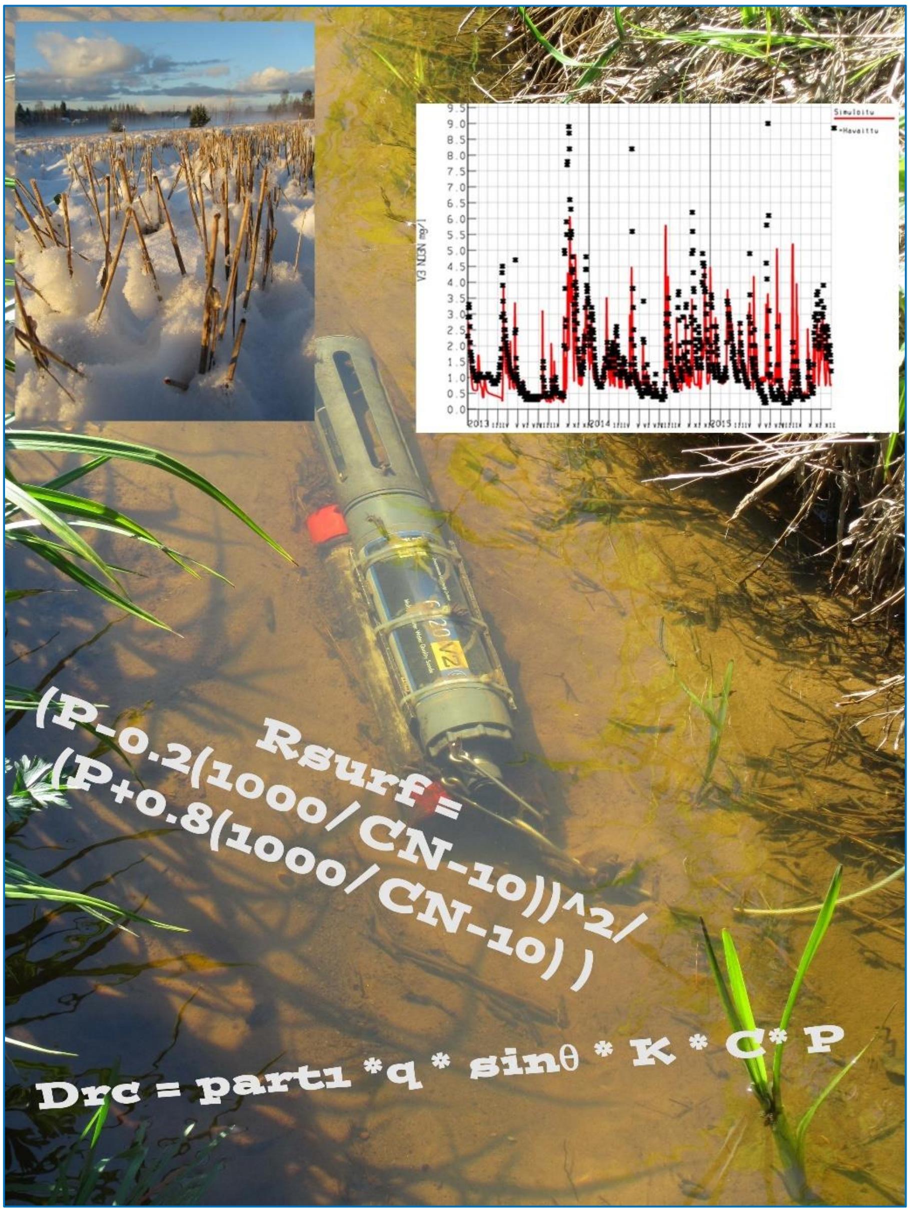


Lohkon ominaispiirteet huomioiva ravinnekuormitusmallinnus ja sen kehittäminen (in English)

Inese Huttunen ja Markus Huttunen, SYKE

Field-scale nutrient loading modeling and its development

Summary

Main tasks accomplished in LOHKO project:

- The field management data from farmers in Lepsämänjoki, Laurinoja, Ryölä, and Kaukanaronoja catchments has been defined in ICECREAM model input data, so that ICECREAM simulates each field with exact management practices (crop, fertilizer, sowing, harvest dates).
- VEMALA-ICECREAM model has been developed further and calibrated against: 1) continuous water quality measurements in streams Lepsämänjoki, Laurinoja. Also observations form Ryölä, Peräsuonoja and Kaukanaronoja has been used for testing of model results, 2) against published field measurements in Kotkanoja, Aurajoki and Kotkaniemi test fields.
- The better ICECREAM model version has been created during this project.
- The new version of ICECREAM has been used to simulate the nutrient loading for each field with different field management practices, fertilization, crops and the results has been delivered for each farmer. The purpose of this action was to provide the information about nutrient loading amounts with different practices to help farmer in the decision making.

There a least two main benefits of the LOHKO project:

- The field scale results delivered to the farmers allows the models to help in the decision making at the farm level scale, which is the scale at which the loading should be reduced since the main agricultural actions (fertilization, crop management) has been done at the farm level scale.
- Improvement of field scale model allows to improve the catchment scale model VEMALA-ICECREAM to simulate the nutrient loading based on process based hydrological and nutrient model. Catchment scale model VEMALA-ICECREAM is then used for many purposes like 1) implementation of WFD in river basin management plans for estimation of present nutrient loadings to water bodies, for climate change effect on nutrient loadings, for simulation of mitigation measures especially in agricultural sector, 2) for HELCOM estimates of nutrient loading to the Baltic Sea and different scenarios to reduce the loading.

1. ICECREAM model description and development

ICECREAM is a field scale model which simulates hydrology, P and N cycle in the soils, as the result giving P and N transport and leaching out of field plot. ICECREAM is a one dimensional model with the daily time step.

1.1. Hydrology in ICECREAM

The simulation of water flow components over and through the soil is the most important for simulation of nutrient transport and leaching, since P and N is transported and leached through different pathways. P is mostly transported with surface runoff and macropore flow, and N is mostly leached with infiltration waters as well as macropore flow.

ICECREAM simulates following flow components – surface runoff, macropore flow and infiltration through the soil matrix. Drainage flow is not directly simulated since ICECREAM is one dimensional model, but we assume that percolation water from the last layer is flowing into the subsurface drain. The total daily amount water input to the ICECREAM model is taken from VEMALA hydrological simulation. Daily liquid precipitation and snowmelt water (variable 'yield') is used as input to ICECREAM model.

Then **surface runoff** is subtracted from total water input to the system. Surface runoff is simulated by (USDA Soil Conservation Service) SCS curve number method. The model simulates the fraction of the water input running as a surface runoff (R_{surf}) depending on the curve number parameter (CN) (Equation 1). P is daily precipitation. CN has a range from 50 to 95. CN depends on the hydrologic soil group, soil cover type, soil treatment, hydrologic condition. The higher is the CN number, the higher is the simulated surface runoff.

$$R_{surf} = \frac{\left(P-0.2\left(\frac{1000}{CN}-10\right)\right)^2}{P+0.8\left(\frac{1000}{CN}-10\right)} \quad (1)$$

CN is an important parameter, which is changed to simulate differences in surface runoff in different crop management practices. CN for clay soils for non-frost conditions are ploughing – 78, reduced tillage – 88, for loam – 78, for silt – 80, for peat soils – 50. The values of the CN are calibrated against field experiment data of runoff components.

Development needs: surface runoff simulation method needs to be changed to some other method. Review of 1-D surface runoff simulation methods should be done and appropriate method should be chosen. It is possible that ICECREAM should be developed to be a 2-D model since we know the slope of the field, roughness of the surface.

Some part of surface runoff is assumed to flow through the macropores as **macropore flow** in clay soils. The proportion of surface runoff flowing through the macropores depends of the slope of the field. For example, in Kotkanoja (with 2% slope) the proportion was 0,67; and in Sjökulla (with 5% slope) the proportion was 0,37.

$$R_{macropore} = \frac{1}{(1+0.2slope)^{100}} R_{surf} \quad (2)$$

Remaining water amount (yield- $R_{surf,1}$ -$R_{macropore}$) infiltrates into the soil profile (micropore system). **Infiltration** (soil moisture distribution in the soil layers and vertical water movement between layers) is simulated by Richard's equation (implemented by Vanamo Piirainen). Richard's equation simulates the change of soil moisture θ (volumetric water content) depending on soil hydraulic conductivity k (cm/d) and soil matrix potential ψ (cm).

Definition: matrix potential is the potential energy of water relative to pure water in reference conditions. When water is in contact with solid particles, intermolecular forces between the water and the solid can be large and important. The matrix potential is always negative because the water attracted by the soil matrix has an energy state lower than that of pure water. Matrix potential only occurs in unsaturated soil above the water table. If the matrix potential approaches a value of zero, nearly all soil pores are completely filled with water. In the case that water drains into less-moist soil zones of similar porosity, the matrix potential is generally in the range of −10 to −30 kPa.

Volumetric water content θ and hydraulic conductivity k are functions of matrix potential ψ, so only unknown variable is ψ. Volumetric water content θ and hydraulic conductivity k are highly non-linear functions of matrix potential ψ, therefore closed-form analytical solutions of Richard's equation does not exist. Numerical solution of Richard's equation is done by Newton-Raphson method.

Development needs: In present model version the macropore and micropore flows are not interconnected, which of course is not true. There happens flow between micro and macropore systems, therefore dual macropore model should be implemented in ICECREAM. Two Richard's equations should be solved including an extra term of water exchange between pore systems, water flows towards the lowest matrix potential.

1.2. Nitrogen processes in ICECREAM

The following N transformation processes in the soil are simulated in ICECREAM – mineralization (AM), nitrification (NI), denitrification (DN), volatilization (VL), immobilization (IM), plant uptake (UP), fixation (FX). In general, most of the processes are simulated as the first-order rate processes, where the processes depend on the amount of N fraction storage in the soil layer, rate (speed) of the process, soil temperature coefficient and soil moisture coefficient.

$$Process = Mass * rate * C_{temperature} C_{soil\ moisture} \quad (3)$$

Figure 1.1. illustrates the example of N inputs and transformation processes in the soil in case of spring wheat cultivation. The biggest inputs to the system are fertilizer application and mineralization of organic N followed by nitrification of ammonium. During the summer the NO_3 concentration peaks in streams are caused by leaching of fertilizer NO_3. During autumn and spring concentration peaks are more caused by mineralization process of organic

N and nitrification. Immobilization of inorganic N is also important process which regulates the N cycle. Whether nitrogen is mineralized or immobilized depends on the C:N ratio of the plant residues. If the C:N ratio is high soil microbes utilize soil mineral nitrogen to decompose organic material (N is immobilized). On the other hand, if C:N ratio is low sufficient nitrogen is supplied to microbes through the decomposition of the organic material and excess N is released into the soil (mineralization). When the C:N ratio is less than 20:1 mineralization can be expected when the microbes decompose organic material (Paasonen-Kivekäs et al., 2009).

Development needs: There is too little NO_3 leaching in autumn, which is caused by too little mineralization of organic N. Probably in the model during autumn when plant residues are added to the fresh organic matter pool, there is too high C:N ratio and N is immobilized into organic N. In reality mineralization should be higher than immobilization and NO_3 should accumulate in the soil, it means that C:N ratio is low during autumn. The balance between mineralization and immobilization processes should be found, immobilization process description developed.

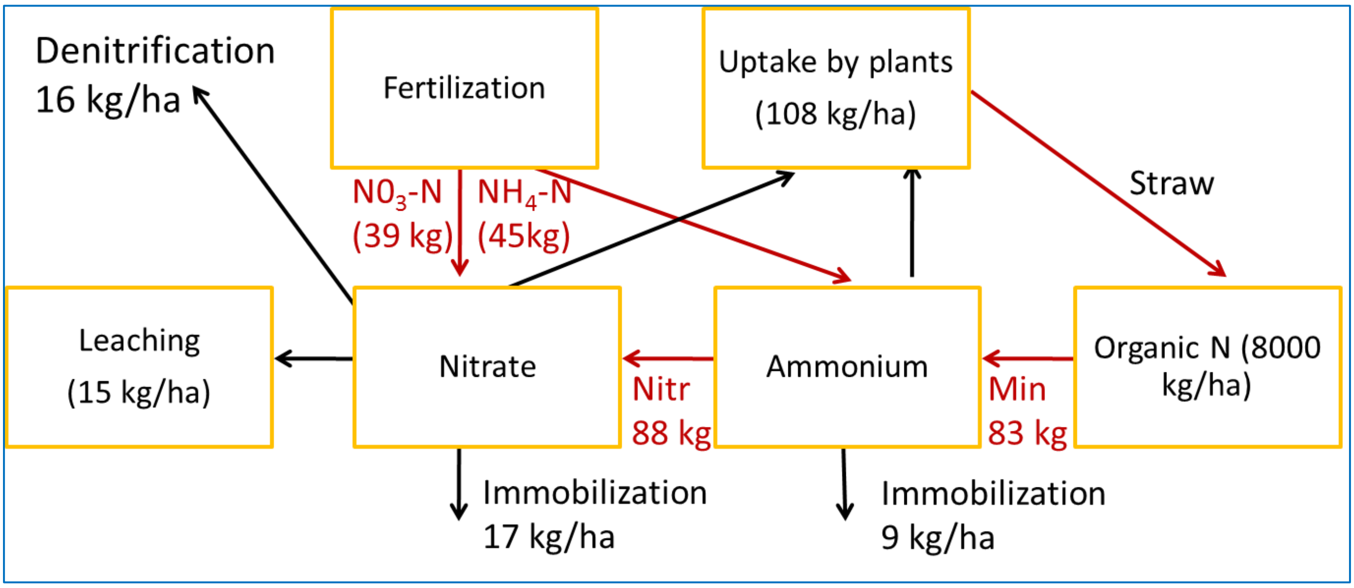


Figure 1.1. Example of annual values of N inputs and transformation processes in the soil.

1.3. Phosphorus processes in ICECREAM

Phosphorus simulation is based on the flow between three mineral P pools (stable, active and labile P) and three organic P pools (manure, fresh organic and stable organic P). The simulated P loading consists of particulate phosphorus (PP) and dissolved phosphorus (DP). They are lost via surface runoff and in clay soils also via macropore flow. In addition, dissolved phosphorus is lost with the water percolating through the soil profile. Losses of PP in surface runoff (and macropore flow) are linked to soil erosion, which is calculated with the modified Universal Soil Loss Equation USLE model. The equation includes the rainfall erosivity factor (R), the soil erodibility factor (K), the topographic factor (S) and the cropping management factors (C and P):

$$D_l = R * S * K * C * P \qquad (4)$$

D_l is soil loss with interrill detachment (kg/m2/h), R rainfall erosivity factor is related to hourly rainfall rate with two calibrated parameters, S slope factor is the function of slope (both modified by Vanamo Piirainen), K, C, P are factors taken from CREAMS model. Rill detachment equation has similar form:

$$D_{rc} = par1 * q * sin\theta * K * C * P \qquad (5)$$

where q is a peak runoff rate (ft^3/s) which depends on runoff volume (in). There is also shear stress acting on the soil simulated in the model, equation can be found in CREAMS manual.

Improvements: In the ICECREAM version we have received, the macropore flow was transporting PP and DP only from the two top soil layers. In reality that is not true since there is an interaction between micropore and macropore systems in terms of exchange of water, soil particles (PP) and solutes (DP). In this version the exchange between two pore systems was included by simple method, where a certain small fraction of PP, DP from micropore soil profile was transported to macropore system in each soil layer. This fraction is a calibrated parameter, constant for all soil layers. This improvement increased the simulated TP concentrations during the middle range runoff peaks, that they matched the observed peaks in Lepsämänjoki better.

1.4. Calibration of ICECREAM model

The calibration of the ICECREAM model has been done. Calibration means adjusting the simulated P, N, SS concentration and load values to match the observed concentrations and loads as much as possible. Daily P, N, SS concentration from Lepsämänjoki and Laurinoja were used to calibrate the ICECREAM model parameters. There are now 33 calibrated parameters added to the ICECREAM model – 18 parameters regarding P processes, 9 parameters regarding N processes and 6 parameters regarding SS transport. Parameter values are found automatically by minimizing the difference between simulated and observed daily concentration values.

2. VEMALA-ICECREAM model results for LOHKO test catchments

There are 5 test catchments simulated in LOHKO project (Lepsämänjoki, Laurinoja, Ryölä, Peräsuonoja, Kaukanaronoja), as well as Savijoki from Aurajoki catchment. The length of observations differs considerably, also the continuous measurements are done only in bigger streams like Lepsämänjoki and Savijoki. In smaller streams concentrations only during spring and autumn runoff events are observed, in low flow periods there is no runoff or it is missed to observe. Therefore, annual loading values can be estimated only for Lepsämänjoki and Savijoki, other smaller streams are not suitable for annual loading estimation and comparison with loading data found in literature. Mean annual TN loading from fields in Lepsämänjoki is 17 kg/ha/year and TP loading is 1.2 kg/ha/year (Table 2.1).

The comparison of simulated and observed cumulative loads for the days with concentration observations has been shown in the Table 2.2. For Lepsämänjoki the difference between observed and simulated is from 1-21%. For Laurinoja the difference is from 13-33%. For Savijoki the difference is 6-24%. For Ryölä there is the highest difference in TN simulation, the model still needs to be developed to simulate grass fields without harvest. For Peräsuonoja TP loading difference is -26%. For Kaukanaronoja the model need to be still developed, the TP loading difference is 53%.

For Lepsämänjoki simulated TP concentration and load simulation is good (Figure 2.1), in general TP concentration pattern is well simulated. The simulation of TP concentrations improved after adding the exchange of PP and DP between the micropore and macropore systems by adding the exchange parameter. The model needs to be still developed so that dual porosity model described by two Richard's equations should be included in ICECREAM.

For Lepsämänjoki simulated NO_3 concentrations are underestimated (Figure 2.2), especially NO_3 peak concentrations are too low in autumn and during the summer after fertilizer application. The NO_3 concentration has correct pattern following the observed concentration pattern. NO_3 load simulation for Lepsämänjoki is good. NO_3 concentration simulation needs to be improved by improving the mineralization simulation during the autumn and winter periods.

The statistical criteria (Nash and Sutcliff efficiency criteria, NSE) showing the goodness of the simulation is quite high 0.61-0.83 for the daily load simulations, and 0.19-0.68 for the daily concentration simulations (Table 2.3). The mean simulated and observed concentrations for Laurinoja cannot be compared, because there are no observations during low flow period, but simulated values are counted for all the days. The best daily concentration simulation is for SS concentrations and not so good model performance is for NO_3 concentration simulation.

Table 2.1. Simulated annual loading divided by sources for Lepsämänjoki catchment (TN=total nitrogen, NO_3=nitrate, TP=total phosphorus).

Lepsämänjoki	Unit	TN	NO_3	TP
diffuse loading	kg/ha/year	11.4	8.6	0.6
fields	kg/ha/year	16.9	11.2	1.2
forest	kg/ha/year	2.5	0.6	0.07

Table 2.2. Comparison of simulated and observed loads for test catchments (SS=suspended solids, DP=dissolved phosphorus).

Catchment, field	Area ha	Sub-stance	Unit	Number of observations	Simulated cumulated load	Observed cumulated load	Difference %
Lepsämänjoki	2300	SS	t	3700	5283	6720	-21
2006-2016	2300	TP	kg	3426	12411	11074	12
	2300	DP	kg	124	139	156	-11
	2300	TN	kg	122	22610	22366	1
	2300	NO_3	kg	2537	138116	135662	2
Laurinoja	124	SS	t	786	243	287	-15
2010-2016	124	TP	kg	786	438	387	13
	124	DP	kg	36	4	5	-15
	124	TN	kg	36	707	931	-24
	124	NO_3	kg	748	3482	5186	-33
Ryölä (plant cover)	0.586	SS	t	93	52	96	-46
2015-2016	0.586	TP	kg	93	145	103	41
	0.586	TN	kg	49	3177	1750	82
	0.586	NO_3	kg	93	4627	4752	-3
Ryölä (tilled)	0.597	SS	t	93	141	177	-20
2015-2016	0.597	TP	kg	93	208	175	19
	0.597	TN	kg	49	2514	1741	44
	0.597	NO_3	kg	93	3815	2296	66
Savijoki	12867	SS	t	572	5584	7339	-24
Long term obs.	12867	TP	kg	691	24837	22563	10
	12867	DP	kg	355	2617	3347	-22
	12867	TN	kg	691	266545	224608	19
	12867	NO_3	kg	571	153244	145168	6
Kaukanaronoja	556	TP	kg	99	39	26	53
2015-2016							
Peräsuonoja	281	TP	kg	121	60	81	-26
2015-2016							

Table 2.3. Mean simulated concentrations and Nash and Sutcliff criteria (RR) for concentrations and loads for Lepsämänjoki and Laurinoja observation points.

Sub-stance	Observation point	Number of observati-ons	Load RR	Ob-served concen-tration mg/l (TP µg/l)	Simu-lated concen-tration mg/l (TP µg/l)	Diffe-rence obser-ved - si-mulated	Concent-ration RR
NO_3	21_043 Lepsämänjoki 27,0 sensor	2572	0.65	1.60	1.49	0.11	0.19
TP	21_043 Lepsämänjoki 27,0 sensor	3519	0.83	101.62	122.10	-20.48	0.60
SS	21_043 Lepsämänjoki 27,0 sensor	3745	0.81	46.82	40.26	6.56	0.68
NO_3	21_045 Laurinoja 0,9	781	0.61	2.38	1.08	1.30	0.29
TP	21_045 Laurinoja 0,9	820	0.78	180.20	161.28	18.92	0.38
SS	21_045 Laurinoja 0,9	819	0.78	121.67	67.23	54.44	0.52

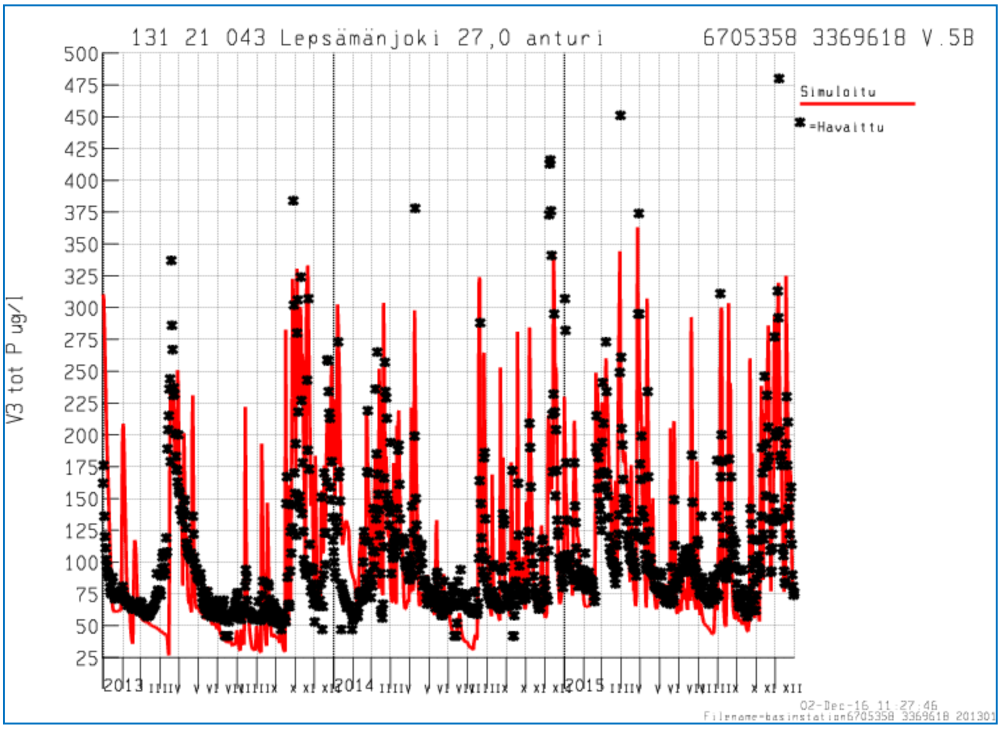


Figure 2.1. Simulated and observed TP concentrations for Lepsämänjoki (2013-2015).

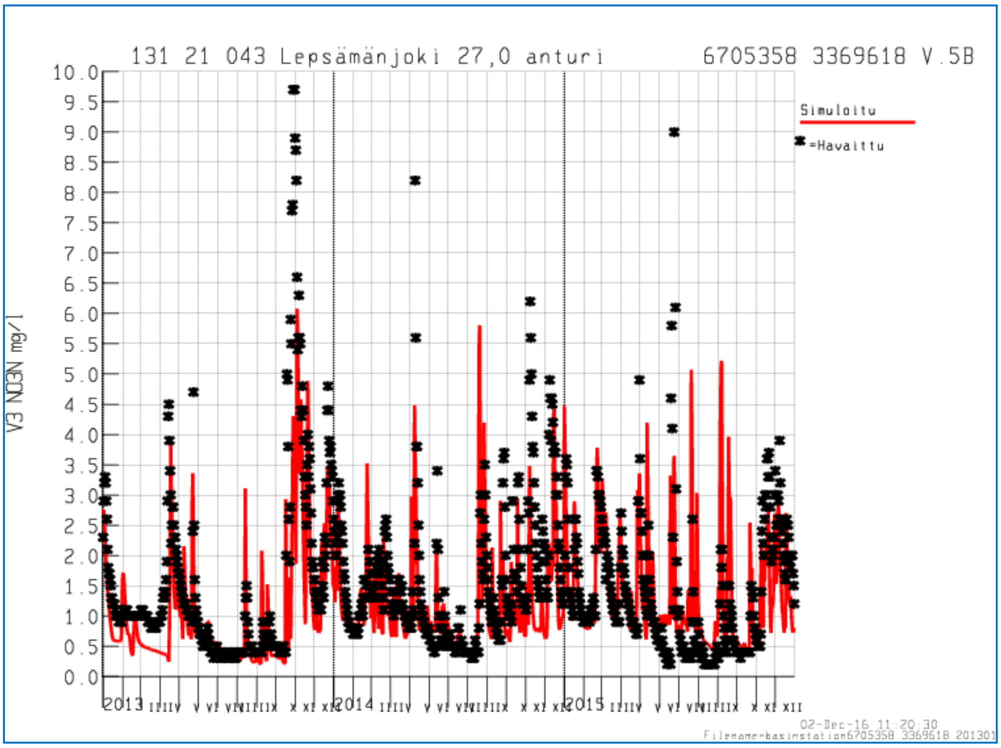


Figure 2.2. Simulated and observed NO_3 concentrations for Lepsämänjoki (2013-2015).

3. ICECREAM model validation against field experiment data

Summary

ICECREAM model was validated against some of the published field experiment P and N loading data. The description of the field experiment data is in the Table 3.1.

Main conclusions about the effect of reduced tillage on the TP loadings in test fields:

- In case of reduced tillage on flat fields TP loading is increasing, but on steep fields TP loading is decreasing.
- Observed TP loading is variating in the very wide range depending on soil, slope and P-test value (Table 3.2). Therefore, the question is how representative are few observations fields to draw conclusions about the effect of reduced tillage on TP loading.
- The effect of reduced tillage also changes from year to year depending on hydrological conditions.

Main conclusions about the effect of direct sowing on TP loading based on Aurajoki test field:

- Observed in Aurajoki field, clay soil, 8% slope, high P-test 24:
  - Surface runoff is increasing in case of direct sowing
  - Erosion is decreasing in case of direct sowing and subsequently also PP is decreasing
  - DRP (dissolved reactive phosphorus) is increasing quite much in the observed field
  - In general, there are very few field observations about direct sowing effect. Here we simulated only one observation field of direct sowing which is very special (high P content, high slope), therefore DRP loading increase is high
  - It cannot be generalized that increase is so high on all fields, the DRP increase in case of direct sowing depends on P content in the soil, soil texture, slope
  - More field measurements of the effect of direct sowing on different soil texture and slope fields are needed

Table 3.1. Field experiment data used for ICECREAM validation.

Field	**Sub-catchment number**	**Soil type**	**Slope %**	**P_{ac} mg/l**	**Period**	**Cultivation method**
Kotkanoja field	35.923	Clay (AS)	2	4	1991-2001	ploughing, reduced tillage
Aurajoki field	28.001	Clay (AS)	8	23.8 (1989)	1989-2002	ploughing, reduced tillage, crop covered, spring tillage only, direct sowing, grass ley
Kotkaniemi field	23.092	Clay loam (HeS)	3.7-5.7	6.5/10	1986-1995	ploughing, reduced tillage

Table 3.2. Observed TP loading in ploughed conditions in Aurajoki, Kotkanoja and Kotkaniemi fields.

Field	**Soil type**	**Slope %**	**P-test value**	**TP, g/ha/year**
Aurajoki	Clay	8	23.8	4290
Kotkanoja	Clay	2	4	953
Kotkaniemi	Loam	5	6.5…10	664

Table 3.3. Comparison of simulated and observed mean annual PP, DRP loading for three test fields for ploughed and reduced tillage conditions.

Field	Soil type	Slope %	P-test value	DRP g/ha/yr			PP g/ha/yr		
				DRP ploughed	DRP reduced tillage	Change %	PP ploughed	PP reduced tillage	Change %
Observed, Kotkanoja	AS	2	4	98	134	38	856	914	7
Simulated, Kotkanoja				263	272	3	1020	718	-30
Observed, Aurajoki	AS	8	23	580	730	26	3710	3420	-8
Simulated, Aurajoki				284	302	6	2785	1985	-29
Observed, Kotkaniemi	HeS	5	6.5…10	78	260	233	586	484	-17
Simulated, Kotkaniemi				251	262	4	902	620	-31

3.1. Kotkanoja field experiment data

Observed data for Kotkanoja field has been published by Uusitalo et al., 2007, and is shown in Figure 1 and 2. Main conclusions from observed data are:

1) DRP loading is slightly increasing in case of reduced tillage. If we exclude extreme year 1993/1994, then DRP loading is increasing by around 30% on average;
2) there is no clear trend in PP loading – on some years PP loading is increasing in reduced tillage case, on some years decreasing. PP loading is in average increasing in reduced tillage case by 7%.

Simulated PP loading 1.02 kg/ha/yr is quite close to observed 0.85 kg/ha/yr in case of ploughing. In case of reduced tillage, simulated PP loading is underestimated. Simulated DRP loading 0.26 kg/ha/yr is two times higher than observed, as well as DRP loading increase in the case of reduced tillage is very low (3%). The main cause of the differences between simulated and observed is low slope and low P-test value in Kotkanoja field.

Table 3.4. Comparison of simulated and observed mean annual DRP, PP loading for Kotkanoja field.

	DRP g/ha/yr			PP, g/ha/yr		
	Ploughed	Reduced tillage	Change %	Ploughed	Reduced tillage	Change %
Observed	98	134	38	856	914	7
Simulated	263	272	3	1020	718	-30

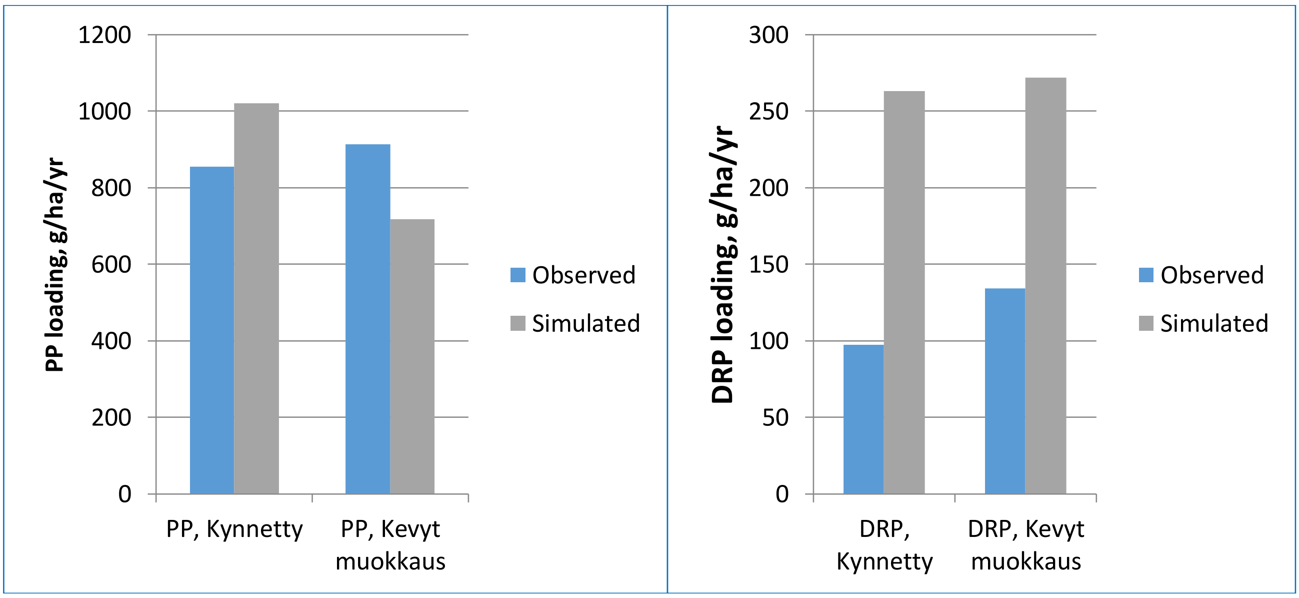


Figure 3.1. Mean annual simulated and observed PP (a) and DRP (b) loading for Kotkanoja field.

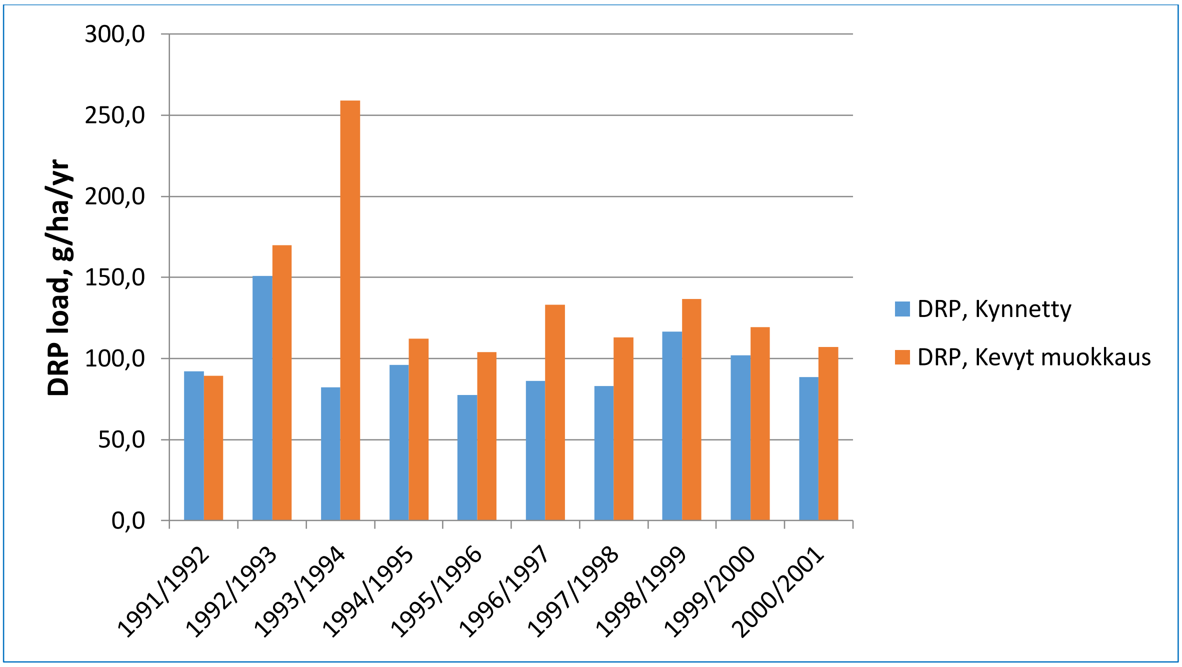


Figure 3.2. Observed DRP load for ploughed (kynnetty) and reduced tillage (kevyt muokkaus) in Kotkanoja field (Uusitalo et al., 2007).

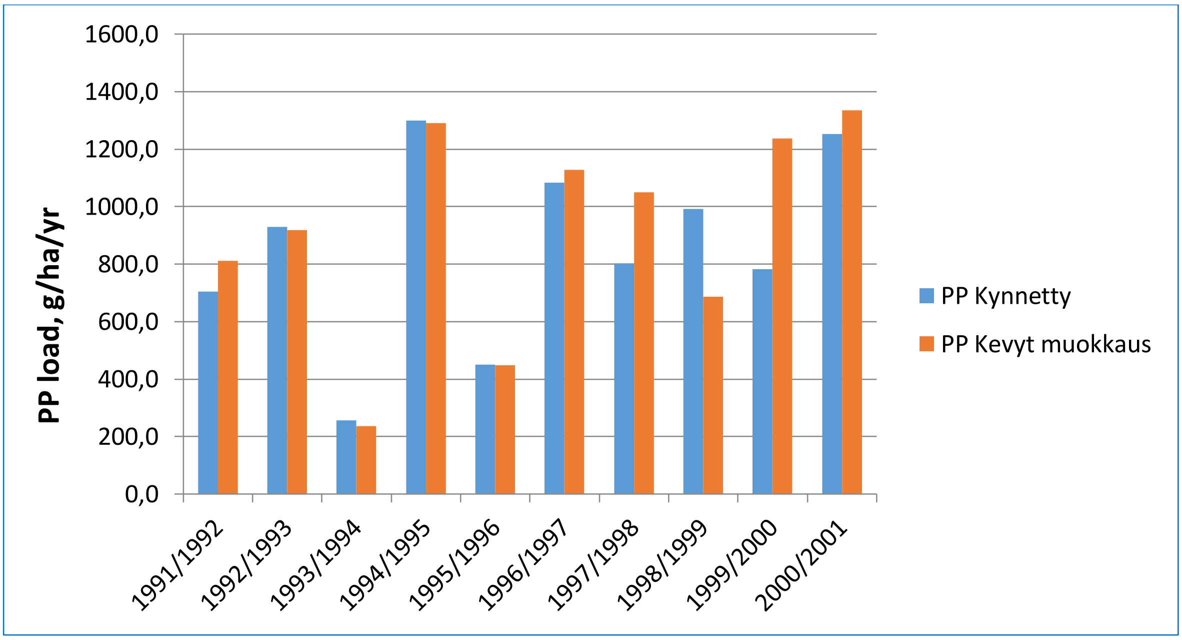


Figure 3.3. Observed PP load for ploughed (kynnetty) and reduced tillage (kevyt muokkaus) in Kotkanoja field (Uusitalo et al., 2007).

3.2. Aurajoki field experiment data

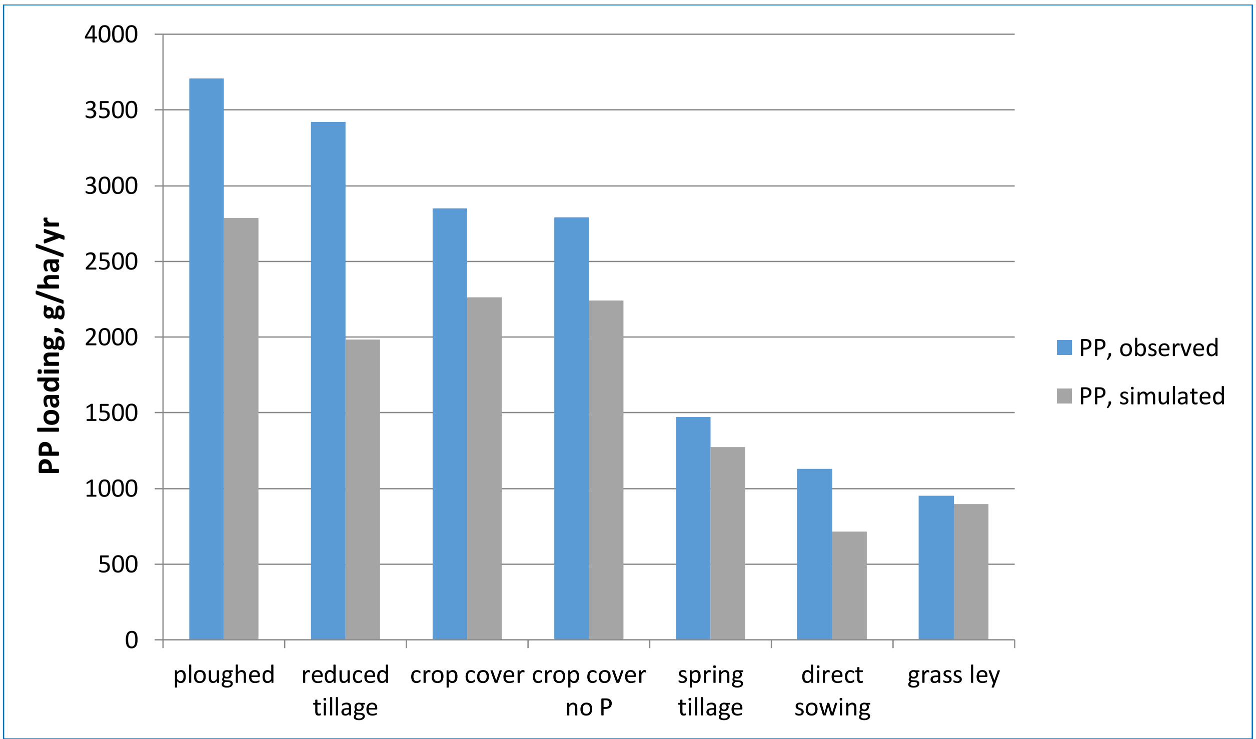
Observed data from Aurajoki field is published by Puustinen et al., 2005. Main conclusions from observed data are:

1. DRP and PP loadings are much higher than from Kotkanoja field due to the slope and higher P content in the soil,
2. PP loading is reducing if we compare ploughed and reduced tillage fields,
3. DRP loading is increasing in case of reduce tillage field, in case of direct sowing DRP loading is increasing considerably.

Simulated PP loading (2.78 g/ha/yr for ploughed) is about two times lower than observed loading (3.71 g/ha/yr), but the decrease of PP loading with different crop management practices is similar to the observed. Simulated DRP loading (0.28 g/ha/yr for ploughed) is about two times lower than observed loading (0.58 g/ha/yr). There is slight increase in simulated DRP in different crop management practices, but increase is too low to compare to observed increase. In case of direct sowing the observed DRP is increasing 130%, simulated DRP is increasing 70%. There is so high increase in DRP, because of high slope and high P content of the field.

Table 3.5. Comparison of simulated and observed DRP and PP annual loadings for Aurajoki test field (PLR=Plough layer runoff).

	PLR mm/yr	Erosion kg/ha/yr	DRP g/ha/yr		PP g/ha/yr	
			Observed	Simulated	Observed	Simulated
Ploughed	234	2100	580	284	3710	2785
Reduced tillage	218	1760	730	302	3420	1985
Crop cover	219	1570	540	312	2850	2262
Crop cover, no P	226	1540	530	305	2790	2241
Spring tillage	208	790	880	338	1470	1275
Direct sowing	233	620	2020	573	1130	715
Grass ley	209	570	910	433	950	898



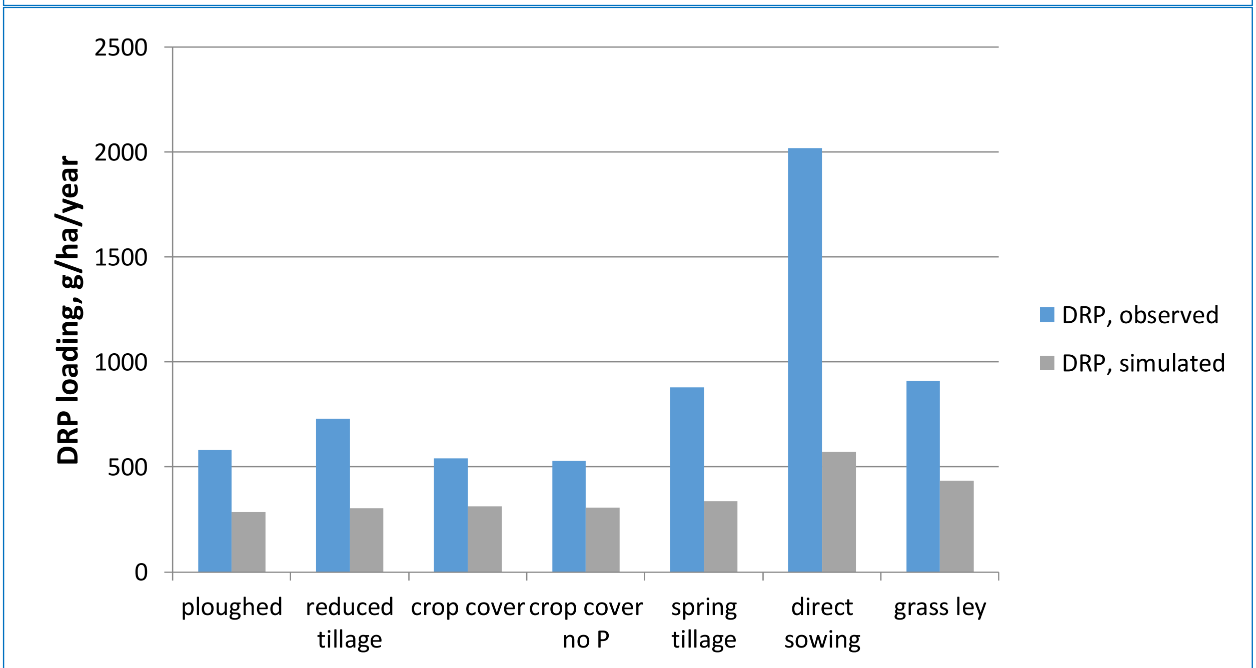


Figure 3.4. Mean annual simulated and observed PP (a) and DRP (b) loading for Aurajoki test field

3.3. Kotkaniemi field experiment data

Observed data from Kotkaniemi field is published by Koskiaho et al., 2002. Main conclusions from observed data are:

1. DRP loading is quite much increasing in case of reduced tillage from 0.08 g/ha/yr to 0.26 g/ha/yr,
2. PP loading is slightly decreasing in case of reduced tillage from 0.59 g/ha/yr to 0.48 g/ha/yr,
3. TP loading is slightly increasing in the case of reduced tillage from 0.66 g/ha/yr to 0.74 g/ha/yr.

Simulated DRP loading is the same in ploughed and reduced tillage, because surface runoff is the same in HeS (clay loam) soils. Simulated PP loading is decreasing in case of reduced tillage. The magnitude of simulated and observed PP loading is quite close to the observed. Simulated DRP loading is overestimated in case of ploughed conditions.

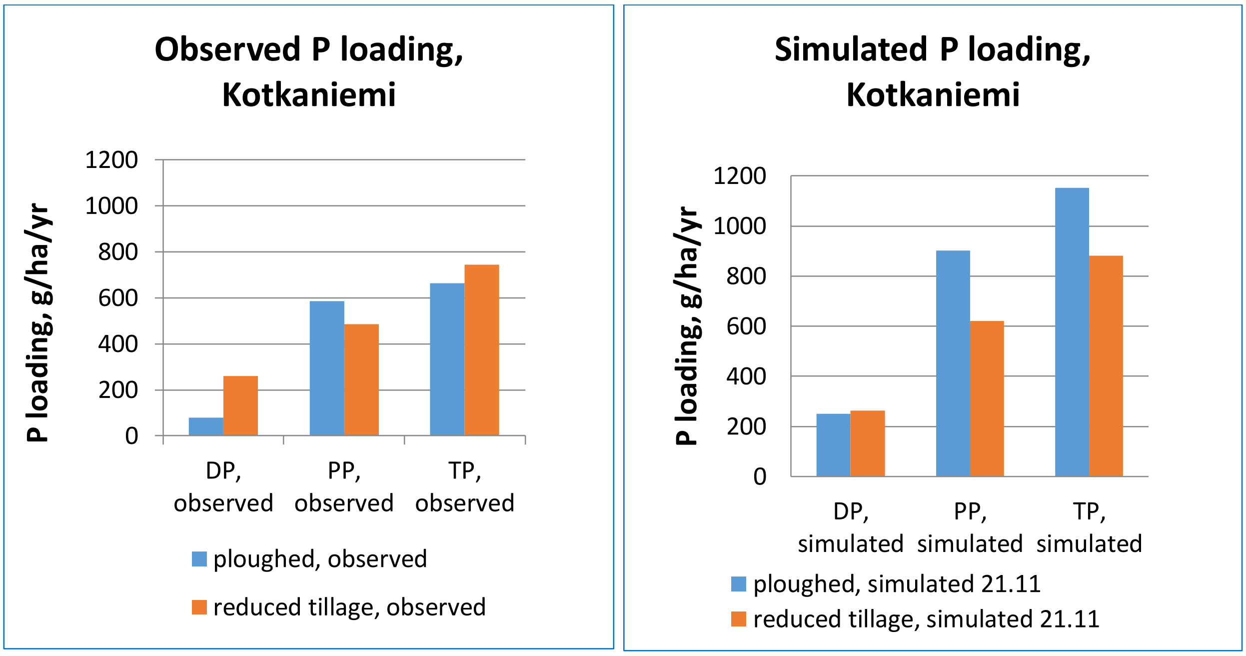


Figure 3.5. Mean annual observed (a) and simulated (b) PP,DRP,TP loadings for Kotkaniemi field.

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