Balancing Food Security and Environmental Sustainability through Seasonal Crop Allocation in Bangladesh

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Introduction:

Ensuring food security is a matter of supreme importance to hundreds of million people in Bangladesh and is among the top priorities for the country's government. Despite steady increase in total annual cropped area from 35.7 to 38.3 million acres during 2010–2017 through doubling and tripling cropping (BBS 2011, 2019), increased input use (such as chemical fertilizers) associated with cropping intensity growth could subsequently induce environmental losses (e.g., air, water, and soil pollution), affecting people's health, and threatening the sustainability of intensification. While nitrogen use per hectare of cropland in Bangladesh was among the highest in 2017 (two times of that in the US) (FAOSTAT 2020), nitrogen use efficiency has been found to be low (Hossain *et al*. 2005; Lassaletta *et al*. 2014). This fact raises concern about the environmental impact of nutrient application in the country.

Objectives:

1. Empirically explores drivers of seasonal crop allocation.
2. Evaluates the impact of increased cropping intensity and fertilizer application on the disservice of nutrient runoff.
3. Simulates alternative scenarios of seasonal crop choices across districts under a seasonal-spatial optimization framework to shed light on possible pathways to improving environmental sustainability of intensification while maintaining food security.

Methods:

➢ ***Land Use Modeling:***

- A farmer's objective is to choose land allocation that maximizes total profit from rice and non-rice crops production across three cropping seasons—spring, summer, and winter.
- Optimal land allocation characterized with a system of six share equations with the arguments of price margins for rice and non-rice crops in each season.
- Assuming logistic form for the share equations, we exploit the generalized linear property of logistic form and convert the nonlinear share equations to a system of linear equations where idle use is a residual category, estimated using the SUR method with cross-sectional district-level data.

➢ ***InVEST Nitrogen Delivery Ratio (NRD) model:***

- InVEST (https://naturalcapitalproject.stanford.edu/software/invest) is a suite of spatially explicit models for evaluating tradeoffs associated with land use induced ecosystem service changes.
- The NDR model simulates nutrient movement across space taking into account both abiotic and biotic factors (Breuer *et al*. 2008). For each growing season, the model assesses: 1) Total nutrient load, 2) Nutrients retained by vegetation and topographic features, and 3) Nutrients delivered to the water outlet.

➢ ***Optimization:***

- Assume the central government's objective is to minimize the national annual agricultural (nitrogen) runoff while maintaining the value of total crop production and guaranteeing food security in the country, this optimization is expressed as:

$$\min_{\{N_{irj},L_{irj}\}} \sum_{i=1}^{64}\sum_{r=1}^{3}\sum_{j=1}^{2}\theta_{ir}N_{irj}L_{irj} \tag{1a}$$

$$\text{s.t.} \quad \sum_{i=1}^{64}\sum_{r=1}^{3}\sum_{j=1}^{2}L_{irj}y_{irj}(N_{irj})p_{irj} \geq v^b \tag{1b}$$

$$\sum_{i=1}^{64}\sum_{r=1}^{3}L_{ir1}y_{ir1}(N_{ir1}) \geq Y_1^b \tag{1c}$$

$$\sum_{j=1}^{2}L_{irj} \leq \bar{L}_{ir}, \quad i=1,\dots,64;\ r=1,2,3 \tag{1d}$$

$$\sum_{r=1}^{3}\sum_{j=1}^{2}L_{irj} \leq CI_i\bar{L}_i, \quad i=1,\dots,64, \tag{1e}$$

- We integrate the econometric land use model into the optimization problem by inserting the share equation into eqs. (1a)–(1e); the share equation is written as a function of marginal effects of price margins (a new decision variable replacing crop areas).

Results and Discussion:

- Econometric land use model results show that the probabilities of growing rice and non-rice crops increase with their own net price growth and decrease with the cross-net price growth except the spring rice price and summer non-rice price (Table 1).
- The probability of growing summer crops increases with road density because summer crops spoil quickly. In winter, rainfall increase reduces the probability of growing rice and increases the probability of growing non-rice crops.

Table 1. Estimated Marginal Effects for the Land Use Model

	Rice	Non-rice
Panel A: Spring		
Rice price margin change (10Tk/kg)	-0.036	0.006
Non-rice price margin change (10Tk/kg)	-0.013 **	0.182 **
Road density change (meter/acre)	-0.005	0.065
Precipitation change (100 mm)	0.008	0.038 ***
Panel B: Summer		
Rice price margin change (10Tk/kg)	0.139 **	-0.057 **
Non-rice price margin change (10Tk/kg)	-0.024	0.030
Road density change (meter/acre)	0.764 **	0.319 *
Precipitation change (100 mm)	-0.006	-0.005
Panel C: Winter		
Rice price margin change (10Tk/kg)	0.931 ***	-0.855 ***
Non-rice price margin change (10Tk/kg)	-0.670 ***	0.697 ***
Road density change (meter/acre)	-0.251	0.191
Precipitation change (100 mm)	-2.126 ***	2.286 ***

Note: Marginal effects and elasticities are evaluated at the means of the data. *, **, and *** indicate statistical significance at the 10, 5, and 1% levels, respectively. N=64 districts

- The InVEST NDR model results on the ratio of total runoff over total nutrient load in each season (Fig. 1) shows strong seasonal and spatial heterogeneity of the ratio and highlight the potential to improve the efficiency of economic-environmental performance by optimization.

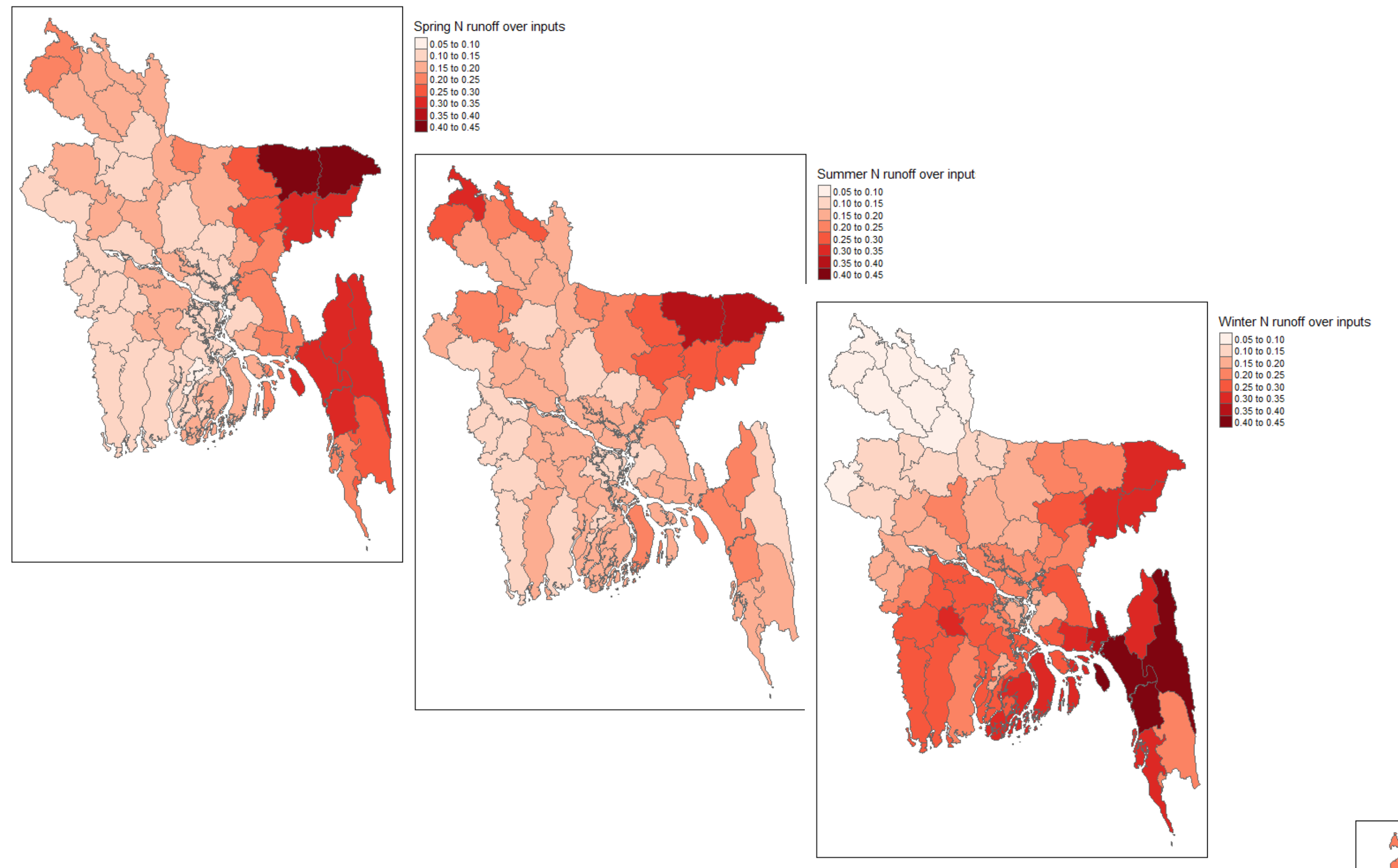

Fig 1. Nitrogen runoff-Load ratio by season

- Table 2 presents the national-level optimization results from various models and constraints.
  - Almost all inefficiency (96%) in producing nitrogen runoff comes from seasonal (instead of spatial) misallocation of crop production and overuse of nitrogen application.
  - Among the aforementioned inefficiency, 58% arises from the overuse of nitrogen and 46% from misallocation of seasonal rice and non-rice crop production, yielding 4% overlapping residuals.

Table 2. Optimization results using various models and constraints

	Baseline	Seasonal opt.			Spatio-seasonal opt.	
Decision variable		N	Area	N and area	N and area	N and Δp
Total output value (billion Tk)	**1410.8**	**1523.9**	**1414.1**	**1416.7**	**1410.8**	**1438.0**
Total rice production (million tonne)	**35.9**	**35.9**	**35.9**	**35.9**	**35.9**	**36.2**
Total N runoff (1,000 tonne)	**106.8**	**57.2**	**67.5**	**21.3**	**18.2**	**33.5**
Spring rice N runoff	*11.5*	*5.2*	*1.6*	*2.2*	*2.3*	*2.1*
Summer rice N runoff	*34.0*	*22.9*	*19.2*	*2.7*	*1.6*	*11.0*
Winter rice N runoff	*37.0*	*12.7*	*37.5*	*10.6*	*10.4*	*10.5*
Spring non-rice N runoff	*10.2*	*5.2*	*5.6*	*2.4*	*2.4*	*2.7*
Summer non-rice N runoff	*3.4*	*2.2*	*0.2*	*1.8*	*0.2*	*1.9*
Winter non-rice N runoff	*10.7*	*9.0*	*3.3*	*1.6*	*1.3*	*5.3*
Total N inputs (1,000 tonne)	**560.2**	**334.8**	**397.4**	**124.6**	**111.5**	**174.2**
Spring rice N inputs	*55.8*	*30.9*	*9.3*	*13.7*	*13.0*	*10.6*
Summer rice N inputs	*174.1*	*126.2*	*113.4*	*16.3*	*11.5*	*56.2*
Winter rice N inputs	*184.3*	*76.6*	*210.5*	*61.7*	*62.8*	*53.6*
Spring non-rice N inputs	*64.7*	*34.4*	*38.7*	*16.8*	*17.7*	*15.9*
Summer non-rice N inputs	*20.8*	*12.7*	*1.6*	*9.2*	*1.1*	*10.7*
Winter non-rice N inputs	*60.6*	*54.0*	*23.8*	*6.9*	*5.4*	*27.2*
Total harvested area (million acres)	**43.6**	**43.6**	**38.8**	**31.1**	**27.9**	**43.5**
Spring rice harvested area	*2.7*	*2.7*	*1.1*	*3.4*	*3.2*	*2.7*
Summer rice harvested area	*14.0*	*14.0*	*10.7*	*4.1*	*2.9*	*14.0*
Winter rice harvested area	*12.0*	*12.0*	*14.7*	*15.4*	*15.7*	*13.4*
Spring non-rice harvested area	*4.0*	*4.0*	*4.0*	*4.2*	*4.4*	*4.0*
Summer non-rice harvested area	*2.7*	*2.7*	*4.3*	*2.3*	*0.3*	*2.7*
Winter non-rice harvested area	*8.2*	*8.2*	*4.2*	*1.7*	*1.4*	*6.8*

  - The baseline nitrogen application for summer rice and winter non-rice crops are inefficient; the inefficiency persists even after various optimizations, leading to a shrink in cropping area.
  - The baseline nitrogen application for spring rice is also inefficient, but there is a great potential to improve the nitrogen application efficiency. Consequently, we observe an increase in cropping area after optimization.
  - The baseline nitrogen application for summer non-rice crops is relatively efficient. After optimization, the application rate is less efficient than spring crops and winter rice, resulting in a reduction in cropping area.
  - The baseline nitrogen applications for winter rice and spring non-rice crops are also relatively efficient, and the efficiency could be further improved through optimization.

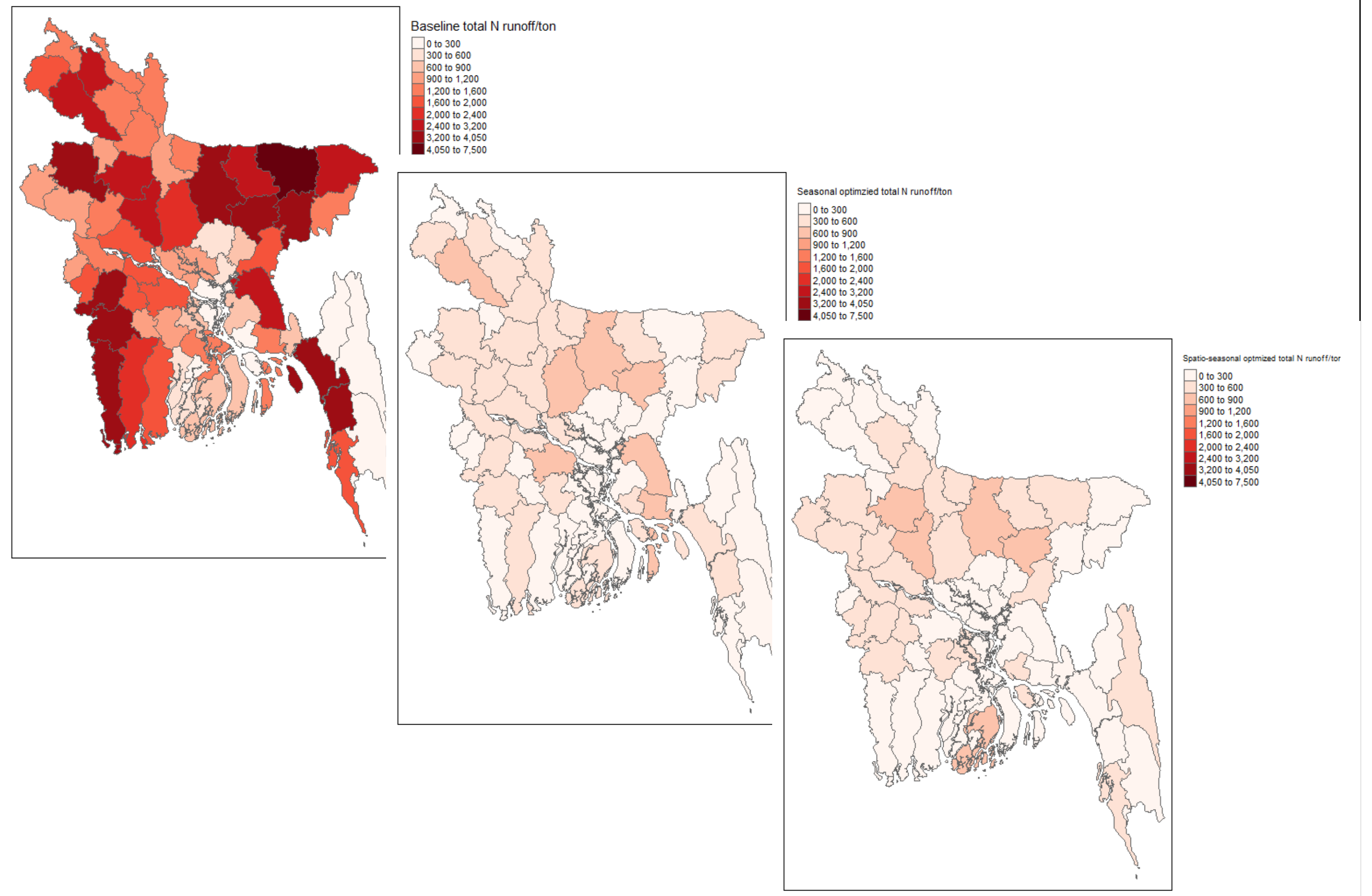

Fig 2. Total nitrogen runoff: Baseline vs. optimization

Conclusions:

When integrating the land use model into the optimization problem, the optimization is not as efficient as the case in which planting areas are optimized because of the reduced degrees of freedom in optimization. It is easier to change winter crop areas through price instruments, but there is little space to reallocate the national production of spring and summer crops by changing crop prices.

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