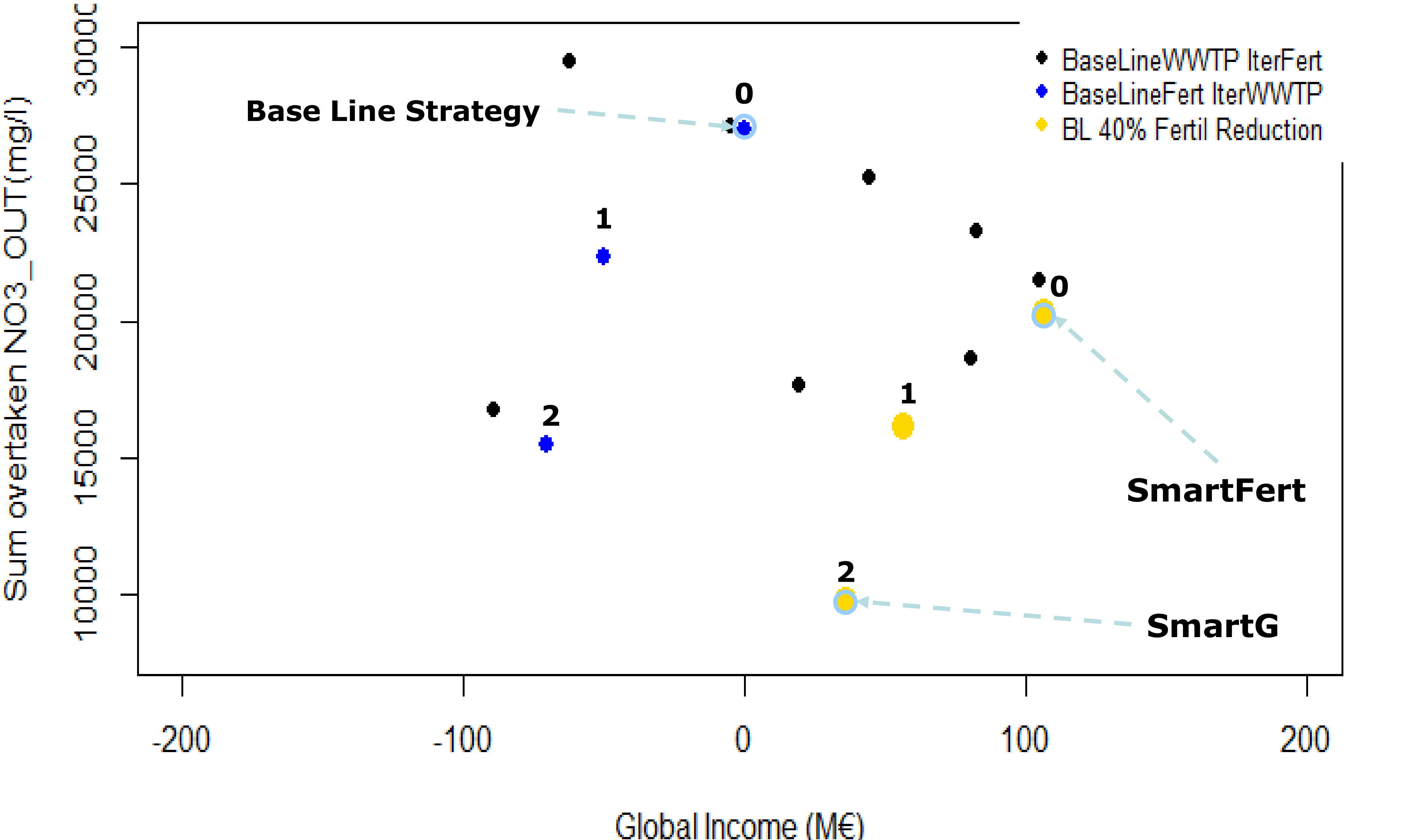


Fertilization (Iterative simulation)

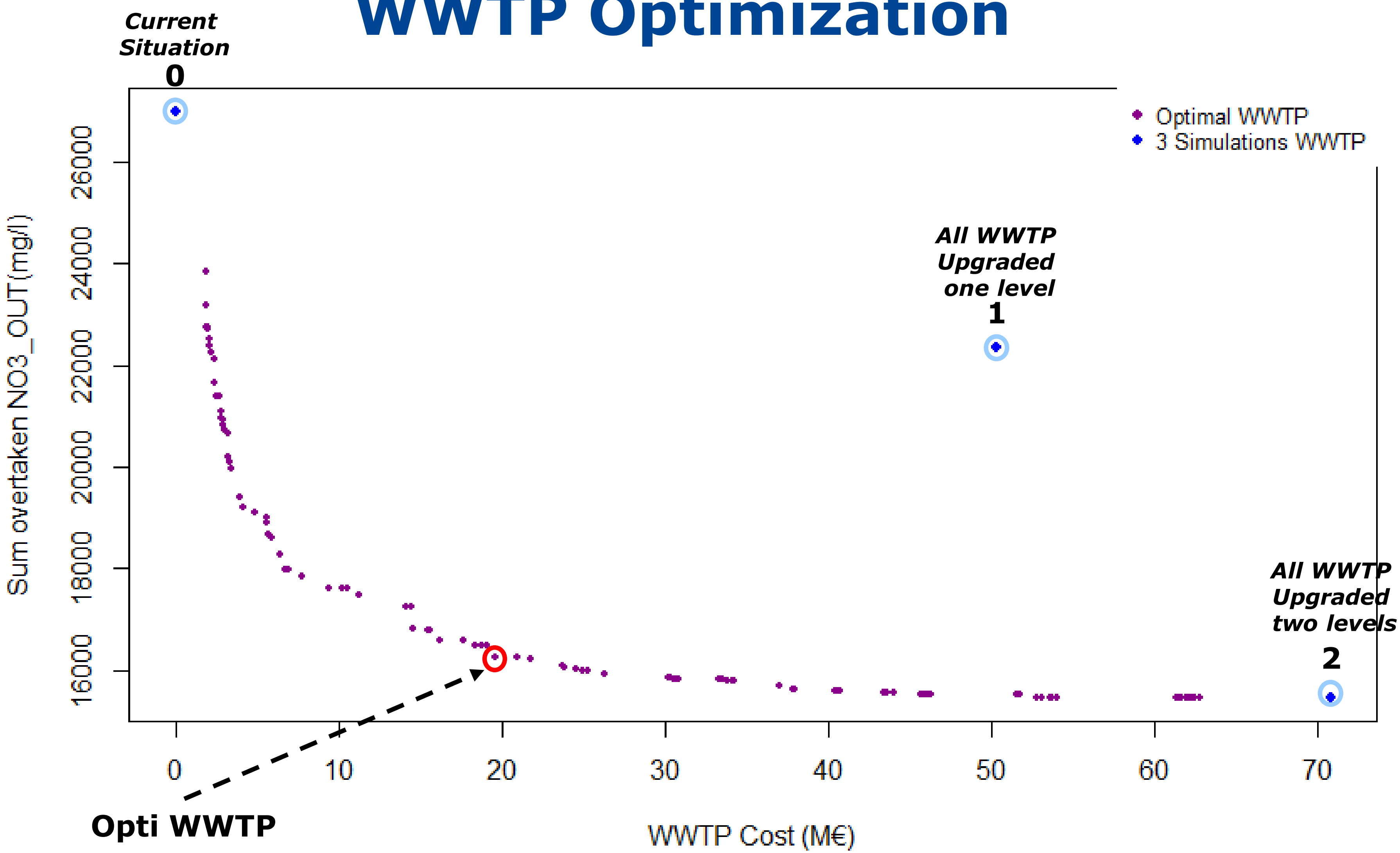
Simultaneous modification in all HRU



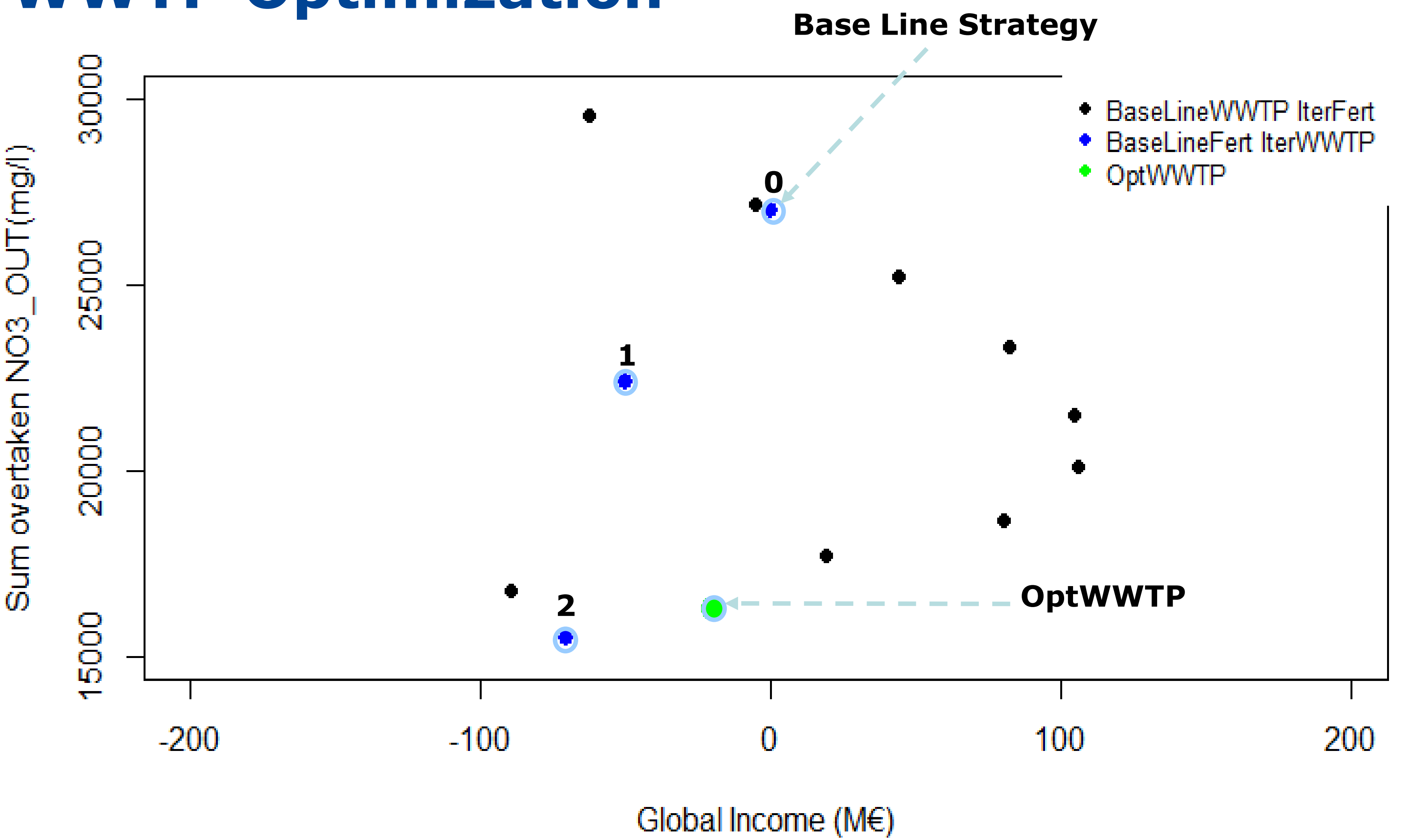
Combination (PS + NPS) (Iterative Simulation)



WWTP Optimization



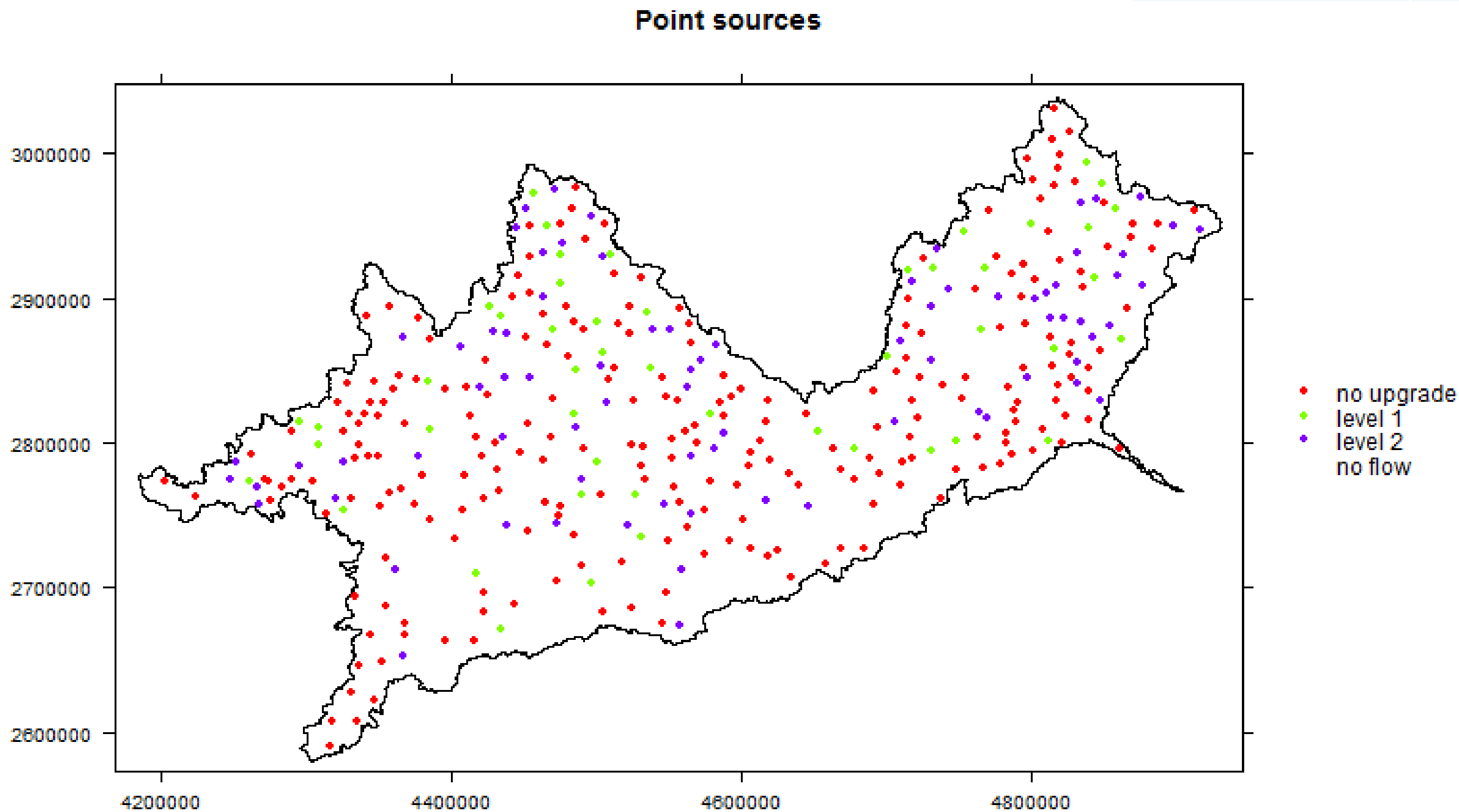
WWTP Optimization



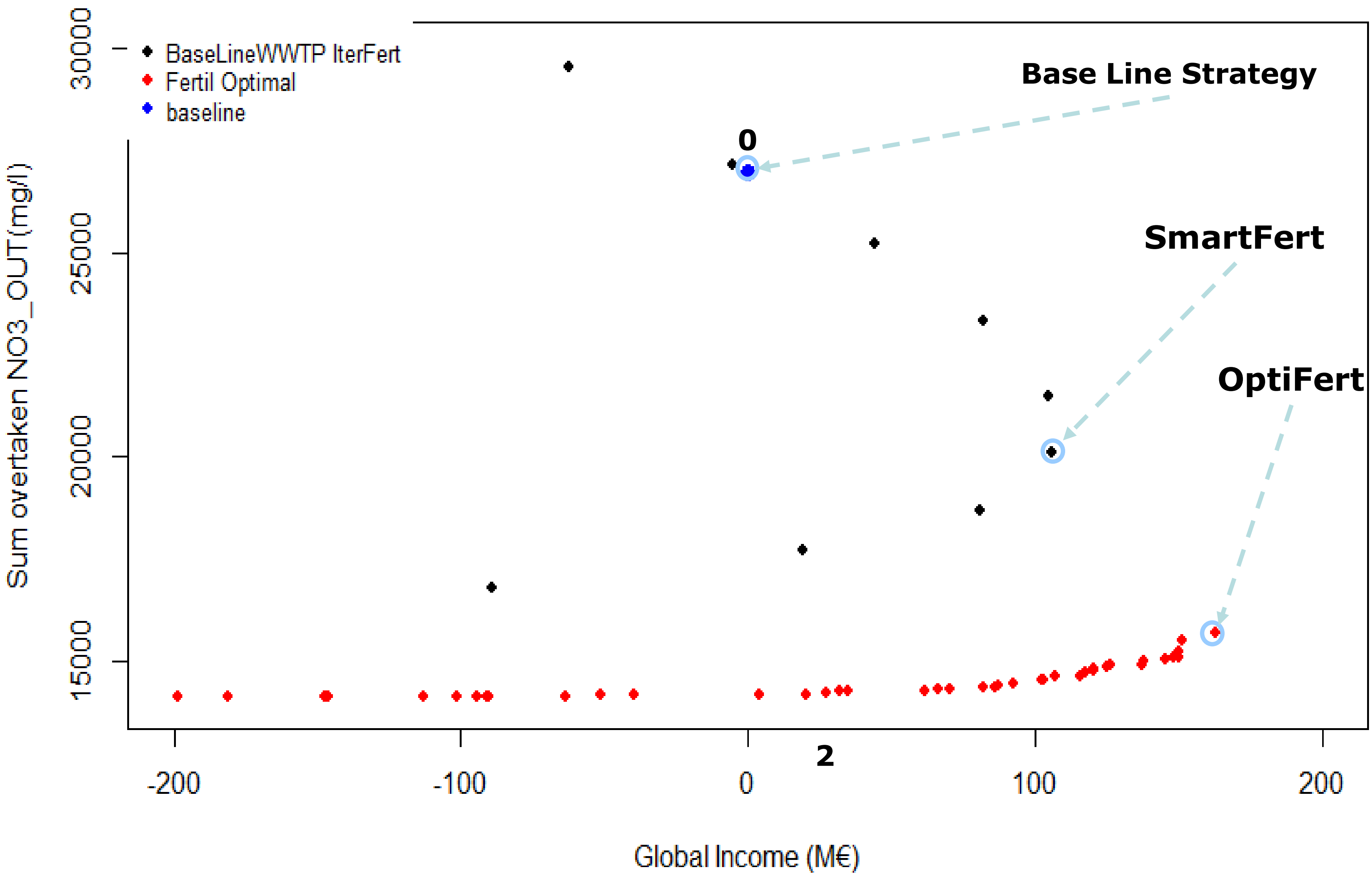
WWTP Optimization

Selected Strategy: 19,5 M€

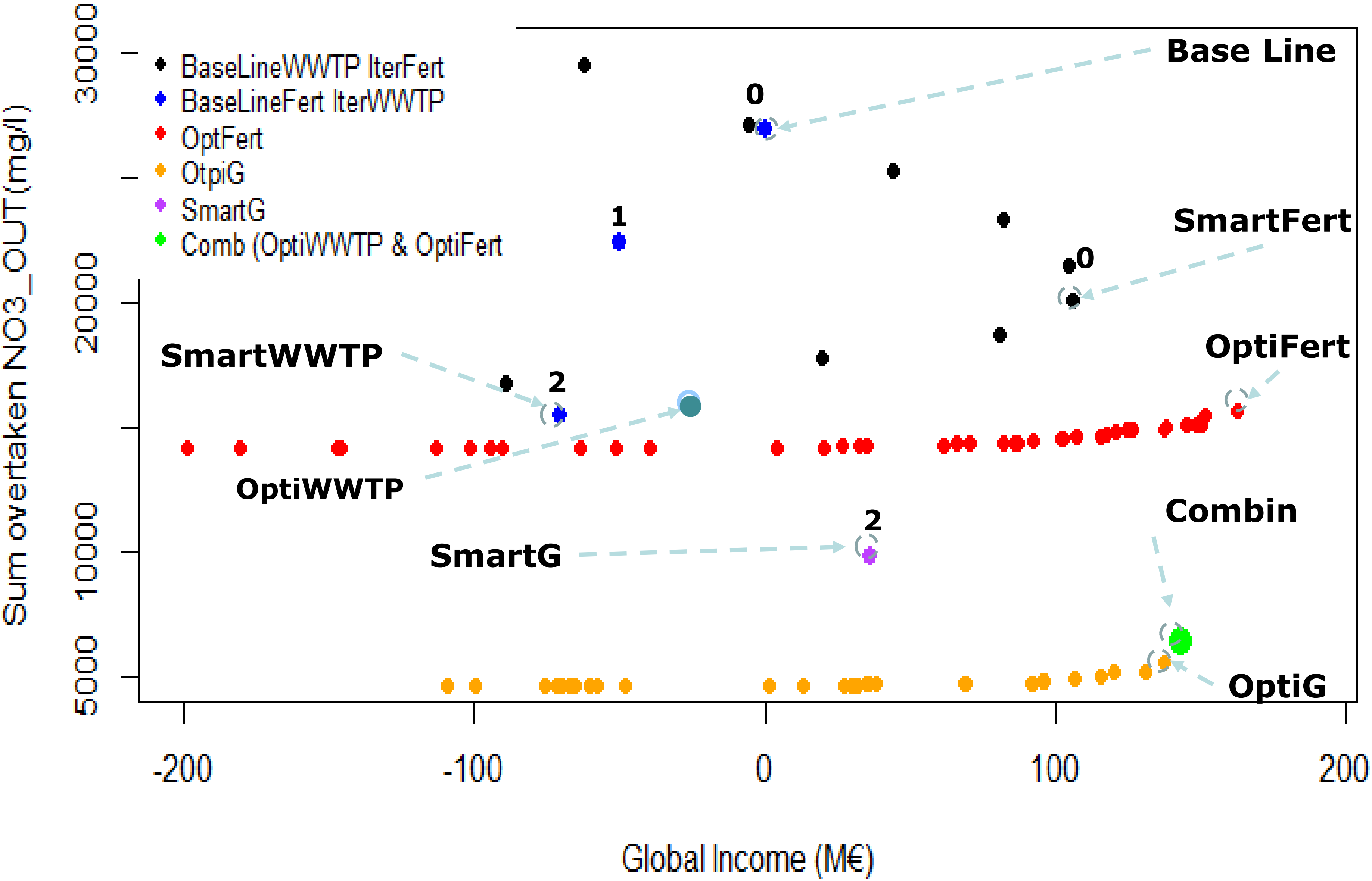
No upgrade	358
Upgrade level 1	65
Upgrade level 2	110



Fertilization: Optimization



Combined



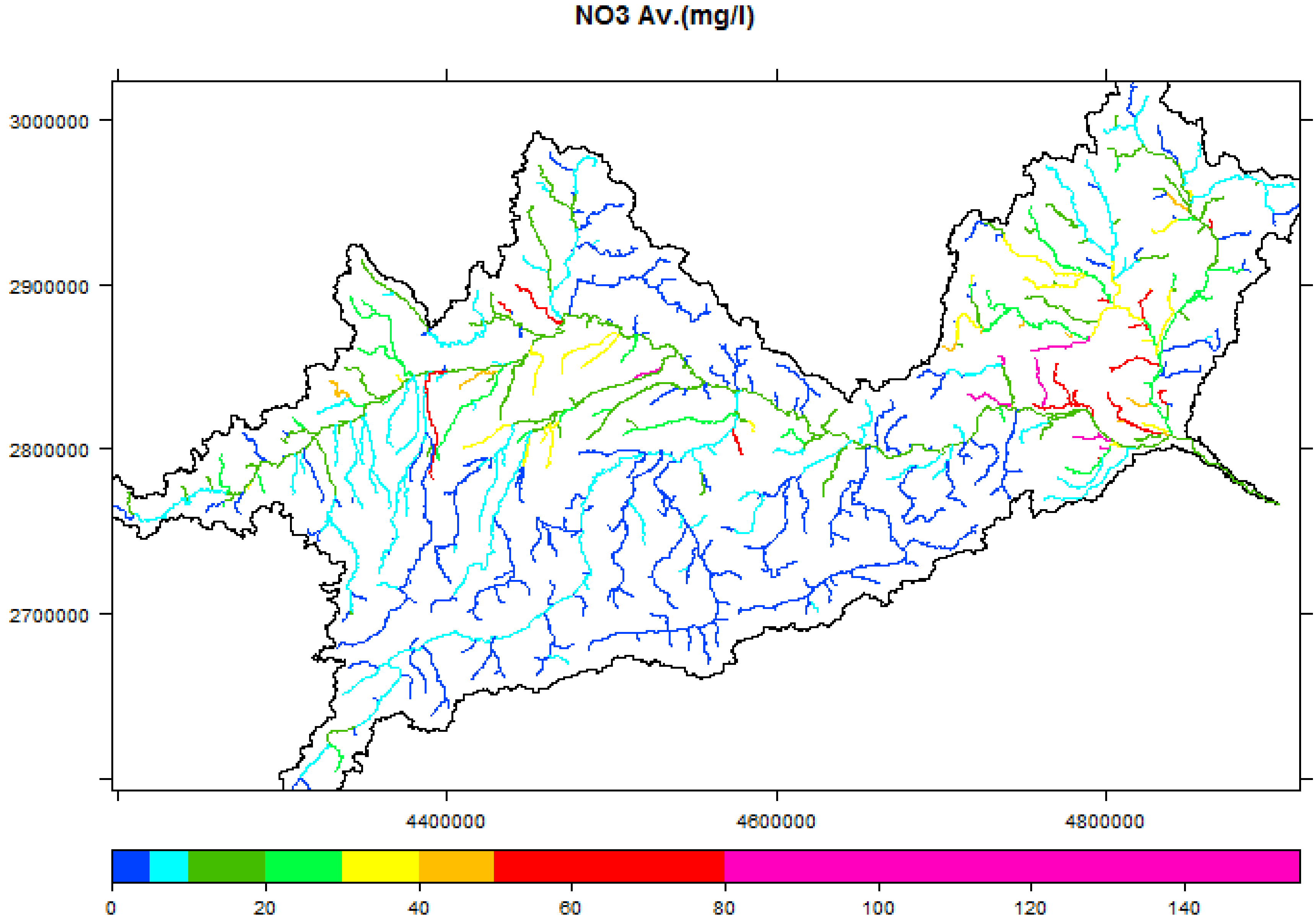
BaseLineWWTP IterFert
BaseLineFert IterWWTP
OptFert
OtpiG
SmartG
Comb (OptiWWTP & OptiFert
Base Line
SmartFert
OptiFert
SmartWWTP
OptiWWTP
SmartG
Combin
OptiG
0
1
2
0
2
Sum overtaken NO3_OUT (mg/l)
30000
20000
10000
5000
-200
-100
0
100
200
Global Income (M€)

Scenarios summary

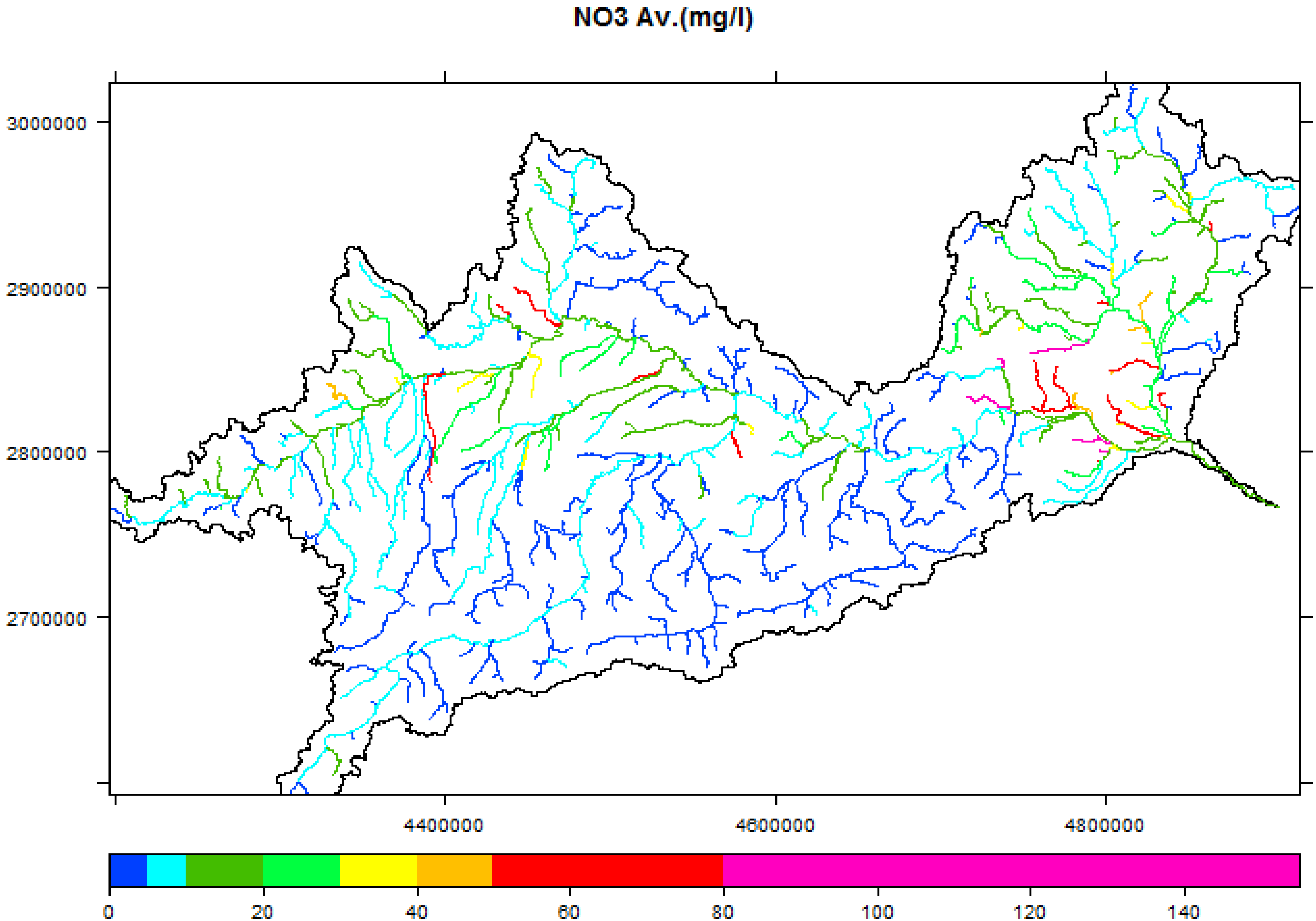
	OF1	OF2	NH4 Av. (mg/l)	NO3 Av. (mg/l)	WWTP Cost (M€)	Crop Income (M€)
Baseline	303	26975	3.01	12.96	0	2049
SmartFert	224	20266	3.01	11.52	0	2156
OptiWWTP	206	16245	2.60	11.50	19.6	2049
OptiFert	168	15681	3.00	11.16	0	2212
SmartG	130	9777	2.04	8.47	70.8	2156
Combin	87	6378	2.58	9.70	19.6	2212
OptiG	73	5508	2.12	8.63	51.2	2238

(O.F.1): Number of stretches and simulations period (months) where the limit WFD 50 mg/l concentration of NO3 is violated.
(O.F.2): Sum of violations for all stretches and simulations period of the 50 mg/l limit for NO3.

Baseline NO3 mg/l

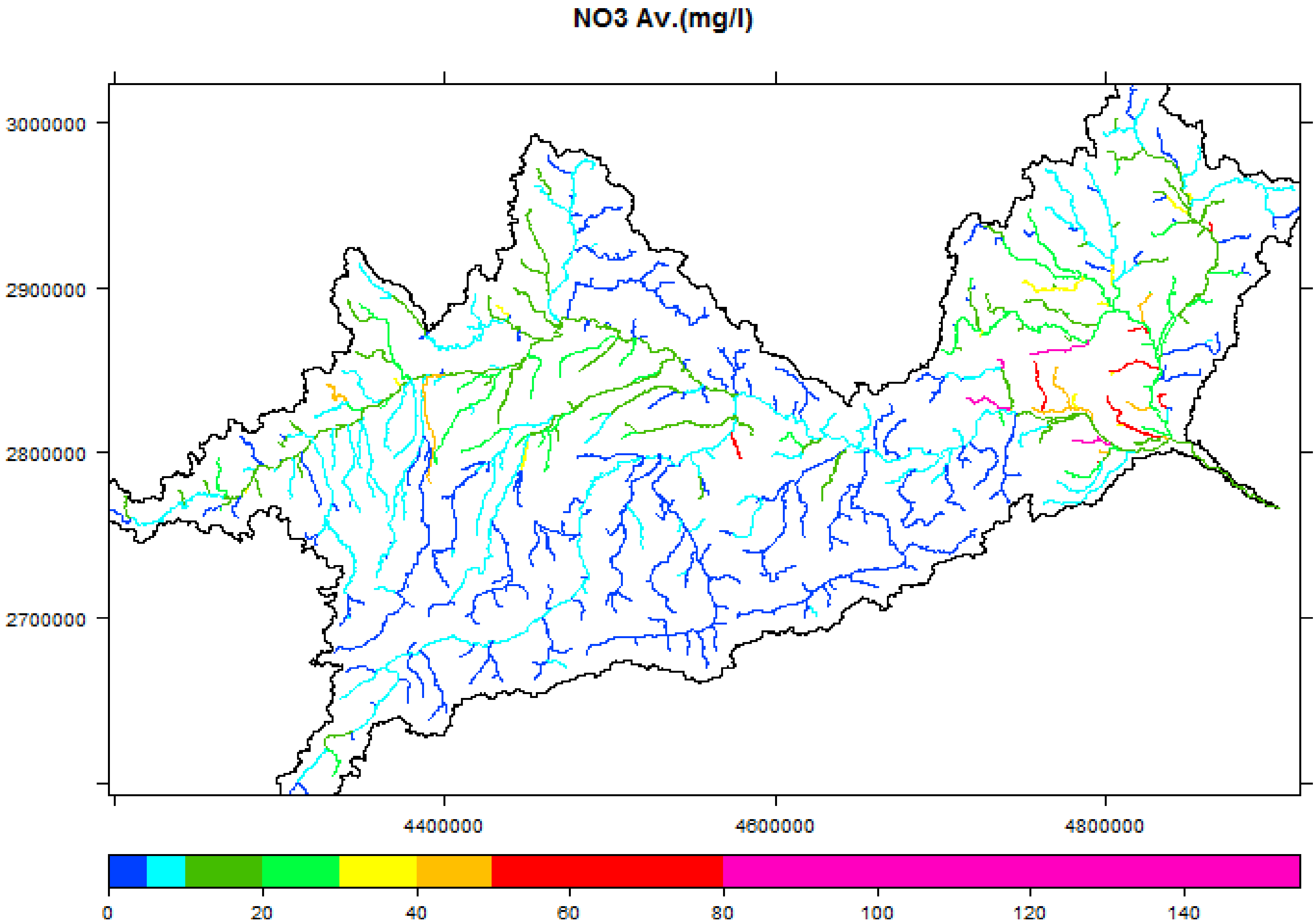


SmartF

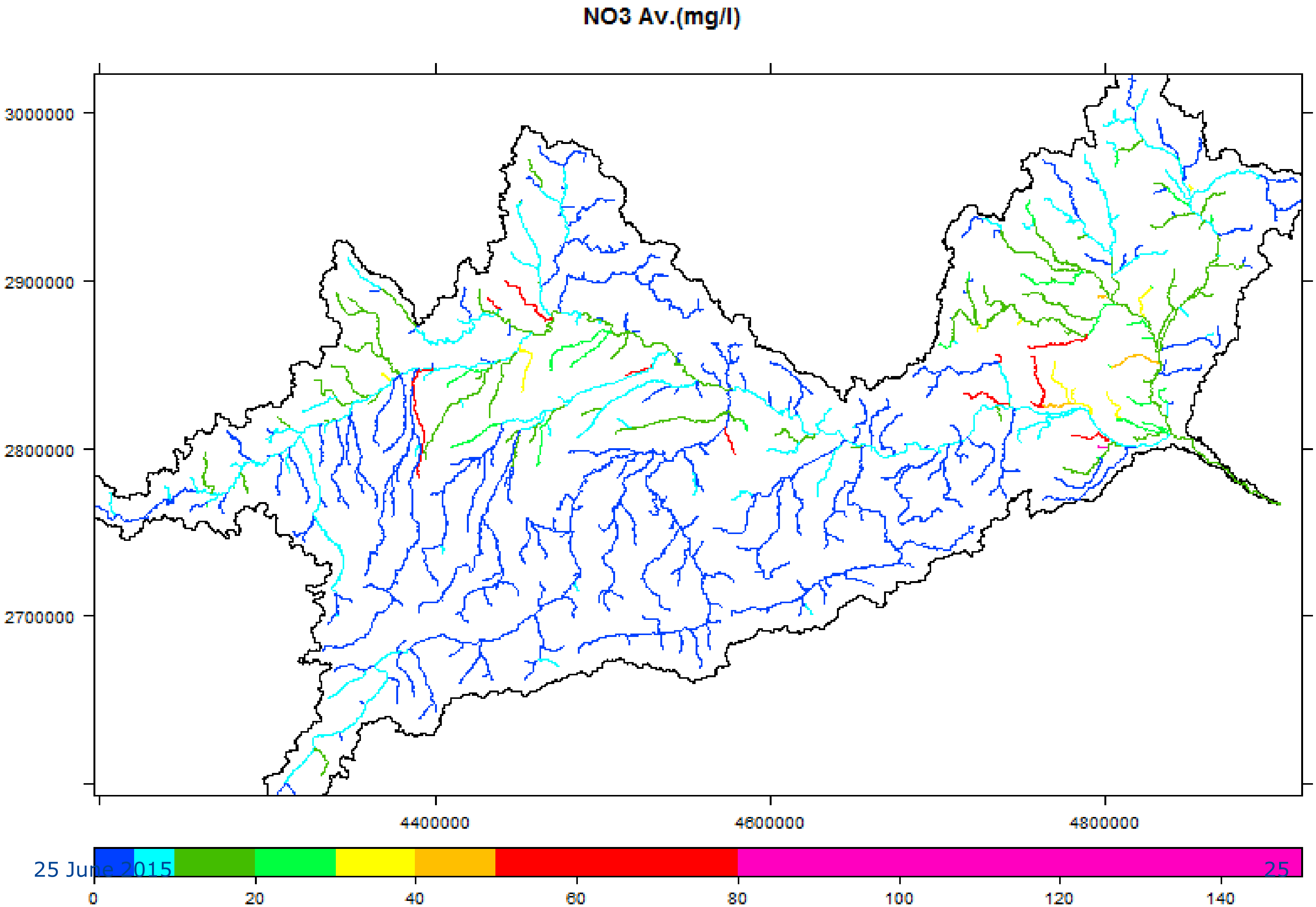


NO3 Av.(mg/l)
3000000
2900000
2800000
2700000
4400000
4600000
4800000
0
20
40
60
80
100
120
140

OptiFert


NO3 Av.(mg/l)
3000000
2900000
2800000
2700000
4400000
4600000
4800000
0
20
40
60
80
100
120
140

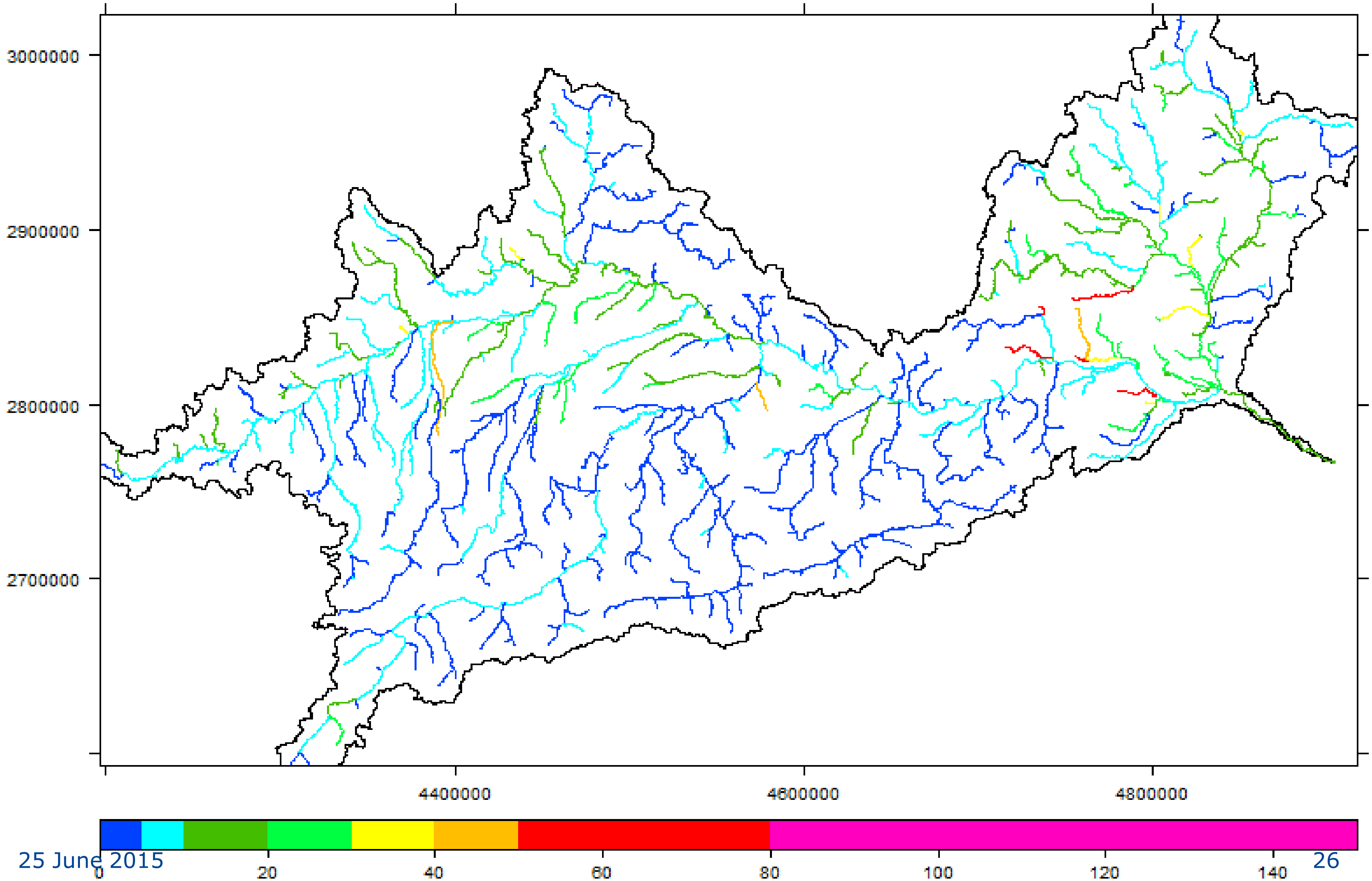
SmartG



NO3 Av.(mg/l)
3000000
2900000
2800000
2700000
4400000
4600000
4800000
0
20
40
60
80
100
120
140

OptiG

NO3 Av.(mg/l)



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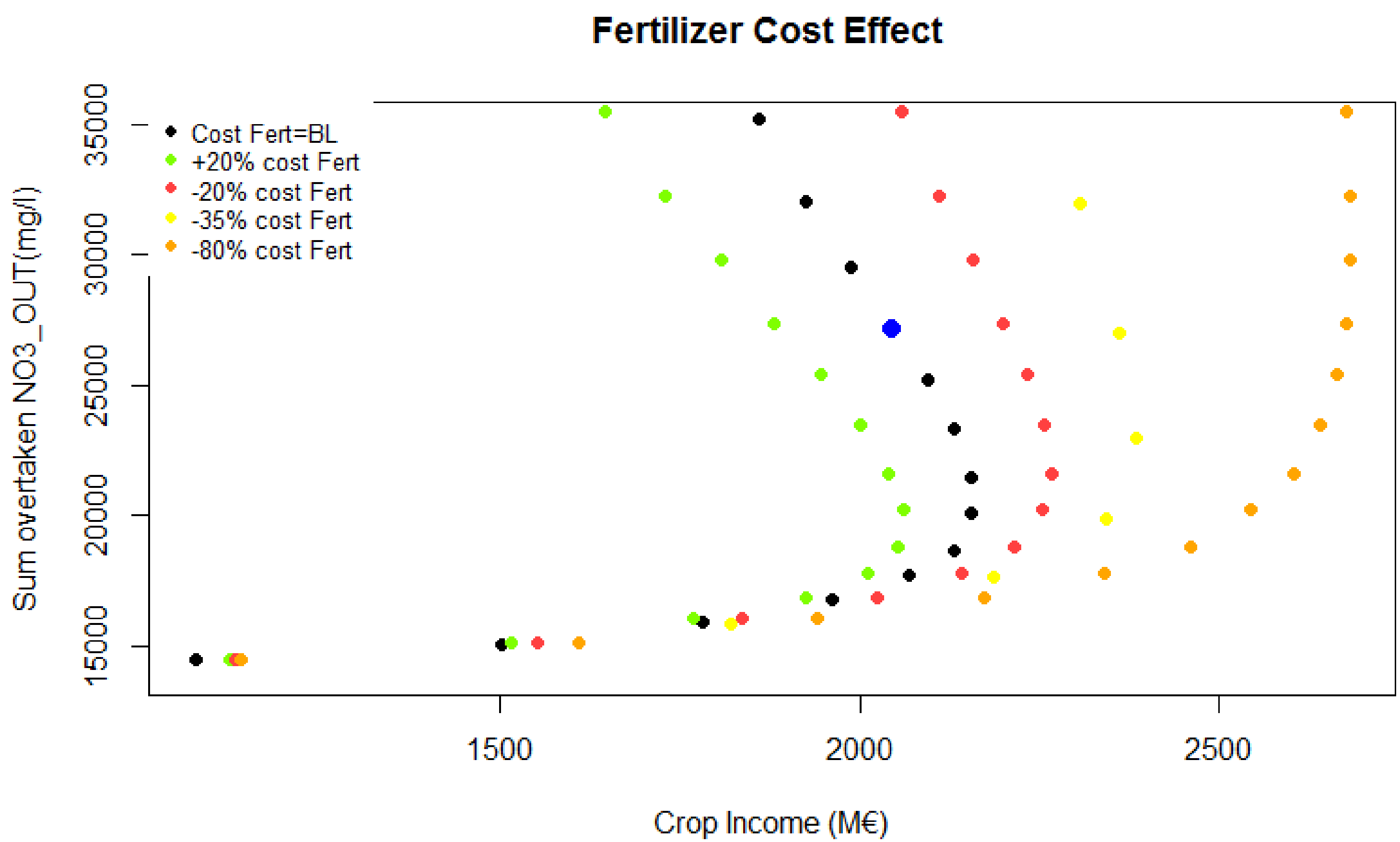
Sensitivity Analysis: Fertilizer Cost



Strengths of the framework

- Open source
- Extensive library of R analysis tools
- Visualization
- Once you have the SWAT model is not so hard
- Flexible: easy to add another aggregation metric, objective functions, optimization routines (Nelder-Meat, etc)

Limits and Future Work

- **Limits:**
  - User need some programming knowledge to use the framework
  - R is slower than other platforms/languages, but 99.99% of the total CPU time is consumed by the SWAT model.
  - Big SWAT models need parallelized version
- **Future Work:**
  - Convert the R-SWAT-DM framework in an open source R package
  - Adapt to Multi-Objective Calibration?

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CONCLUSIONS

- The R-SWAT-DM uses ***SWAT as biophysical model*** for simulation of management scenario, but adds tools for analysis, optimization, and visualization.
- R-SWAT-DM is developed in R language, using only open source libraries, and born with the purpose of *becoming an* ***open source package***.
- The R-SWAT-DM framework helps stakeholder in decision making for ***efficient allocation*** of Best Management Practices.
- In the ***Upper Danube Case Study*** the framework allowed ***identifying efficient scenarios*** of mineral fertilization and WWTP upgrading management, by which nutrients concentration could be substantially reduced while at the same time that increasing total net income.

THANKS FOR YOUR ATTENTION

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