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Pesticide leaching to the groundwater in drinking water abstraction areas

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Pesticide leaching to the groundwater in drinking water abstraction areas

Analysis with the GeoPEARL model

R. Kruijne
A. Tiktak
D. van Kraalingen
J.J.T.I. Boesten
A.M.A. van der Linden

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ABSTRACT

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In the new Dutch decision tree for the evaluation of pesticide leaching from soils, leaching to the shallow groundwater is assessed with the spatially distributed model GeoPEARL. The relative vulnerability of the groundwater in the drinking water abstraction areas is estimated. The general conclusion is that the groundwater within the drinking water abstraction areas as a whole is up to five times more vulnerable to pesticide leaching than the groundwater in Dutch agriculture. The higher vulnerability of the groundwater in the drinking water abstraction areas is primarily caused by lower soil organic matter contents.

Keywords: groundwater, drinking water, pesticide leaching, GeoPEARL, modelling

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Preface

In the new Dutch decision tree for the evaluation of pesticide leaching from soils, leaching to the shallow groundwater is assessed via a tiered approach. In the first tier, leaching is assessed via calculations for one of the FOCUS groundwater scenarios (Kremsmünster). The first part of the second tier is based on calculations with the spatially distributed model GeoPEARL, considering the area of use of a pesticide.

In the working group that prepared the tiered leaching approach, the question was raised whether the new procedure sufficiently protects the groundwater in drinking water abstraction areas. This study was initiated to answer this question.

Summary

In the new Dutch decision tree for the evaluation of pesticide leaching from soils, leaching to the shallow groundwater is assessed with the spatially distributed model GeoPEARL. The assessment is based on the area of use of a pesticide within Dutch agriculture. The question was raised whether an assessment for this area of use sufficiently protects the groundwater in drinking water abstraction areas. To answer this question, pesticide leaching was calculated for all crops considered in GeoPEARL. Two types of calculations were made: in the first, the area of use in Dutch agriculture was considered; in the second, the area of the same crop in drinking water abstraction areas was considered.

Six hypothetical substances were selected for this analysis, which represent a wide range of sorption constants to organic matter and degradation half-lives. Both spring and autumn applications were considered. Non-sorbing substances, substances with pH-dependent sorption behaviour, and substances with degradation depending on soil properties (e.g. clay content) were excluded from this analysis. The spatial 90th percentiles of the leaching concentration within drinking water abstraction areas as a whole and in Dutch agriculture were used to characterise the difference in vulnerability.

The spatial 90th percentile concentrations for drinking water abstraction areas are generally higher than those for Dutch agriculture. The general conclusion is that the groundwater within the drinking water abstraction areas as a whole is up to five times more vulnerable to pesticide leaching than the groundwater in Dutch agriculture.

Pesticide leaching towards the groundwater is most sensitive to soil organic matter. For all major crops except potatoes, the contribution to the crop area of soils with the lowest organic matter contents is larger within the drinking water abstraction areas than in Dutch agriculture.

There was no important difference between spring and autumn applied pesticides. The higher vulnerability of the groundwater in drinking water abstraction areas to the leaching of pesticides is primarily caused by lower soil organic matter contents in drinking water abstraction areas.

1 Introduction

In the new decision tree for the evaluation of pesticide leaching from soils (Van der Linden *et al.*, 2004), leaching to the shallow groundwater is assessed with the spatially distributed model GeoPEARL (Tiktak *et al.*, 2002; 2003). The model is used to calculate the median leaching concentration over a period of twenty years. The spatial 90^{th} percentile of the area of use is the criterion for further decision making. A substance is admitted if this value is less than 0.1 $\mu g\ L^{-1}$.

The assessments with GeoPEARL as part of the Dutch decision tree replace the current Dutch standard scenario, which is based on a single location with a model parameterisation representing an approximate 90% vulnerability condition to pesticide leaching (Van der Linden *et al.*, 2004).

The general aim of the Dutch pesticide registration procedure is to protect the groundwater as a source of drinking water. The question was raised whether a general criterion derived for the area of use in Dutch agriculture sufficiently protects the groundwater in drinking water abstraction areas. To answer this question, the leaching within drinking water abstraction areas was compared to the leaching in Dutch agriculture. Leaching was assessed with the GeoPEARL model. The aim of these assessments is to estimate the vulnerability of the groundwater in drinking water abstraction areas to pesticide leaching, relatively to the vulnerability of the groundwater in Dutch agriculture.

2 Procedure

The aim of the GeoPEARL assessments was to estimate the relative vulnerability of the groundwater in drinking water abstraction areas to pesticide leaching compared to Dutch agriculture. The procedure was to compare the spatial 90th percentile of the leaching concentration for the crop area within drinking water abstraction areas as a whole and for the crop area in Dutch agriculture.

The following steps were taken:

- Prepare a map of drinking water abstraction areas in the Netherlands;
- Derive agricultural land-use within these drinking water abstraction areas;
- Use GeoPEARL to calculate the spatial 90th percentile of leaching concentrations;
- Express the vulnerability of the groundwater in drinking water abstraction areas with the ratio *R*.

$$R = \frac{\text{spatial } 90^{th} \text{ percentile within drinking water abstraction areas}}{\text{spatial } 90^{th} \text{ percentile in Dutch agriculture}}$$

If *R* is greater than one, the groundwater in drinking water abstraction areas as a whole is more vulnerability to the leaching of pesticides than in Dutch agriculture.

2.1 Drinking water abstraction areas

The map with the drinking water abstraction areas used for this analysis is composed of different sources. For most drinking water production wells, the abstraction areas were obtained in separate studies with the saturated groundwater model LGM (Kovar *et al.*, 1992; 1998). The size and shape of these areas result from the calculated streamlines in the saturated groundwater. Within the boundaries of these areas, water percolating into the saturated zone will finally reach the drinking water production well, no matter how long the travel time may be.

In the coastal regions and in the most southern part of the Netherlands the streamlines around the drinking water production wells were not calculated yet. In these regions, drinking water production areas were selected instead of drinking water abstraction areas. The boundaries of these areas may result from calculated travel times of the saturated groundwater towards the well (e.g. 25 years), but the shape of these areas is also based on local topography. As a result of this, especially in the most southern part of the Netherlands these areas will not fully coincide with the true abstraction areas.

In this report, the term *drinking water abstraction areas* is used to refer to the entire area indicated in Figure 1.

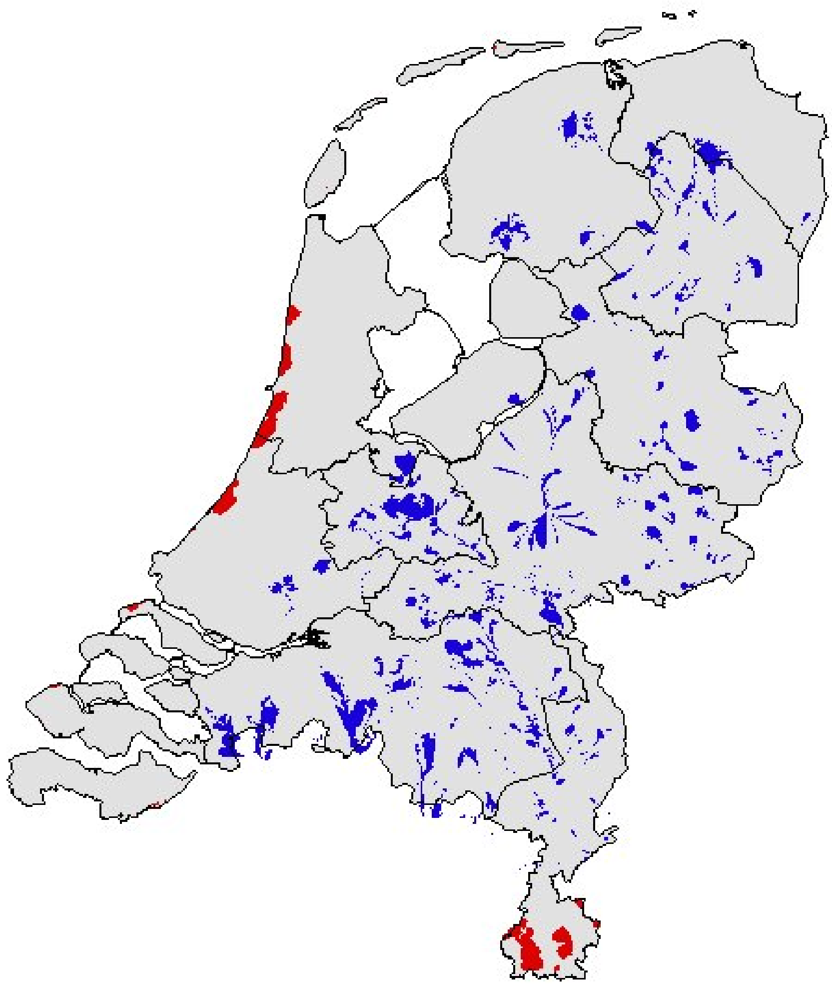

Figure 1. Map with the drinking water abstraction areas as used in this study. Areas in blue are abstraction areas obtained from model calculations, areas in red are drinking water production areas (Kovar et al., 1998)

2.2 Area of crops

The GeoPEARL database contains information about the area of the arable crops in Dutch agriculture. Maps with this area were derived from land-use data and crop statistics (Annex 1). The area of these crops within drinking water abstraction areas was derived in a similar way, using only the area covered by the cells of the map shown in Figure 1.

About 4% of the Dutch agricultural area is located within drinking water abstraction areas. For the individual crops in GeoPEARL, this fraction ranges between 0.6 and 9.7%. More details are presented in Annex 1, Table 1-4.

The crops grass, maize, cereals, potatoes and sugar beets together represent 90% of the agricultural area in the Netherlands. The distribution of agricultural area amongst these crops within drinking water abstraction areas and in Dutch agriculture is shown in Figure 2. This figure shows that the major crops within drinking water abstraction areas are the same, but the relative area of maize is larger.

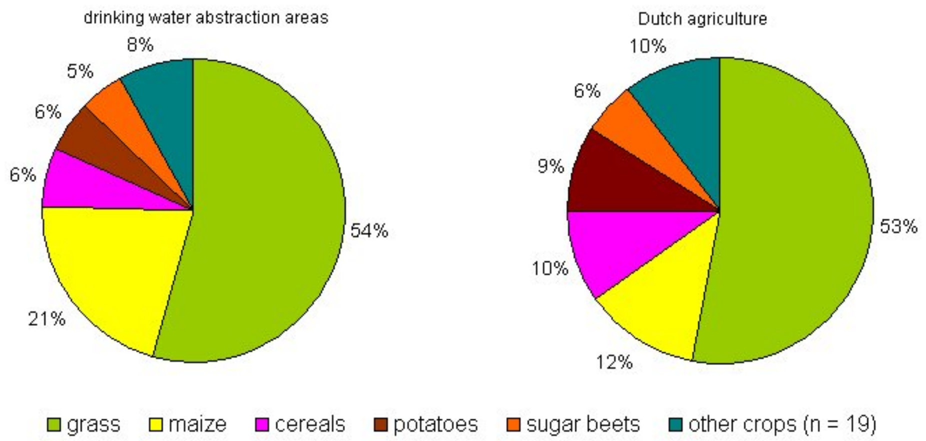

Figure 2. The relative area of the major crops within drinking water abstraction areas (left) and in Dutch agriculture (right).

2.3 Substance properties and application data

Six hypothetical substances were selected, which represent a wide range of sorption constants to organic matter and degradation half lives (Table 2).

Table 2: Sorption coefficient to organic matter and degradation half life for six hypothetical substances.

Substance no.	K_{om}	$DegT_{50}$
	$dm^3\ kg^{-1}$	d
1	10	10
2	70	40
3	25	50
4	50	50
5	75	50
6	200	120

Only non-volatile substances were selected. Their solubility in water equals 500 mg L^{-1}. Each substance was applied with an annual dosage of 1 kg ha^{-1} and the application interval was 1 year. Two different application dates were defined:

- Spring application on May 26;
- Autumn application on November 1.

Non-sorbing substances were excluded from this analysis. The same applies to substances with pH-dependent sorption behaviour, and to substances with degradation depending on soil properties (e.g. clay content).

2.4 The GeoPEARL model

GeoPEARL is based on the spatial schematisation and the hydrologic parameterisation of the nutrient fate model STONE (Kroes *et al.*, 2002; Wolf *et al.*, 2003). This schematisation contains 6405 different plots, and is combined with maps of 24 crops in Dutch agriculture. The leaching model PEARL is run for a period of 20 years, with the plots contributing to the area of use of a pesticide. The model is described in (Tiktak *et al.*, 2002; 2003). Details on the calculation of the area of the GeoPEARL crops are included in Annex 1 of this report.

Once the median leaching concentration over a period of 20 years is calculated for each hypothetical substance and all the plots of the STONE schematisation, the spatial 90th percentile can be calculated for any crop or combination of crops, using the relative contribution of each plot to the area of use. A prototype of the GeoPEARL model was used for this study.

3 Results

The spatial 90th percentiles of the leaching concentration within drinking water abstraction areas and in Dutch agriculture were expressed as ratios (see Chapter 2). Values higher than one indicate that the vulnerability of the groundwater to the leaching of that particular substance is higher within the drinking water abstraction areas as a whole than in Dutch agriculture; values less than one indicate a lower vulnerability of drinking water abstraction areas. For the five major crops indicated in Chapter 2.2, the ratios are shown in Figures 3 and 4.

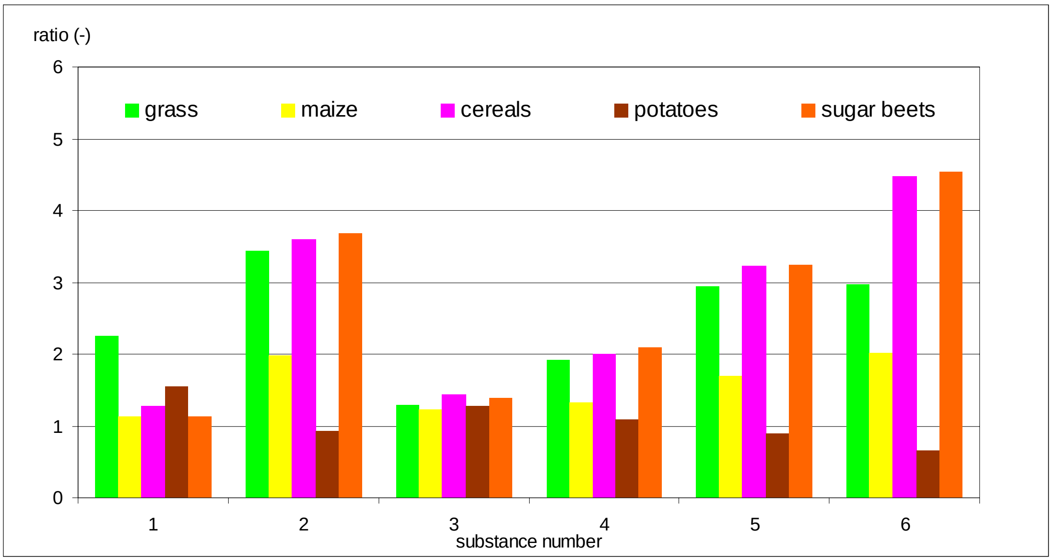

Figure 3. Ratios of the spatial 90th percentile within drinking water abstraction areas and in Dutch agriculture, for the leaching concentration of six substances and five crops. Spring application

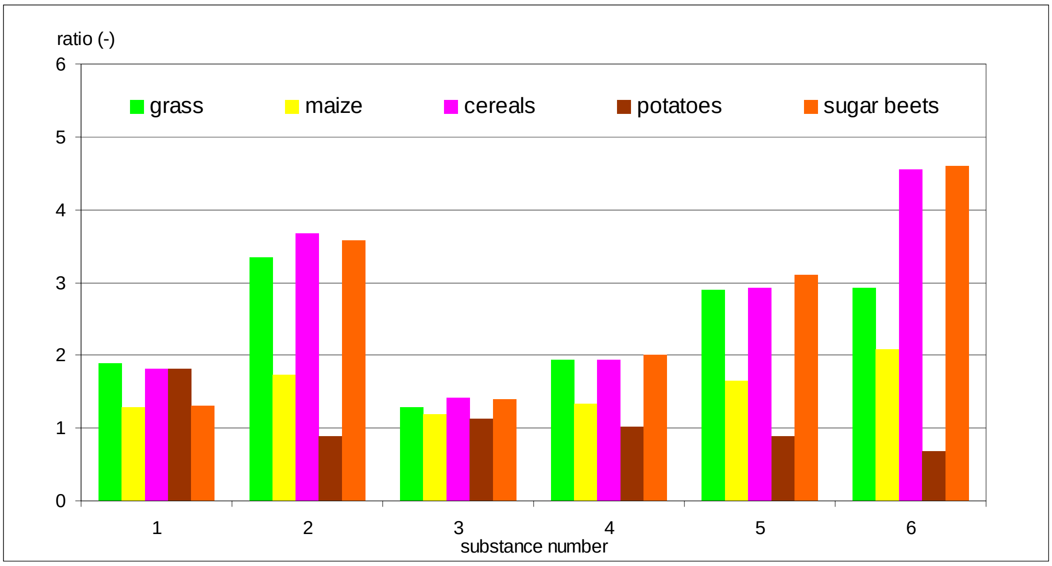

Figure 4. Ratios of the spatial 90th percentile within drinking water abstraction areas and in Dutch agriculture, for the leaching concentration of six substances and five crops. Autumn application

The results for the major crops and for all crops together are shown in Table 3 (spring application) and Table 4 (autumn application). The spatial 90th percentile concentrations of all crops and substances, and the corresponding ratios are included in Annex 2.

Table 3. Ratios of the spatial 90th percentile within drinking water abstraction areas and in Dutch agriculture. Spring application

Crop name	Substance number					
	1	2	3	4	5	6
Grass	2.3	3.4	1.3	1.9	2.9	3.0
Maize	1.1	2.0	1.2	1.3	1.7	2.0
Cereals	1.3	3.6	1.4	2.0	3.2	4.5
Potatoes	1.6	0.9	1.3	1.1	0.9	0.7
Sugar beets	1.1	3.7	1.4	2.1	3.2	4.5
All crops together (n = 24)	1.6	1.2	1.4	1.2	1.2	1.3

Table 4. Ratios of the spatial 90th percentile within drinking water abstraction areas and in Dutch agriculture. Autumn application

Crop name	Substance number					
	1	2	3	4	5	6
Grass	1.9	3.3	1.3	1.9	2.9	2.9
Maize	1.3	1.7	1.2	1.3	1.7	2.1
Cereals	1.8	3.7	1.4	1.9	2.9	4.6
Potatoes	1.8	0.9	1.1	1.0	0.9	0.7
Sugar beets	1.3	3.6	1.4	2.0	3.1	4.6
All crops together (n = 24)	1.5	1.2	1.2	1.2	1.2	1.4

All the ratios calculated for the crops grass, maize, cereals, and sugar beets are higher than one, indicating a higher vulnerability of the groundwater within the drinking water abstraction areas as a whole. The maximum values are obtained for cereals and sugar beets with substance number 6. Some of the ratios calculated for potatoes are less than one, indicating a lower vulnerability of the groundwater within the drinking water abstraction areas. For 11 crops, ratios less than one are calculated (see Annex 2). Except for potatoes, these are minor crops with an area within drinking water abstraction areas of less than 635 ha.

The ratios calculated for spring and autumn applications are more or less the same.

4 Discussion

An earlier sensitivity analysis with the precursor of GeoPEARL showed that pesticide leaching towards the groundwater is most sensitive to soil organic matter (Tiktak *et al.*, 1996). For this reason, the hypothesis was tested that lower soil organic matter contents cause higher leaching concentrations within the drinking water abstraction areas as a whole.

Figure 5 shows the frequency distributions of the average soil organic matter content (0-1 m below soil surface) within the area of the major crops and the area of all crops together. In the case of cereals and sugar beets, soils with low organic matter are more strongly represented within drinking water abstraction areas than in Dutch agriculture. These are also the crops with the highest ratios of the leaching concentration (see Tables 3 and 4). To a lesser extent, the same applies to grass and maize, and to the area of all crops together. The contributions of soils with very low organic matter content to the crop area can also be read from the spatial 10th percentile of organic matter content, as shown in Table 5.

Table 5. The spatial 10th percentile of soil organic matter (0-1 m below soil surface) within drinking water abstraction areas and in Dutch agriculture

Crop name	Drinking water abstraction areas	Dutch agriculture
Grass	0.017	0.020
Maize	0.017	0.018
Cereals	0.011	0.014
Potatoes	0.016	0.015
Sugar beets	0.011	0.014
All crops together (n = 24)	0.016	0.018

For potatoes, the differences in soil organic matter content are less clear. For this crop, ratios less than one were calculated for substances with higher sorption constants and ratios larger than one were calculated for substances with lower sorption constants. Some of the differences between the ratios calculated for the major crops can be explained by the spatial distribution of soils with low organic matter contents. For example, in the south-western part of the Netherlands clay soils with low organic matter contents predominate (Figure 6). So, relatively high leaching concentrations will be calculated in this region. Since there are no drinking water abstraction areas in this part of the Netherlands, these higher leaching concentrations contribute to the spatial 90th percentile for Dutch agriculture only. This leads to lower values of the ratio *R*, especially for crops with a large part of the area located in the south-western part of the Netherlands.

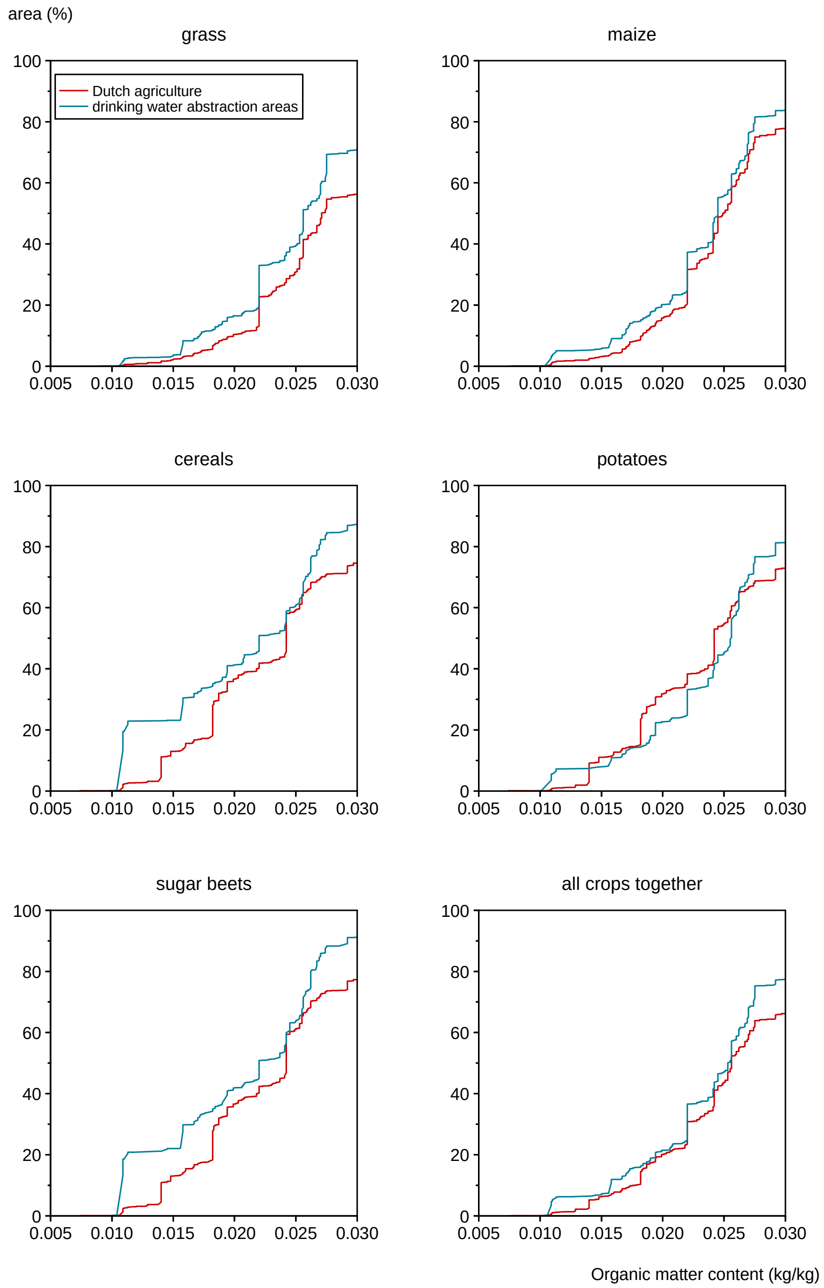

Figure 5. Frequency distribution of soil organic matter content for the area within drinking water abstraction areas and in Dutch agriculture (for the major crops and for all crops together)

Besides potatoes, ratios less than one are calculated for 10 minor crops. For these minor crops, the area within drinking water abstraction areas is below the limit of 2500 ha, reported as the smallest scale level for application of the hydrological schematisation (Kroes *et al.*, 2002). Hence, the spatial 90th percentile of the leaching concentrations calculated for these minor crops within drinking water abstraction areas are less accurate.

This analysis considers only the drinking water abstraction areas as a whole. The results cannot be safely extrapolated to the abstraction area of any individual drinking water production well. The GeoPEARL model cannot be used for individual abstraction areas because the database was not designed for this purpose. For individual abstraction areas, information at a more detailed level has to be collected.

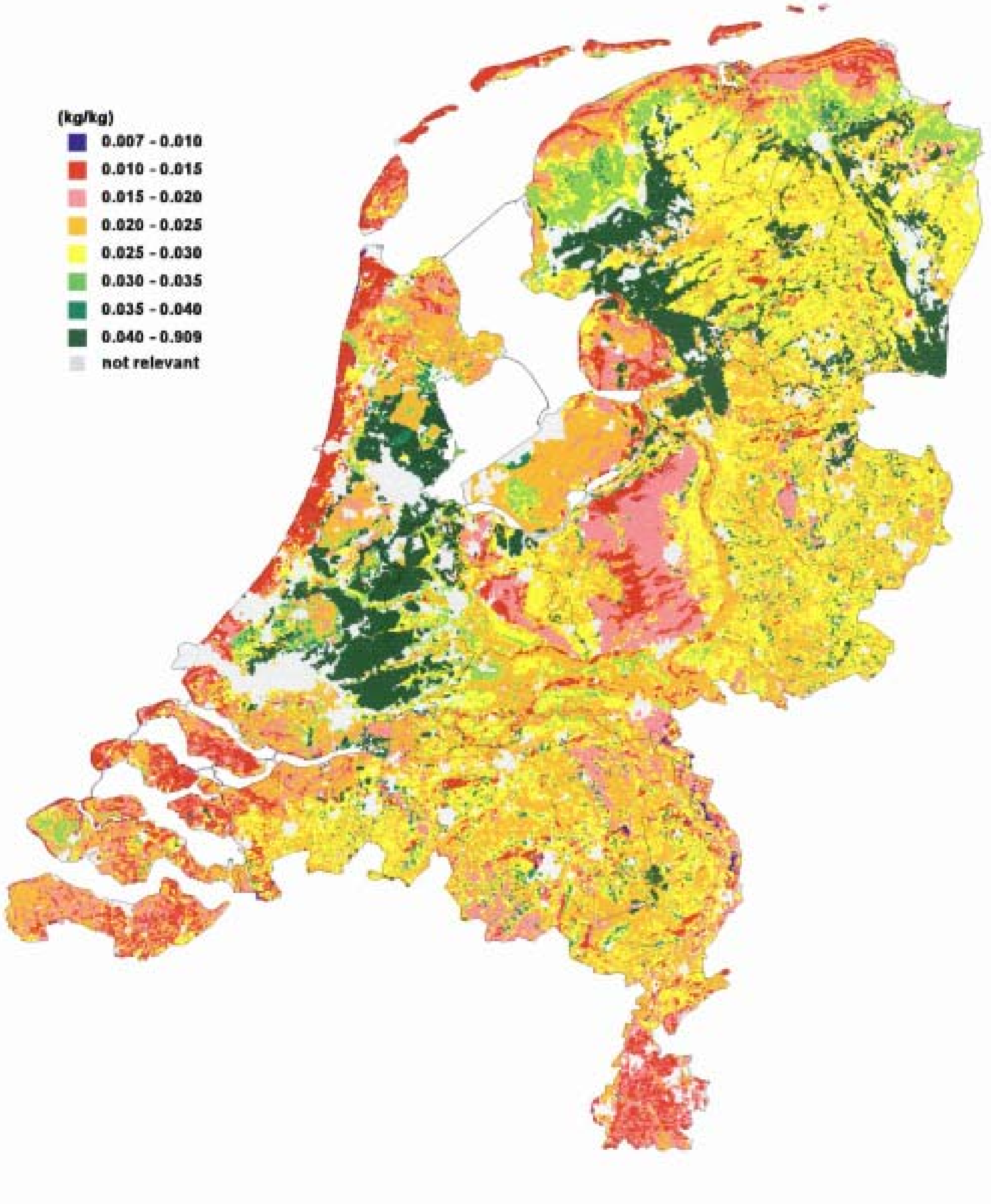

Figure 6. The average soil organic matter content in the upper metre of the soil (in kg/kg)

5 Conclusions

The 90th percentile concentrations for drinking water abstraction areas as a whole are generally higher than those for Dutch agriculture. The general conclusion is that the groundwater within the drinking water abstraction areas as a whole is up to five times more vulnerable to pesticide leaching than the groundwater in Dutch agriculture.

There was no important difference between spring and autumn applied pesticides. The higher vulnerability of the groundwater in drinking water abstraction areas to the leaching of pesticides is primarily caused by lower soil organic matter contents in drinking water abstraction areas.

For some of the crops, the vulnerability of the groundwater in drinking water areas as a whole is lower than for Dutch agriculture. This is particularly true in the case of potatoes. Part of the potatoes is grown in areas with light sandy clay soils with very low organic matter contents. These soils are situated in regions without drinking water abstraction areas.

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Appendix 1 The area of the GeoPEARL crops

This appendix describes how the maps were prepared with the area of the GeoPEARL crops.

1 Dutch agriculture

Geographical land-use data were obtained from a database on land-use based on satellite images of the years 1999 and 2000. The LGN4 (www.lgn.nl) describes land-use in the Netherlands at a resolution of 25 m by 25 m (a pixel). The map of LGN4 has 24 land-use classes, including nine agricultural land-use classes. The land-use data were combined with crop areas from the Agricultural Economics Research Institute (LEI-DLO, BedrijvenInformatieNet 1998). These crop areas were available for 540 out of 548 municipalities in the Netherlands. The crop definitions are based on a classification system of Statistics Netherlands (CBS, 1998).

The number of land-use classes in LGN4 was reduced by clustering the non-agricultural land-use into the land-use types *urban area, nature area,* and *open water area*. These land-use types were combined with the 9 agricultural classes of LGN4 (*pasture, maize, potatoes, sugarbeet, cereals, greenhouses, fruit orchards, flower bulbs,* and *other crops*). The land-use data were aggregated to gridcells of 250 m by 250 m, by calculating the distribution of the land-use classes from the 100 pixels within each gridcell. The national acreage of these land-use classes is shown in Table 1-1.

Table 1-1: The national acreage and number of crops related to each land-use class (based on LGN4)

Land-use class	Acreage (1000 ha)	Number of crops
Pasture	1251	3
Maize	259	3
Potatoes	179	5
Sugarbeet	114	2
Cereals	187	7
Greenhouses	14	37
Fruit orchards	28	5
Flower bulbs	23	8
Other crops	185	51
Urban areas (land-use type)	649	2
Nature areas (land-use type)	474	-
Open water areas (land-use type)	141	-
Total area	3505	123

The crops were related to the land-use classes using the classification system of Statistics Netherlands. Within each unit of the Municipality Map of the Netherlands (GEODAN, 1998), crop areas were spatially distributed among the gridcells using the area of the related land-use class expressed as a fraction of the total area of the land-use class in the municipality;

$$A_{X,GC} = A_{X,Y} \bullet A_{Z,GC} / A_{Z,Y}$$

with;

$A_{X,GC}$ area of crop X in a gridcell in municipality Y (ha)
$A_{X,Y}$ area of crop X in municipality Y (ha)
$A_{Z,GC}$ area of land-use class Z in a gridcell (ha)
$A_{Z,Y}$ total area of land-use class Z in municipality Y (ha);

Each GeoPEARL crop is defined as a group of similar crops of Statistics Netherlands. Because the area of crops is related to the location of farms in the database of Statistics Netherlands, differences will occur with the area of the corresponding land-use class. These differences decrease with larger scale levels (i.e. groups of adjacent municipalities). It can be seen in Table 1-2, that the combination of the crop statistics with land-use maps results in a slight decrease of the GeoPEARL crop area. The exception is flower bulbs; the area of this GeoPEARL crop decreases with 11% (the area difference in Table 1-2).

An overlay of the map of the crops and the map of the hydrological schematisation of the Netherlands resulted in the area with a STONE plot available for calculation of the leaching concentration. The coverage with STONE plots ranges between 89 and 96% of the crop area (Table 1-3).

Table 1-2: The area of 24 GeoPEARL crops, and the area all crops together (based on LGN4 and Statistics Netherlands, 1998)

GeoPEARL crop	number of crops (Statistics)	Area (Statistics) (ha)	Crop area (ha)	Area difference (%)	Number of cells	Average area per cell (ha)	Land-use type(s)
Potatoes	5	181302	177967	1.8	94742	1.88	Potatoes
Strawberries	1	1968	1955	0.6	79860	0.02	other crops
Asparagus	1	2304	2304	0.0	75850	0.03	other crops
Sugar beets	3	114598	113183	1.2	103109	1.10	sugar beet (99.6%), other crops (0.4%)
Leaf vegetables	3	5651	5650	0.0	84954	0.07	other crops
Plants for commercial purposes	4	5761	5750	0.2	62117	0.09	other crops
Floriculture	6	5213	5195	0.4	108489	0.05	other crops (92.1%), greenhouses (7.9%)
Flower bulbs	8	21355	19077	10.7	11561	1.65	flower bulbs
Tree nurseries	7	10375	10246	1.2	108808	0.09	other crops (96.9%), greenhouses (3.1%)
Fallow	1	12371	12372	0.0	366061	0.03	Grass
Fruit culture	7	22431	22405	0.1	77571	0.29	fruit orchards (99.5%), other crops (0.5%)
Cereals	7	191872	187982	2.0	96140	1.96	Cereals
Grass	2	1031770	1029794	0.2	380226	2.71	Grass
Grass-seed	1	28418	28389	0.1	98168	0.29	other crops
Green manuring	2	8603	8590	0.2	101047	0.09	other crops
Vegetables	9	20871	20802	0.3	106050	0.20	other crops (99.2%), greenhouses (0.8%)
Cannabis	1	1083	1083	0.0	17411	0.06	other crops
Silviculture	1	2698	2691	0.2	84489	0.03	other crops
Cabbage	5	10582	10525	0.5	97267	0.11	other crops
Maize	3	239399	238304	0.5	146927	1.62	Maize
Remaining arable crops	1	8451	8434	0.2	98440	0.09	other crops
Legumes	6	14243	14133	0.8	97439	0.15	other crops
Leek	1	3641	3641	0.0	77331	0.05	other crops
Onions	3	18349	18326	0.1	80821	0.23	other crops
All crops together	88	1963307	1923356	2.0	449892	4.28	-

Table 1-3: The area with a STONE plot, available for calculation of the spatial distribution of the leaching concentration (24 GeoPEARL crops, and all crops together).

GeoPEARL crop	Area with a STONE plot (ha)	coverage of the crop area (%)	number of STONE plots	average plot area (ha)
Grass	967759	94	6392	151
Maize	228971	96	6097	38
Cereals	179708	95	5285	34
Potatoes	171193	96	5372	32
Sugar beets	108912	96	5305	21
Grass-seed	26921	95	5405	5
Fruit culture	20819	92	4775	4
Vegetables	19758	95	5498	4
Flower bulbs	18096	95	1450	12
Onions	17378	95	4635	4
Legumes	13335	94	5211	3
Fallow	11174	89	6384	2
Cabbage	9849	93	5061	2
Tree nurseries	9648	94	5640	2
Green manuring	8132	94	5389	2
Remaining arable crops	8000	95	5358	1
Plants for commercial purposes	5428	94	3532	2
Leaf vegetables	5318	94	4731	1
Floriculture	4822	92	5617	1
Leek	3437	94	4815	1
Silviculture	2560	95	5266	0.5
Asparagus	2182	94	4391	1
Strawberries	1839	94	4983	0.4
Cannabis	1032	95	1302	1
All crops together	1846097	96	6394	289

2 Drinking water abstraction areas

Similar to the procedure for the crops in Dutch agriculture as a whole, land-use data and crop statistics were used to calculate the area of the GeoPEARL crops within the drinking water abstraction areas. Next, the area with a STONE plot available for calculation of the leaching concentration was obtained from an overlay of the map of the crops and the map of the hydrological schematisation of the Netherlands. The results are shown in Table 1-4.

Table 1-4: The area available for calculation of the spatial distribution of the leaching concentration within drinking water abstraction areas

GeoPEARL crop	Area with a STONE plot (ha)	number of STONE plots	average plot area (ha)	fraction of the crop area in Dutch agriculture (%)
Grass	41313	2532	16.3	4.0
Maize	16031	1834	8.7	6.7
Cereals	4872	921	5.3	2.6
Potatoes	4367	931	4.7	2.4
Sugar beets	3609	887	4.1	3.2
Fruit culture	1473	944	1.6	6.6
Tree nurseries	671	1134	0.6	6.5
Vegetables	635	1035	0.6	3.1
Legumes	546	959	0.6	3.9
Grass-seed	434	997	0.4	1.5
Fallow	388	2504	0.2	3.1
Remaining agricultural crops	233	984	0.2	2.8
Leek	208	953	0.2	5.7
Strawberries	189	950	0.2	9.7
Leaf vegetables	185	917	0.2	3.3
Floriculture	183	1101	0.2	3.5
Green-manuring	181	1010	0.2	2.1
Asparagus	158	799	0.2	6.9
flower bulbs	149	86	1.7	0.8
Onions	138	621	0.2	0.8
Cabbage	118	904	0.1	1.1
Silviculture	86	945	0.1	3.2
Cannabis	48	96	0.5	4.1
Plants for commercial purposes	32	297	0.1	0.6
All crops together	76106	2621	29.0	3.9

Appendix 2 Results

Tables with spatial 90th percentile concentrations and ratios *R* for the area of the crops in GeoPEARL and 6 hypothetical substances;

2-1 drinking water abstraction areas, spring application
2-2 Dutch agriculture as a whole, spring application
2-3 the ratios *R* for spring application
2-4 drinking water abstraction areas, autumn application
2-5 Dutch agriculture as a whole, autumn application
2-6 the ratios *R* for autumn application

$$R = \frac{\text{spatial } 90^{th} \text{ percentile within drinking water abstraction areas}}{\text{spatial } 90^{th} \text{ percentile in Dutch agriculture}}$$

Table 2-1: Spatial 90th percentile of the leaching concentration within drinking water abstraction areas (µg L⁻¹). Spring application.

Crop	substance number					
	1	2	3	4	5	6
Potatoes	0.044	0.056	10.18	1.36	0.175	0.089
Strawberries	0.045	0.216	11.14	2.61	0.530	0.422
Asparagus	0.034	0.030	7.59	0.88	0.098	0.044
Sugar beets	0.033	0.307	11.62	3.19	0.759	0.664
Leaf vegetables	0.064	0.180	11.14	2.47	0.472	0.283
Plants for commercial purposes	0.038	0.017	7.54	0.65	0.071	0.036
Floriculture	0.086	0.261	12.56	3.05	0.692	0.414
flower bulbs	0.592	0.851	29.12	7.52	1.840	1.107
Tree nurseries	0.044	0.061	10.05	1.41	0.184	0.101
Fallow	0.055	0.049	10.11	1.35	0.161	0.089
Fruit culture	0.033	0.308	11.62	3.19	0.770	0.669
Cereals	0.036	0.301	11.62	3.19	0.760	0.664
Grass	0.048	0.042	7.95	1.08	0.138	0.065
Grass-seed	0.044	0.048	8.71	1.20	0.153	0.082
Green-manuring	0.044	0.043	8.70	1.24	0.139	0.059
Vegetables	0.038	0.081	11.00	1.58	0.226	0.124
Cannabis	0.013	0.007	4.51	0.38	0.029	0.012
Silviculture	0.050	0.017	7.74	0.72	0.065	0.029
Cabbage	0.033	0.276	11.60	3.11	0.724	0.632
Maize	0.038	0.054	9.29	1.25	0.166	0.089
Remaining agricultural crops	0.062	0.061	9.58	1.35	0.181	0.090
Legumes	0.064	0.066	10.31	1.46	0.199	0.107
Leek	0.044	0.053	8.71	1.37	0.173	0.076
Onions	0.034	0.048	9.94	1.39	0.153	0.084
All crops together	0.044	0.048	10.06	1.27	0.157	0.089

Table 2-2: Spatial 90th percentile of the leaching concentration in Dutch agriculture as a whole (µg L^{-1}). Spring application

Crop	substance number					
	1	2	3	4	5	6
Potatoes	0.029	0.060	7.98	1.25	0.197	0.137
Strawberries	0.030	0.059	8.21	1.29	0.184	0.101
Asparagus	0.040	0.046	8.40	1.18	0.150	0.076
Sugar beets	0.029	0.083	8.35	1.52	0.234	0.146
Leaf vegetables	0.019	0.060	7.25	1.23	0.196	0.137
Plants for commercial purposes	0.015	0.059	7.20	1.21	0.193	0.133
Floriculture	0.078	0.152	11.27	2.26	0.429	0.278
Flower bulbs	0.096	0.387	14.07	3.82	0.956	0.629
Tree nurseries	0.028	0.038	7.43	1.01	0.129	0.065
Fallow	0.026	0.045	7.23	1.08	0.144	0.083
Fruit culture	0.022	0.061	7.81	1.29	0.197	0.138
Cereals	0.028	0.084	8.04	1.60	0.235	0.148
Grass	0.021	0.012	6.15	0.56	0.047	0.022
Grass-seed	0.026	0.064	7.98	1.31	0.208	0.138
Green-manuring	0.024	0.060	7.29	1.23	0.194	0.133
Vegetables	0.030	0.108	8.54	1.73	0.315	0.234
Cannabis	0.034	0.013	6.13	0.63	0.051	0.020
Silviculture	0.031	0.029	6.74	0.87	0.102	0.050
Cabbage	0.023	0.091	8.35	1.65	0.275	0.190
Maize	0.033	0.027	7.56	0.94	0.098	0.044
Remaining agricultural crops	0.028	0.060	8.01	1.29	0.197	0.138
Legumes	0.025	0.056	7.48	1.22	0.184	0.114
Leek	0.036	0.048	8.35	1.18	0.152	0.078
Onions	0.020	0.062	7.49	1.27	0.200	0.138
All crops together	0.027	0.039	7.25	1.06	0.132	0.071

Table 2-3: Ratio of the spatial 90th percentile of the leaching concentration within drinking water abstraction areas and in Dutch agriculture as a whole. Spring application

Crop	Substance number					
	1	2	3	4	5	6
Grass	2.3	3.4	1.3	1.9	2.9	3.0
Maize	1.1	2.0	1.2	1.3	1.7	2.0
Cereals	1.3	3.6	1.4	2.0	3.2	4.5
Potatoes	1.6	0.9	1.3	1.1	0.9	0.7
Sugar beets	1.1	3.7	1.4	2.1	3.2	4.5
Fruit culture	1.5	5.1	1.5	2.5	3.9	4.9
Tree nurseries	1.6	1.6	1.4	1.4	1.4	1.6
Vegetables	1.3	0.8	1.3	0.9	0.7	0.5
Legumes	2.6	1.2	1.4	1.2	1.1	0.9
Grass-seed	1.7	0.8	1.1	0.9	0.7	0.6
Fallow	2.1	1.1	1.4	1.2	1.1	1.1
Remaining agricultural crops	2.2	1.0	1.2	1.1	0.9	0.7
Leek	1.2	1.1	1.0	1.2	1.1	1.0
Strawberries	1.5	3.7	1.4	2.0	2.9	4.2
Leaf vegetables	3.3	3.0	1.5	2.0	2.4	2.1
Floriculture	1.1	1.7	1.1	1.3	1.6	1.5
Green-manuring	1.9	0.7	1.2	1.0	0.7	0.4
Asparagus	0.9	0.6	0.9	0.7	0.7	0.6
Flower bulbs	6.2	2.2	2.1	2.0	1.9	1.8
Onions	1.7	0.8	1.3	1.1	0.8	0.6
Cabbage	1.4	3.0	1.4	1.9	2.6	3.3
Silviculture	1.6	0.6	1.1	0.8	0.6	0.6
Cannabis	0.4	0.5	0.7	0.6	0.6	0.6
Plants for commercial purposes	2.5	0.3	1.0	0.5	0.4	0.3
All crops together	1.6	1.2	1.4	1.2	1.2	1.3

Table 2-4: Spatial 90th percentile of the leaching concentration within drinking water abstraction areas (µg L^{-1}). Autumn application

Crop	substance number					
	1	2	3	4	5	6
Potatoes	2.66	0.137	18.4	2.48	0.346	0.122
Strawberries	2.29	0.485	23.3	5.18	1.010	0.478
Asparagus	1.99	0.071	14.1	1.68	0.189	0.059
Sugar beets	2.04	0.659	23.8	5.58	1.337	0.866
Leaf vegetables	3.17	0.405	23.0	4.17	0.886	0.356
Plants for commercial purposes	2.22	0.046	14.2	1.22	0.138	0.046
Floriculture	5.12	0.486	23.9	5.28	1.112	0.462
Flower bulbs	11.46	1.091	38.8	8.97	2.246	1.188
Tree nurseries	2.64	0.149	18.7	2.68	0.349	0.129
Fallow	2.13	0.117	18.1	2.30	0.300	0.122
Fruit culture	2.03	0.679	23.8	5.72	1.337	0.879
Cereals	2.64	0.678	23.8	5.63	1.337	0.868
Grass	2.02	0.098	14.2	1.93	0.262	0.084
Grass-seed	2.96	0.111	15.8	1.98	0.290	0.113
Green-manuring	2.64	0.101	17.0	2.04	0.264	0.074
Vegetables	2.72	0.174	20.4	2.97	0.415	0.153
Cannabis	1.05	0.017	8.8	0.67	0.056	0.015
Silviculture	2.09	0.046	14.1	1.45	0.137	0.040
Cabbage	2.04	0.624	23.0	5.37	1.281	0.821
Maize	2.91	0.124	17.2	2.24	0.315	0.121
Remaining agricultural crops	3.03	0.137	18.1	2.57	0.347	0.122
Legumes	3.95	0.168	18.6	2.73	0.390	0.137
Leek	3.03	0.123	17.5	2.23	0.315	0.100
Onions	2.05	0.116	18.1	1.93	0.296	0.114
All crops together	2.20	0.117	17.4	2.24	0.301	0.121

Table 2-5: Spatial 90th percentile of the leaching concentration in Dutch agriculture as a whole (μgL⁻¹). Autumn application

Crop	substance number					
	1	2	3	4	5	6
Potatoes	1.46	0.154	16.3	2.41	0.387	0.180
Strawberries	2.02	0.133	17.3	2.38	0.345	0.129
Asparagus	2.72	0.110	17.0	2.23	0.292	0.099
Sugar beets	1.56	0.184	17.0	2.79	0.431	0.188
Leaf vegetables	1.12	0.153	16.0	2.41	0.387	0.180
Plants for commercial purposes	1.01	0.151	16.0	2.39	0.380	0.177
Floriculture	4.40	0.326	22.1	3.85	0.742	0.349
Flower bulbs	6.46	0.859	30.4	7.50	1.700	0.756
Tree nurseries	1.92	0.095	15.0	1.86	0.247	0.086
Fallow	1.24	0.106	14.9	1.97	0.281	0.111
Fruit culture	1.21	0.155	16.1	2.45	0.389	0.181
Cereals	1.46	0.185	16.8	2.90	0.456	0.190
Grass	1.07	0.029	11.0	0.99	0.091	0.029
Grass-seed	1.28	0.160	16.8	2.44	0.402	0.182
Green-manuring	1.24	0.151	16.0	2.40	0.371	0.174
Vegetables	1.52	0.256	17.9	3.32	0.610	0.297
Cannabis	1.37	0.030	11.5	1.08	0.092	0.026
Silviculture	1.46	0.071	13.3	1.52	0.195	0.064
Cabbage	1.17	0.221	17.5	3.07	0.515	0.237
Maize	2.25	0.072	14.5	1.68	0.190	0.058
Remaining agricultural crops	1.52	0.154	16.7	2.42	0.389	0.180
Legumes	1.46	0.142	16.0	2.32	0.357	0.146
Leek	2.52	0.121	16.9	2.28	0.319	0.102
Onions	1.06	0.155	16.5	2.42	0.390	0.182
All crops together	1.42	0.098	14.7	1.93	0.259	0.089

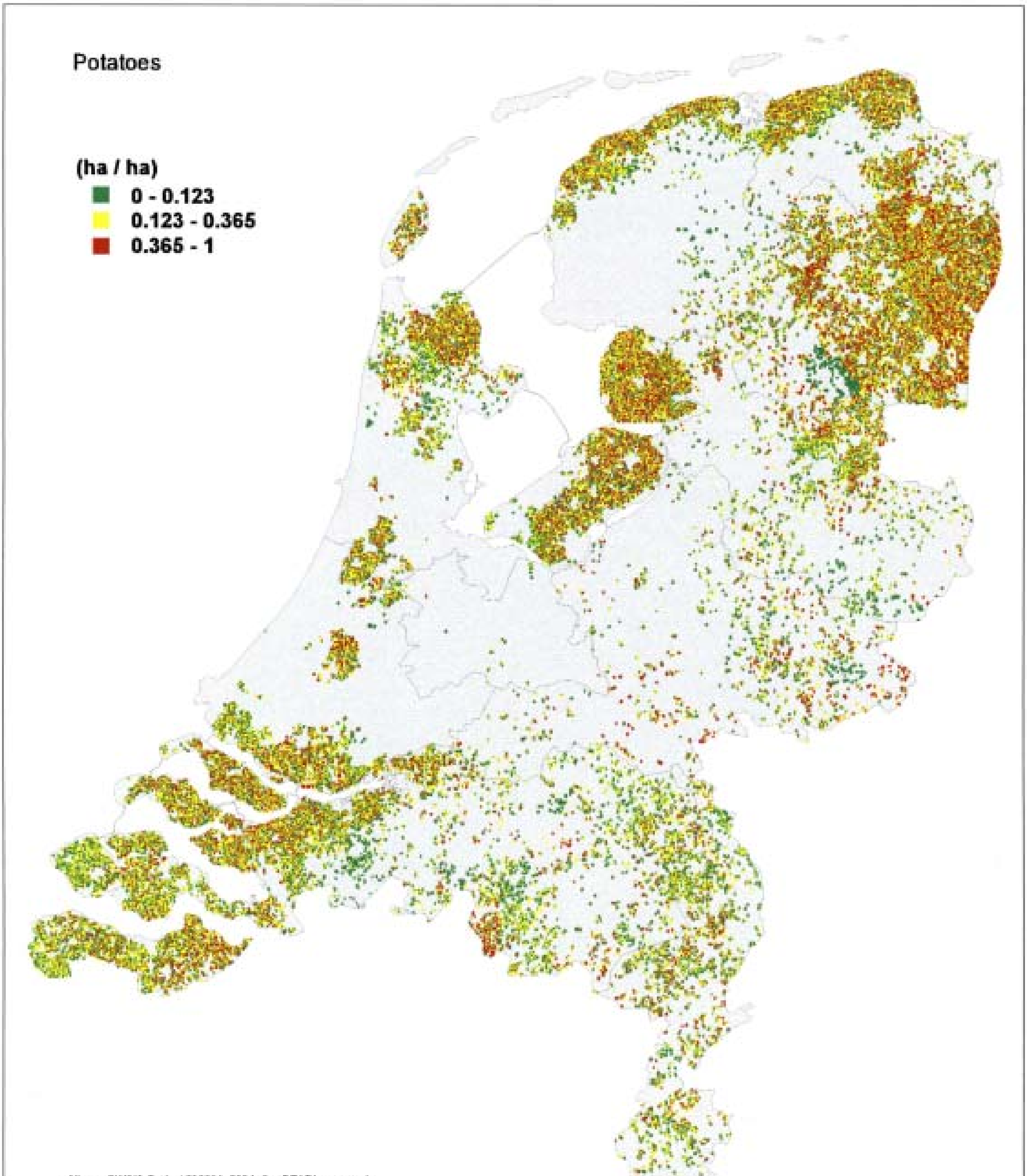
Table 2-6: Ratio of the spatial 90th percentile of the leaching concentration within drinking water abstraction areas and in Dutch agriculture as a whole. Autumn application

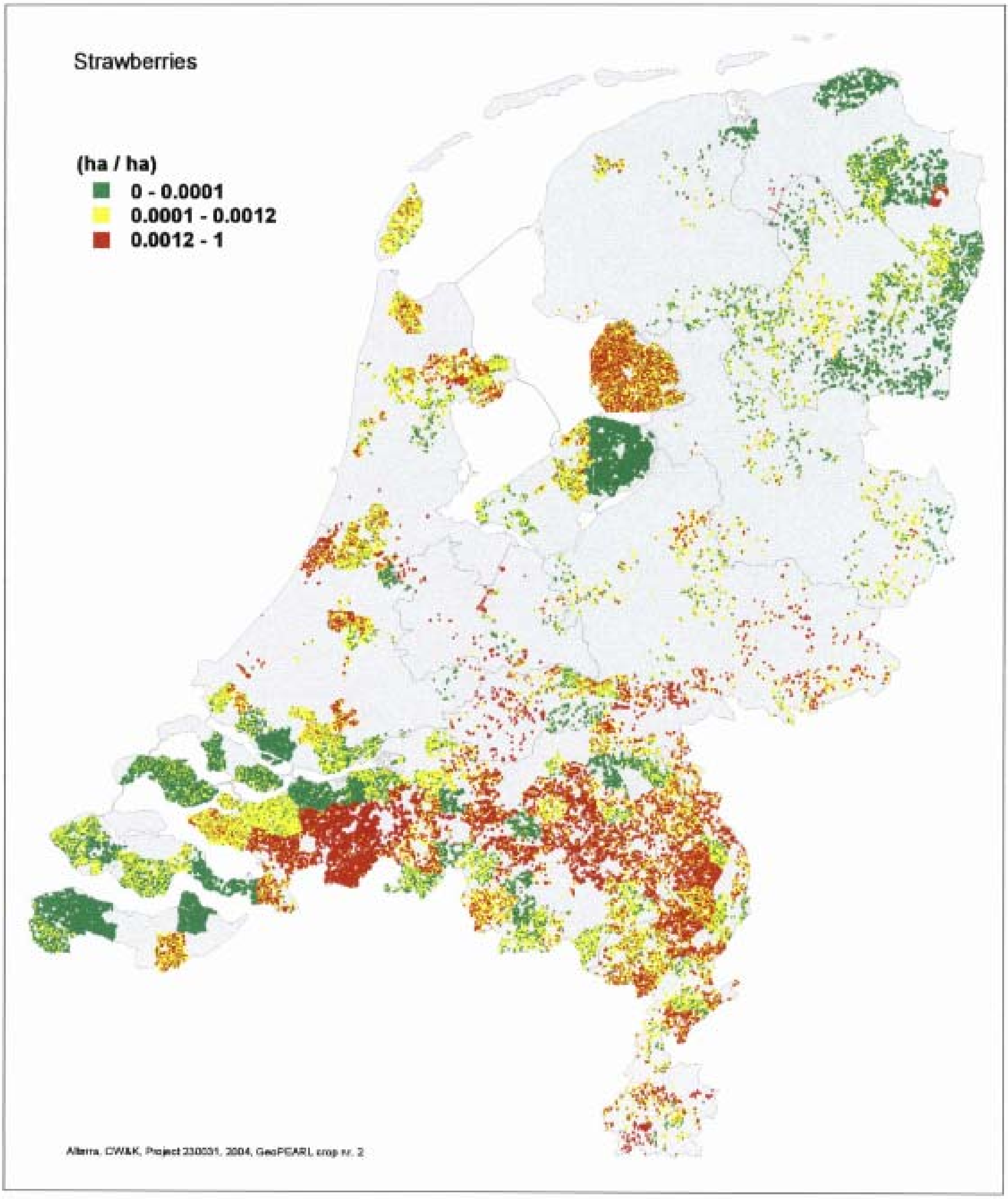
Crop	Substance number					
	1	2	3	4	5	6
Grass	1.9	3.3	1.3	1.9	2.9	2.9
Maize	1.3	1.7	1.2	1.3	1.7	2.1
Cereals	1.8	3.7	1.4	1.9	2.9	4.6
Potatoes	1.8	0.9	1.1	1.0	0.9	0.7
Sugar beets	1.3	3.6	1.4	2.0	3.1	4.6
Fruit culture	1.7	4.4	1.5	2.3	3.4	4.9
Tree nurseries	1.4	1.6	1.3	1.4	1.4	1.5
Vegetables	1.8	0.7	1.1	0.9	0.7	0.5
Legumes	2.7	1.2	1.2	1.2	1.1	0.9
Grass-seed	2.3	0.7	0.9	0.8	0.7	0.6
Fallow	1.7	1.1	1.2	1.2	1.1	1.1
Remaining agricultural crops	2.0	0.9	1.1	1.1	0.9	0.7
Leek	1.2	1.0	1.0	1.0	1.0	1.0
Strawberries	1.1	3.6	1.3	2.2	2.9	3.7
Leaf vegetables	2.8	2.6	1.4	1.7	2.3	2.0
Floriculture	1.2	1.5	1.1	1.4	1.5	1.3
Green-manuring	2.1	0.7	1.1	0.8	0.7	0.4
Asparagus	0.7	0.6	0.8	0.8	0.6	0.6
Flower bulbs	1.8	1.3	1.3	1.2	1.3	1.6
Onions	1.9	0.7	1.1	0.8	0.8	0.6
Cabbage	1.7	2.8	1.3	1.8	2.5	3.5
Silviculture	1.4	0.7	1.1	1.0	0.7	0.6
Cannabis	0.8	0.6	0.8	0.6	0.6	0.6
Plants for commercial purposes	2.2	0.3	0.9	0.5	0.4	0.3
All crops together	1.5	1.2	1.2	1.2	1.2	1.4

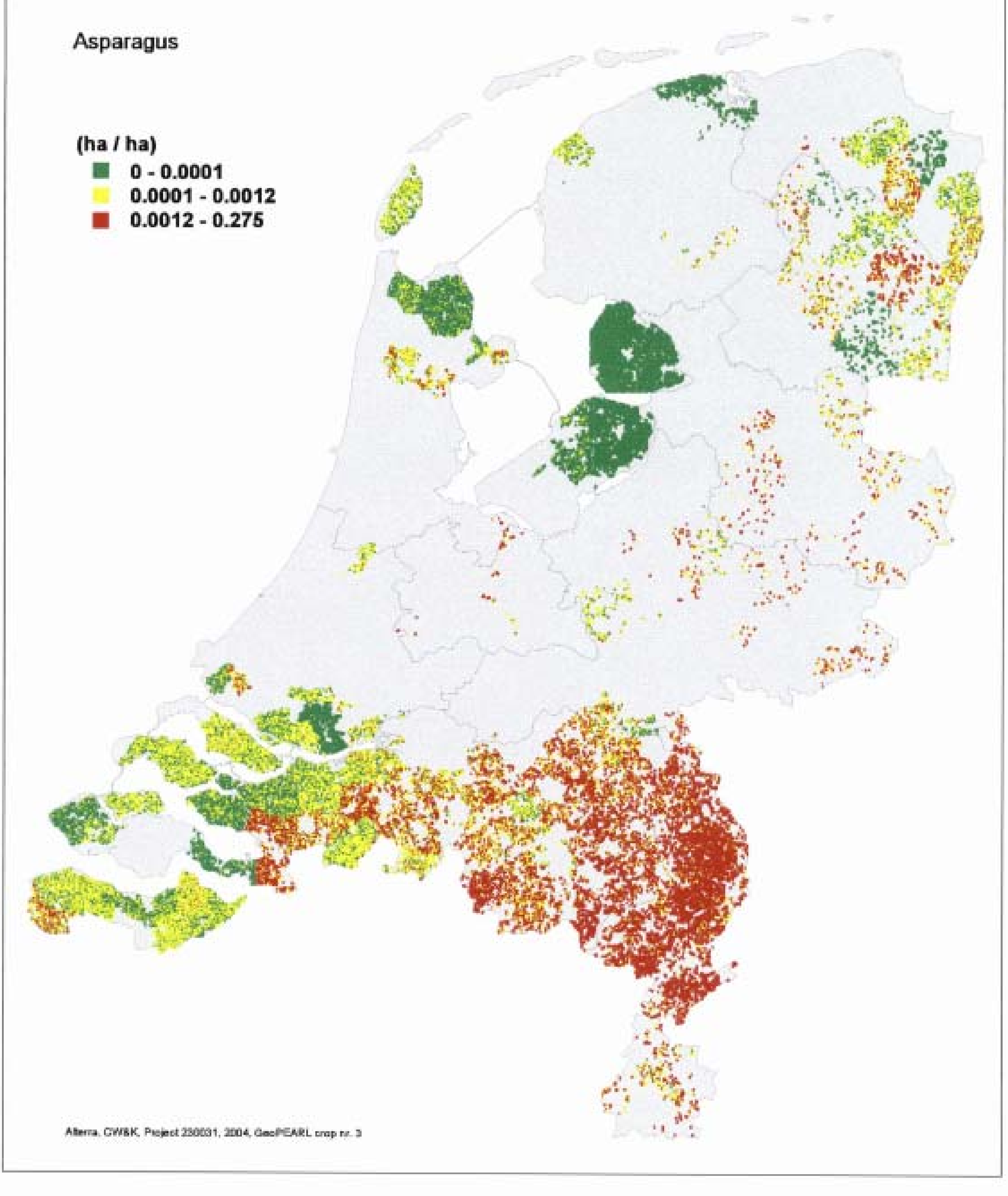
Appendix 3 Maps of the GeoPEARL crops

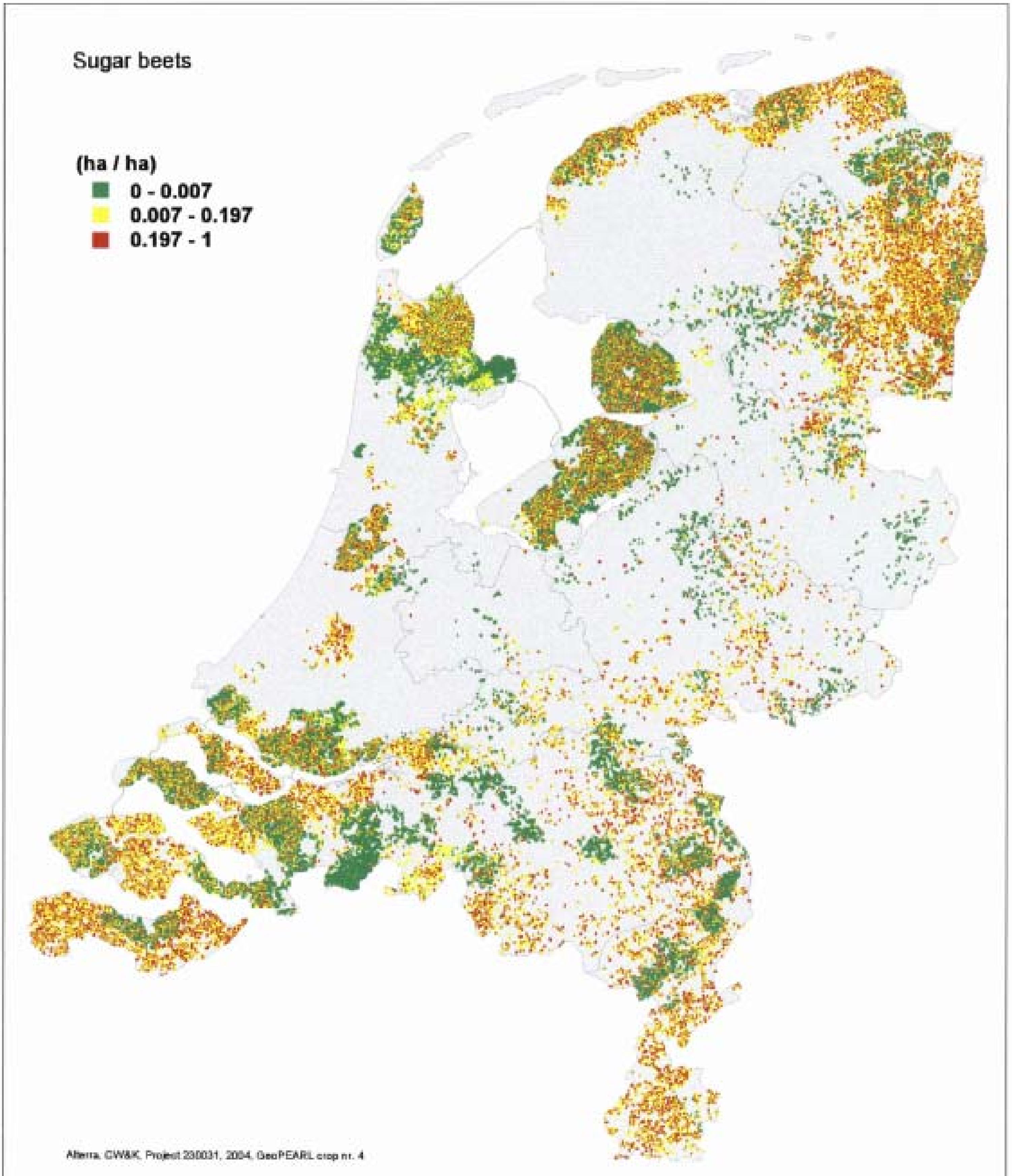
For each map in this appendix, the legend class boundaries were calculated by distributing the crop area among four classes with equal number of grid cells.

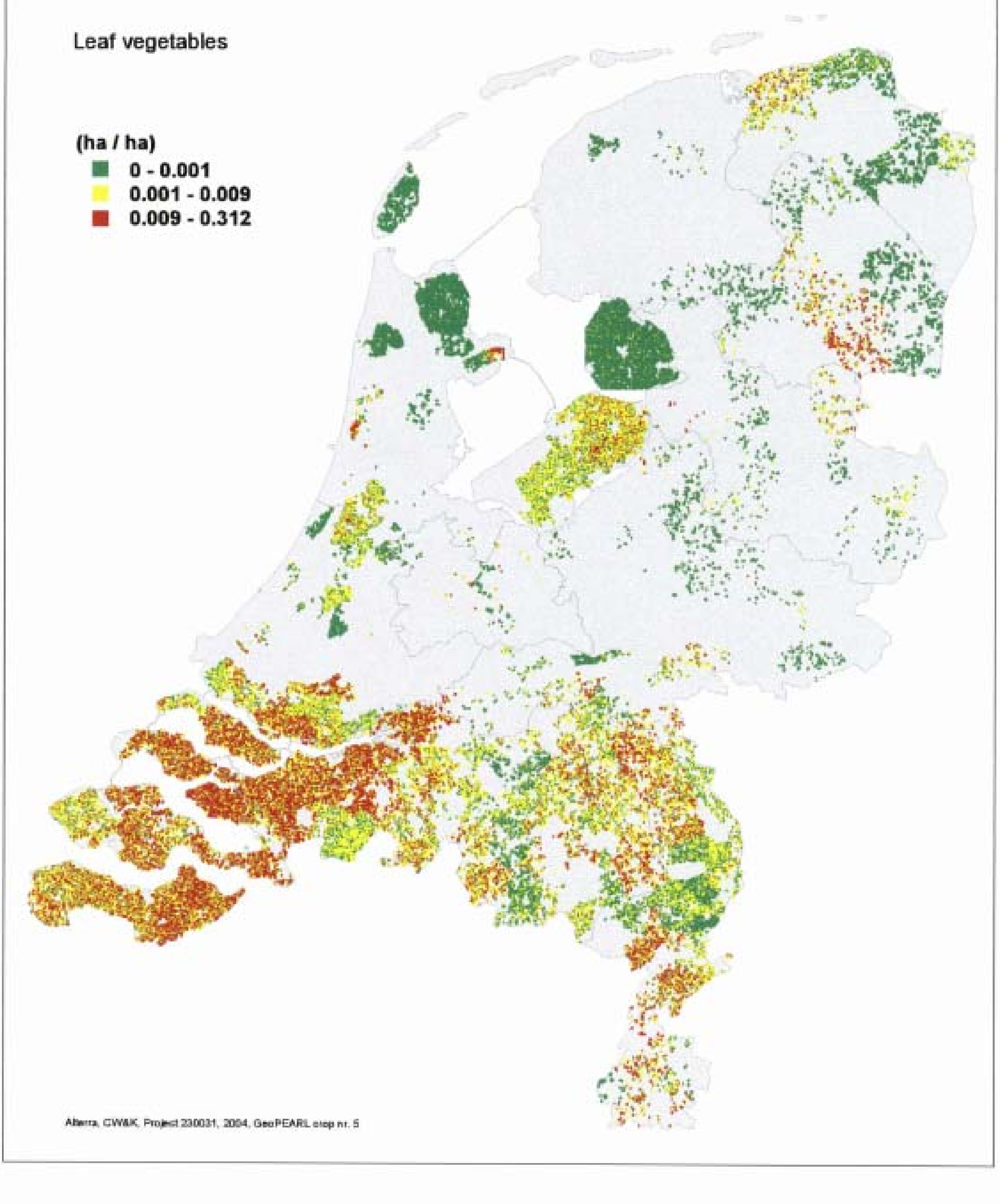
Map No.	Crop name
1	Potatoes
2	Strawberries
3	Asparagus
4	Sugar beets
5	Leaf vegetables
6	Plants for commercial purposes
7	Floriculture
8	flower bulbs
9	Tree nurseries
10	Fallow
11	Fruit culture
12	Cereals
13	Grass
14	Grass seed
15	Green manuring
16	Vegetables
17	Cannabis
18	Silviculture
19	Cabbage
20	Maize
21	Remaining arable crops
22	Legumes
23	Leek
24	Onions
25	All crops together

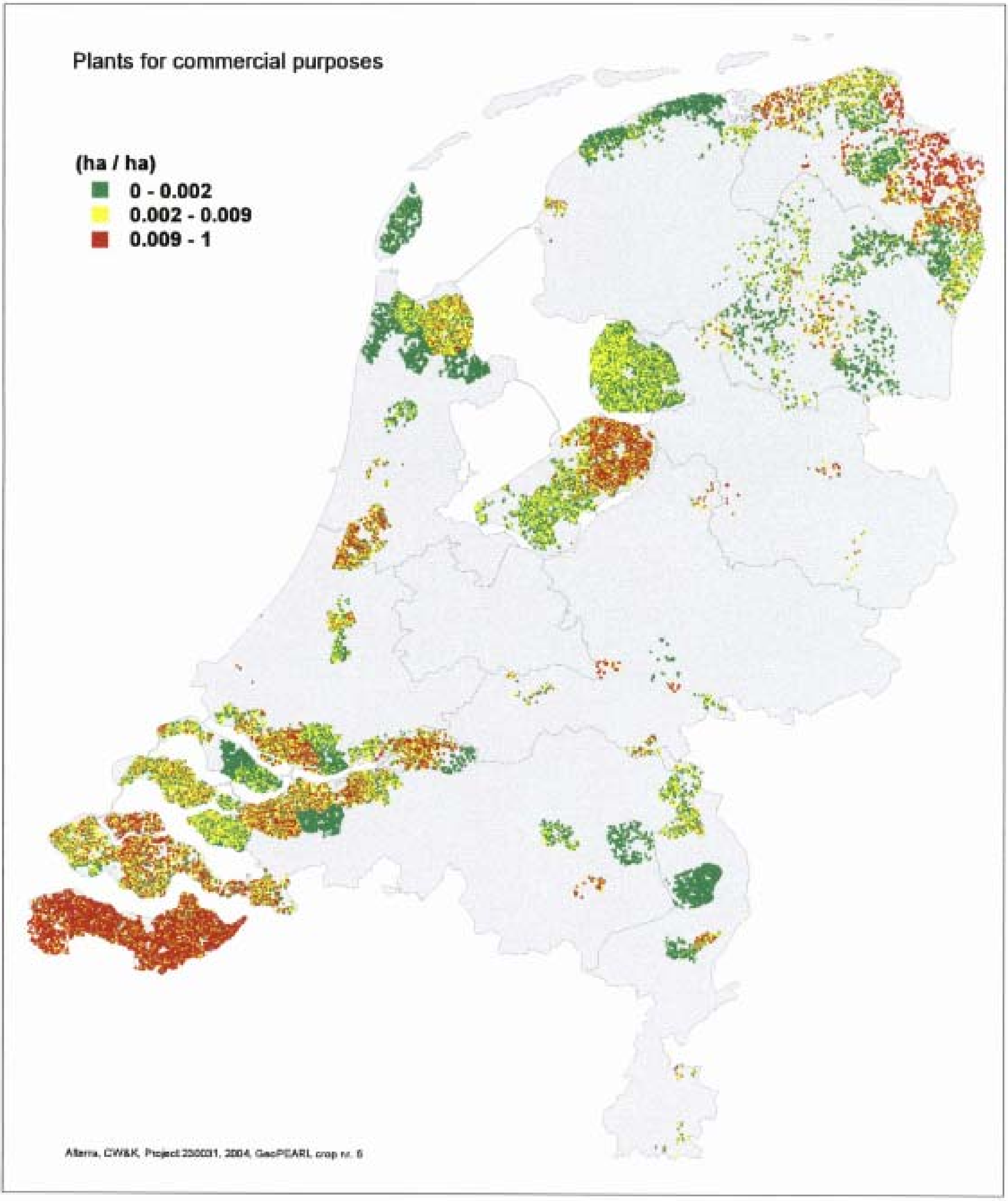

Potatoes
(ha / ha)
0 - 0.123
0.123 - 0.365
0.365 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 1

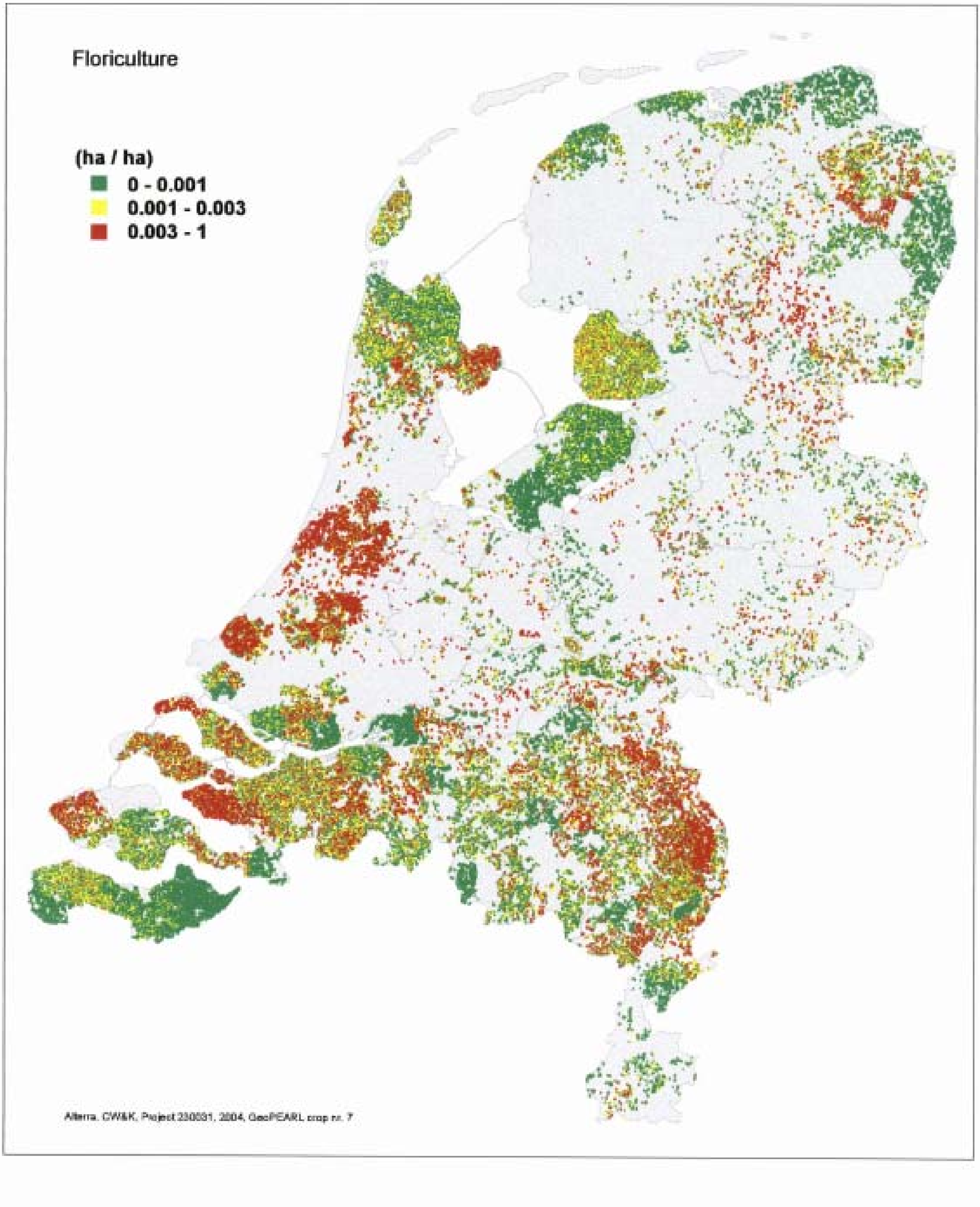

Strawberries
(ha / ha)
0 - 0.0001
0.0001 - 0.0012
0.0012 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 2

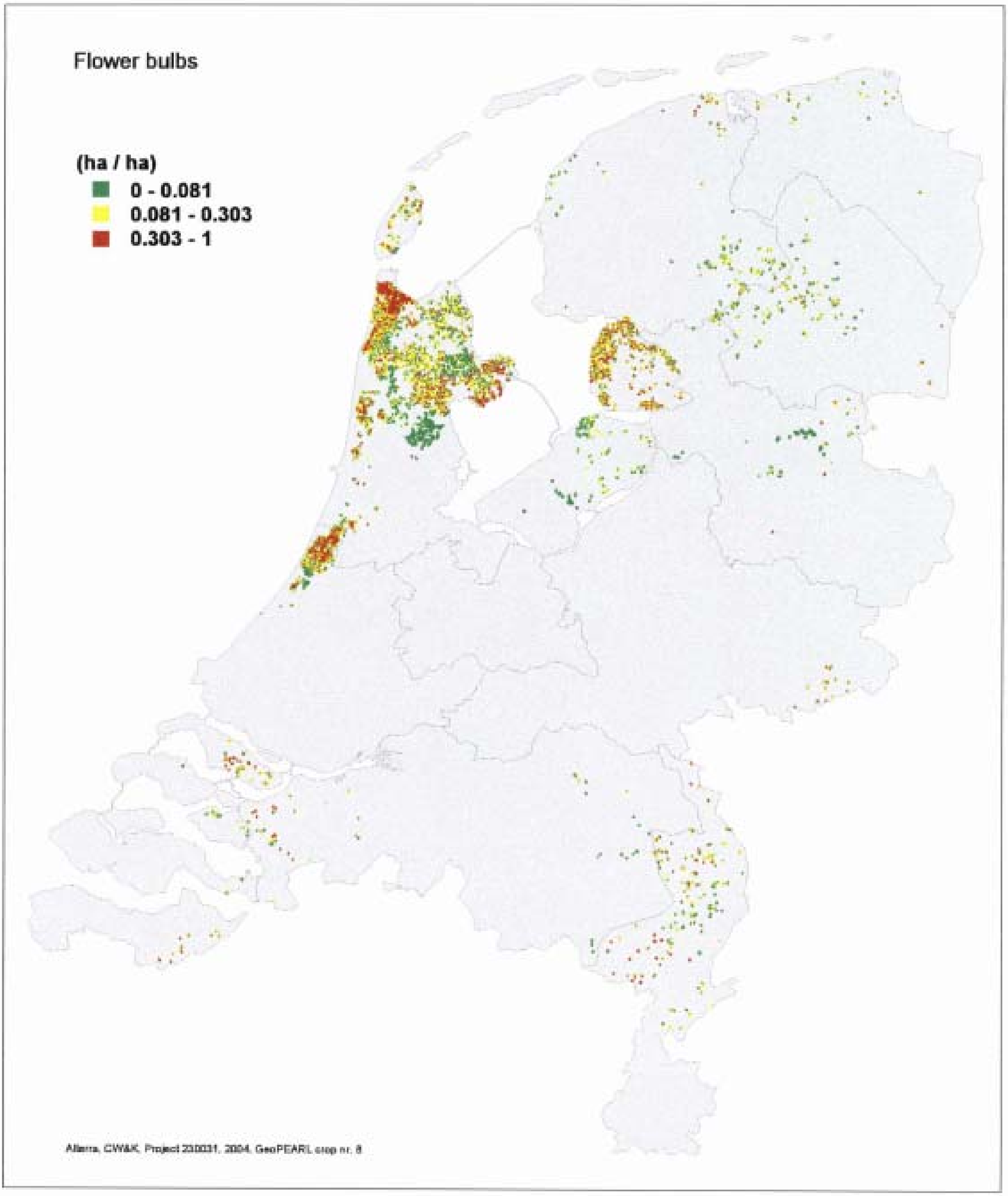

Asparagus
(ha / ha)
0 - 0.0001
0.0001 - 0.0012
0.0012 - 0.275
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 3

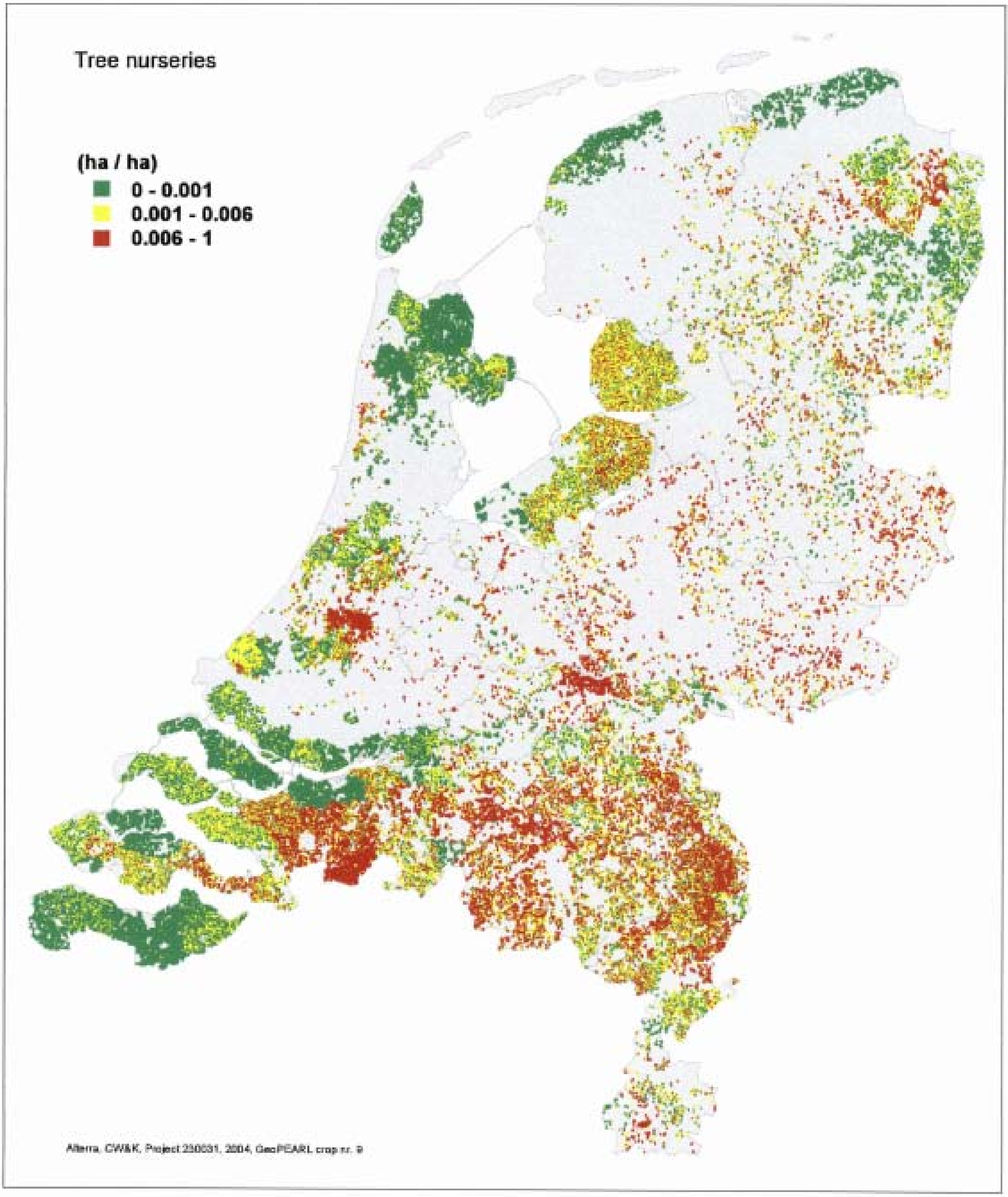

Sugar beets
(ha / ha)
0 - 0.007
0.007 - 0.197
0.197 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 4

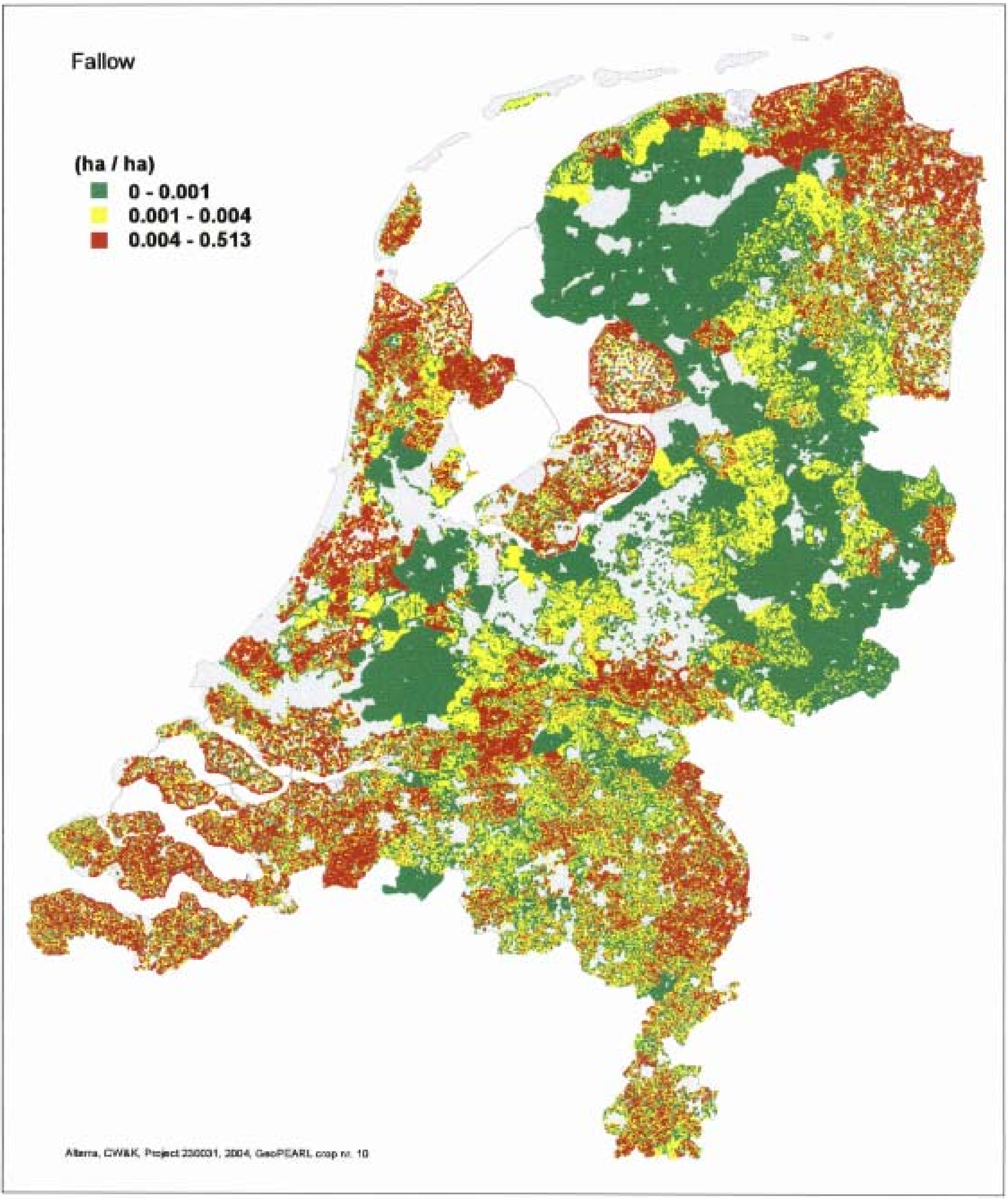

Leaf vegetables
(ha / ha)
0 - 0.001
0.001 - 0.009
0.009 - 0.312
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 5

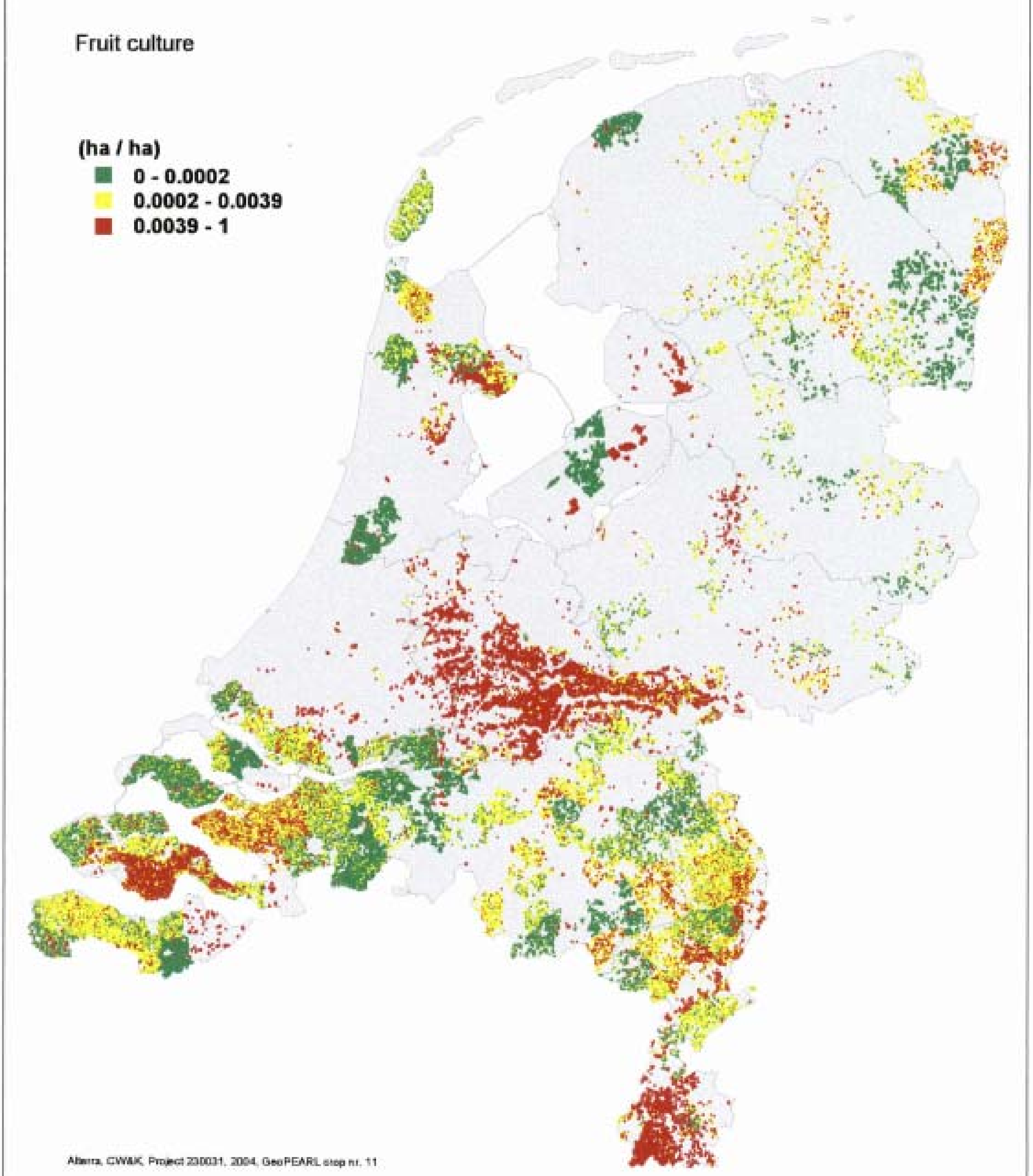

Plants for commercial purposes
(ha / ha)
0 - 0.002
0.002 - 0.009
0.009 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 6

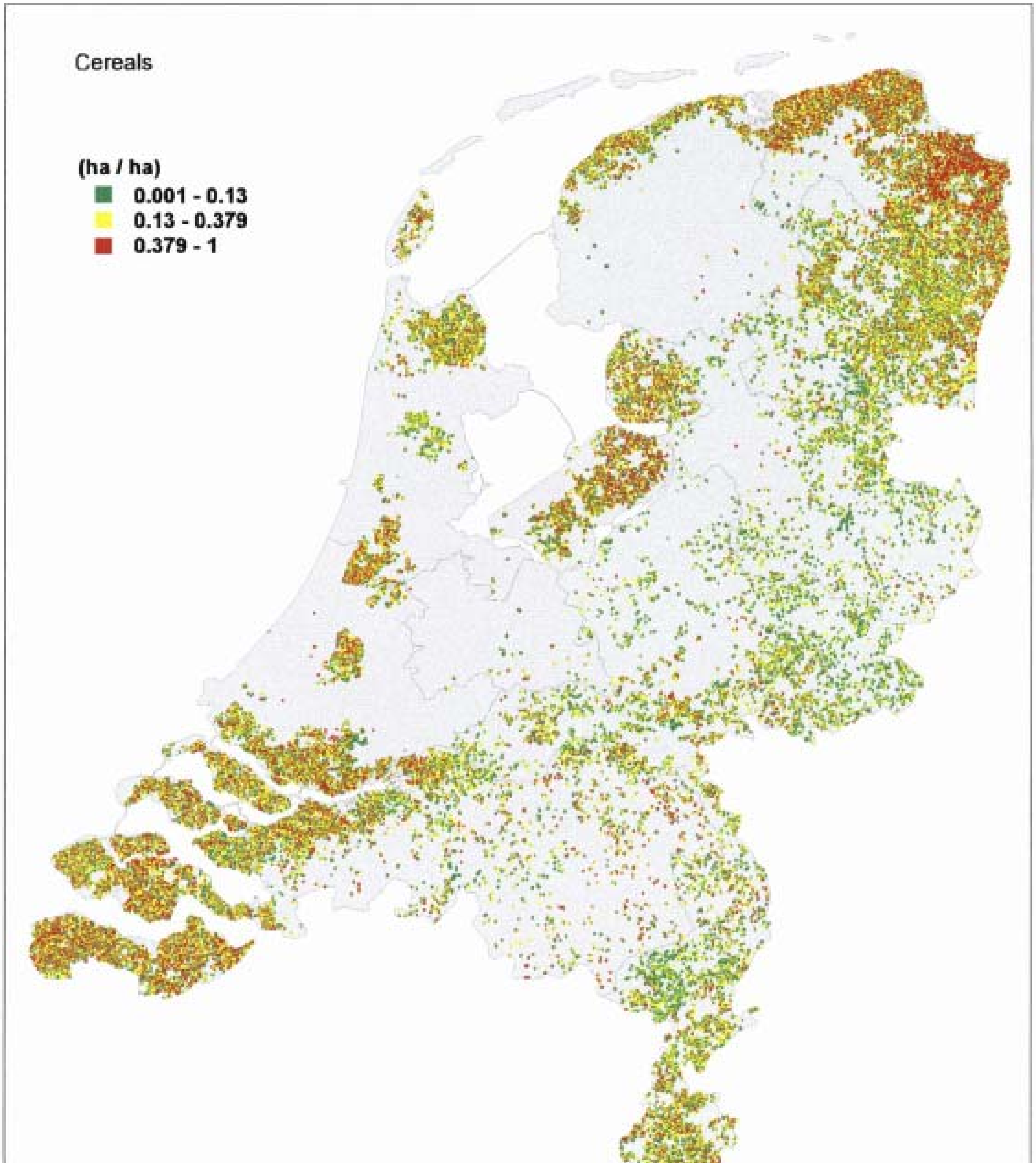

Floriculture
(ha / ha)
0 - 0.001
0.001 - 0.003
0.003 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 7

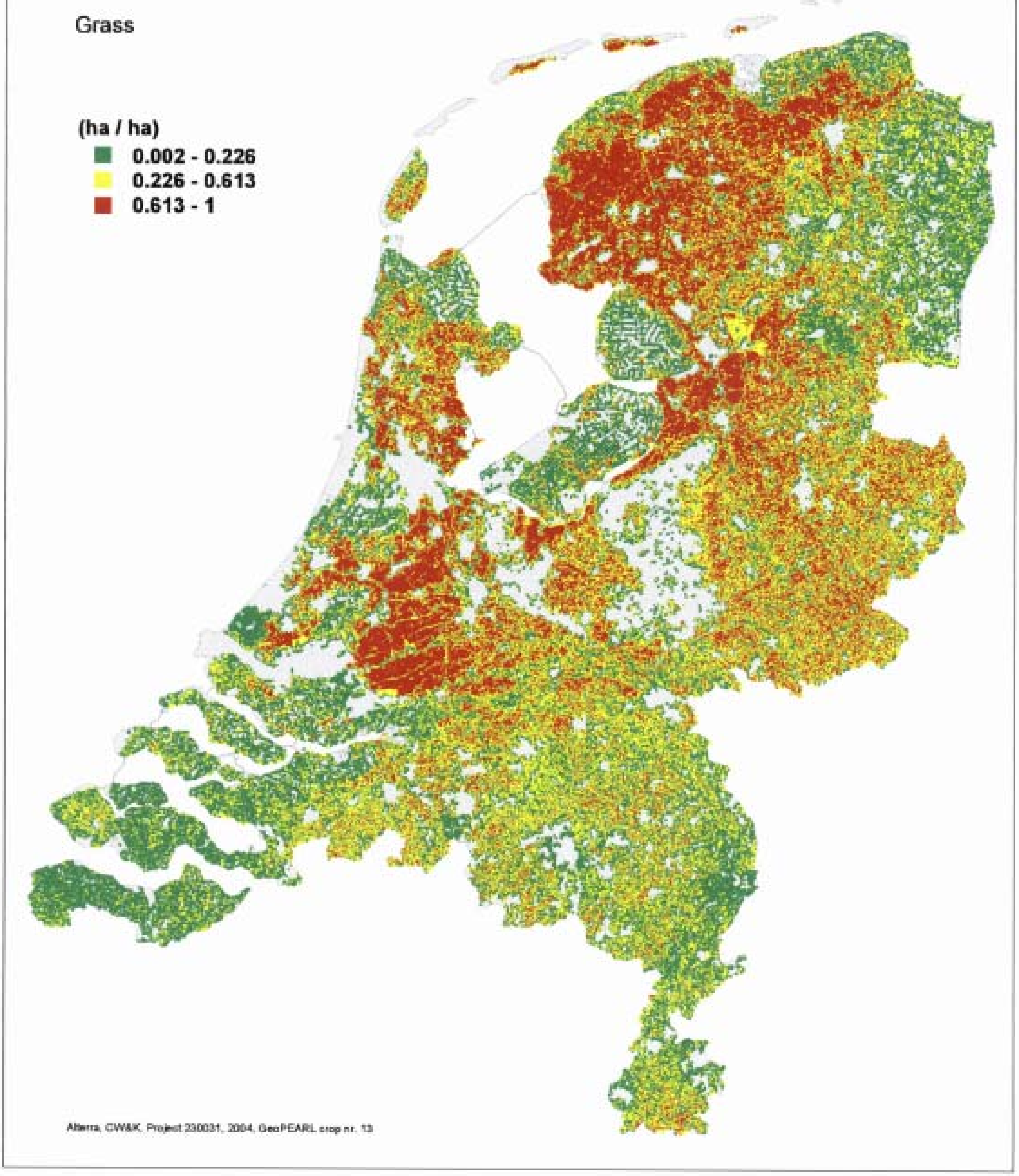

Flower bulbs
(ha / ha)
0 - 0.081
0.081 - 0.303
0.303 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 8


Tree nurseries
(ha / ha)
0 - 0.001
0.001 - 0.006
0.006 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 9

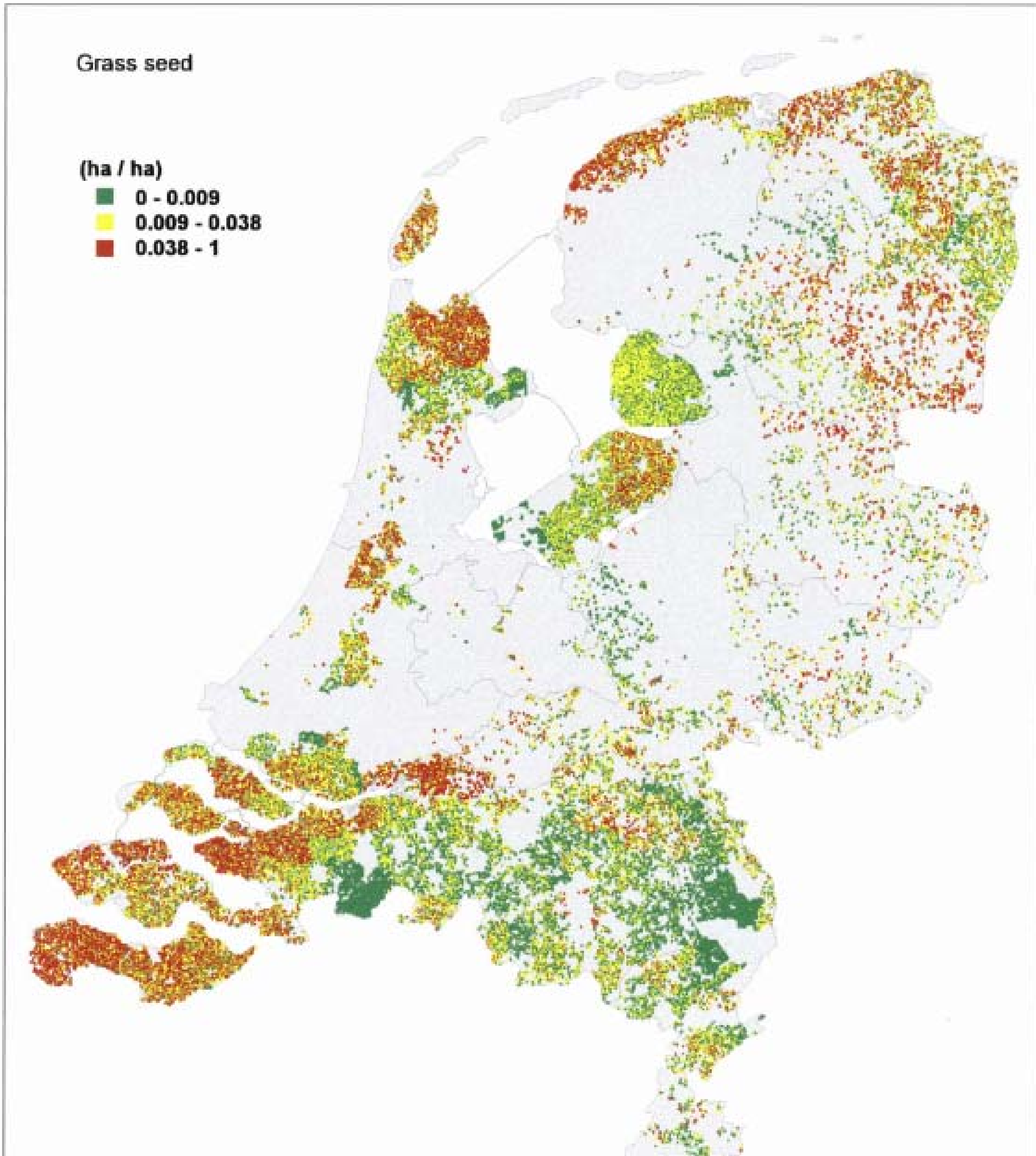

Fallow
(ha / ha)
0 - 0.001
0.001 - 0.004
0.004 - 0.513
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 10

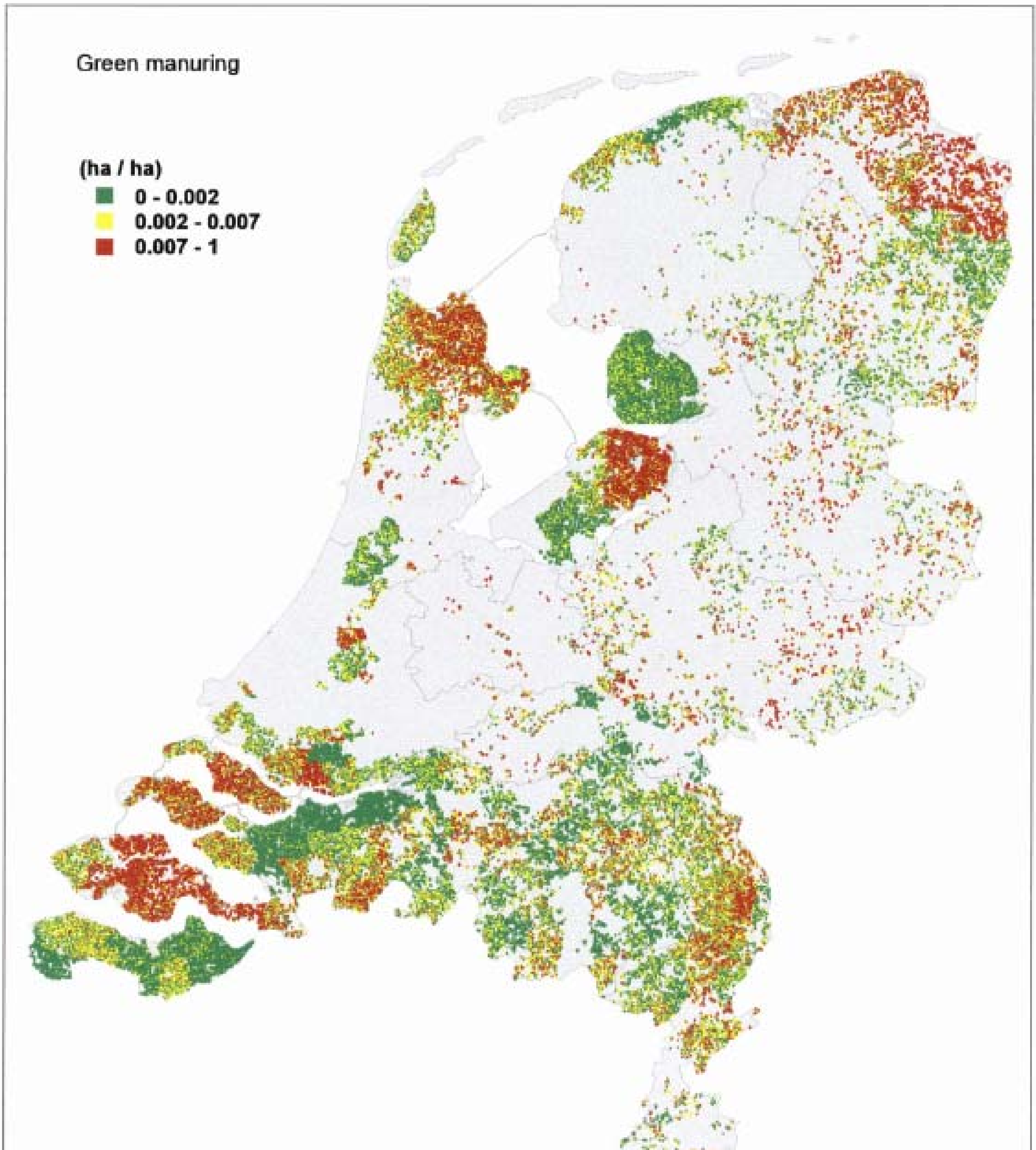

Fruit culture
(ha / ha)
0 - 0.0002
0.0002 - 0.0039
0.0039 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 11

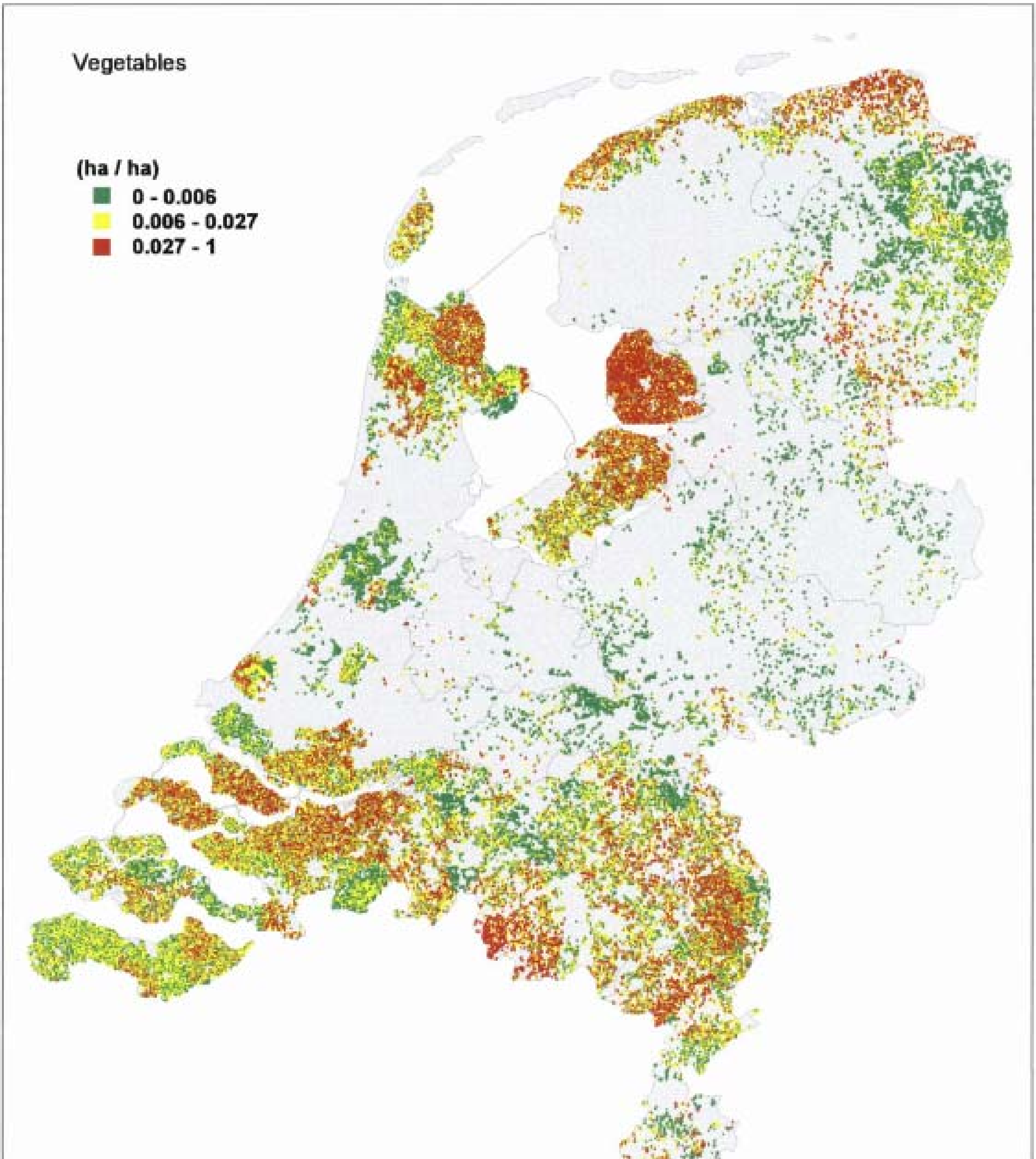

Cereals
(ha / ha)
0.001 - 0.13
0.13 - 0.379
0.379 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 12



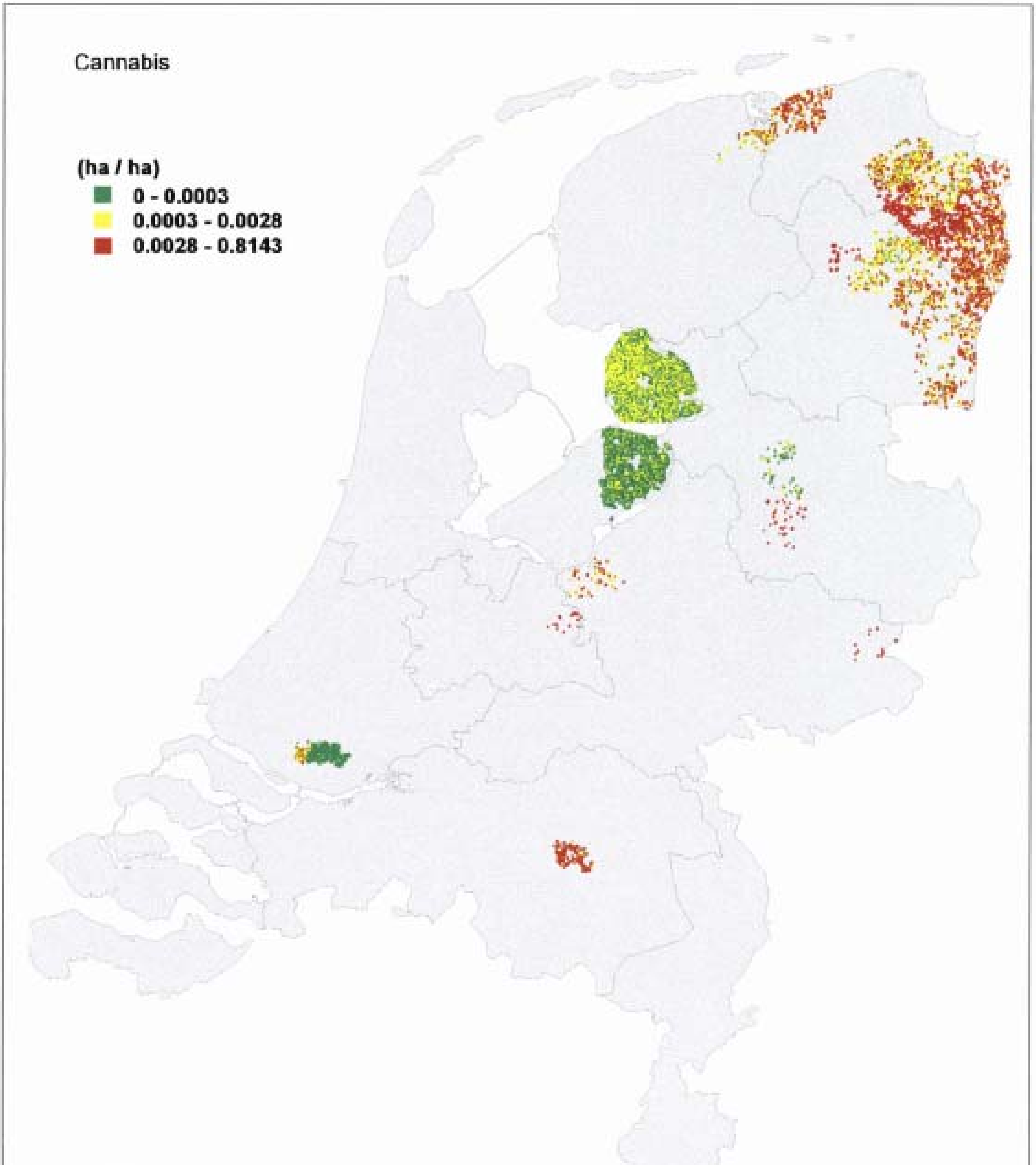
Grass
(ha / ha)
0.002 - 0.226
0.226 - 0.613
0.613 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 13

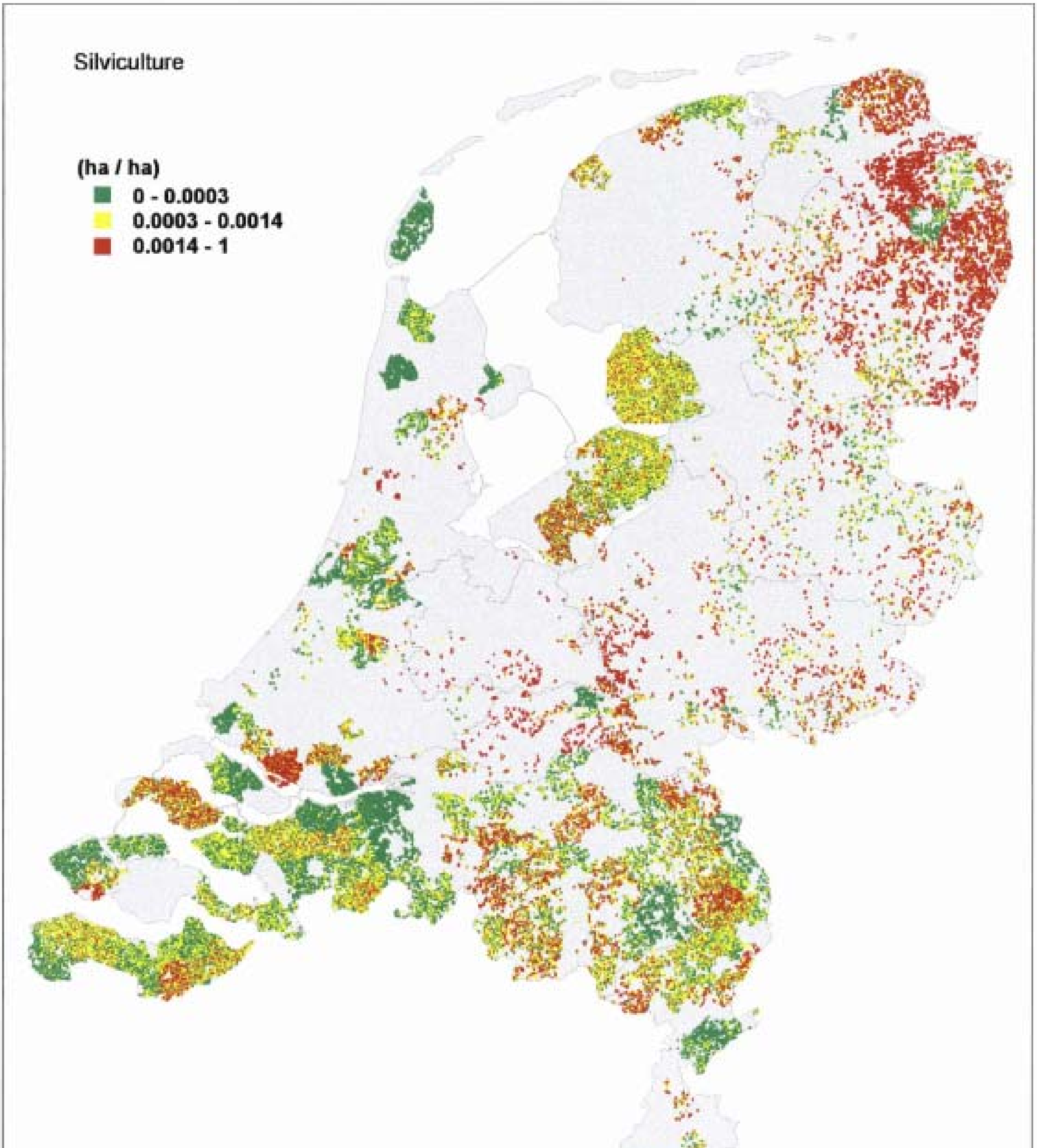

Grass seed
(ha / ha)
0 - 0.009
0.009 - 0.038
0.038 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 14

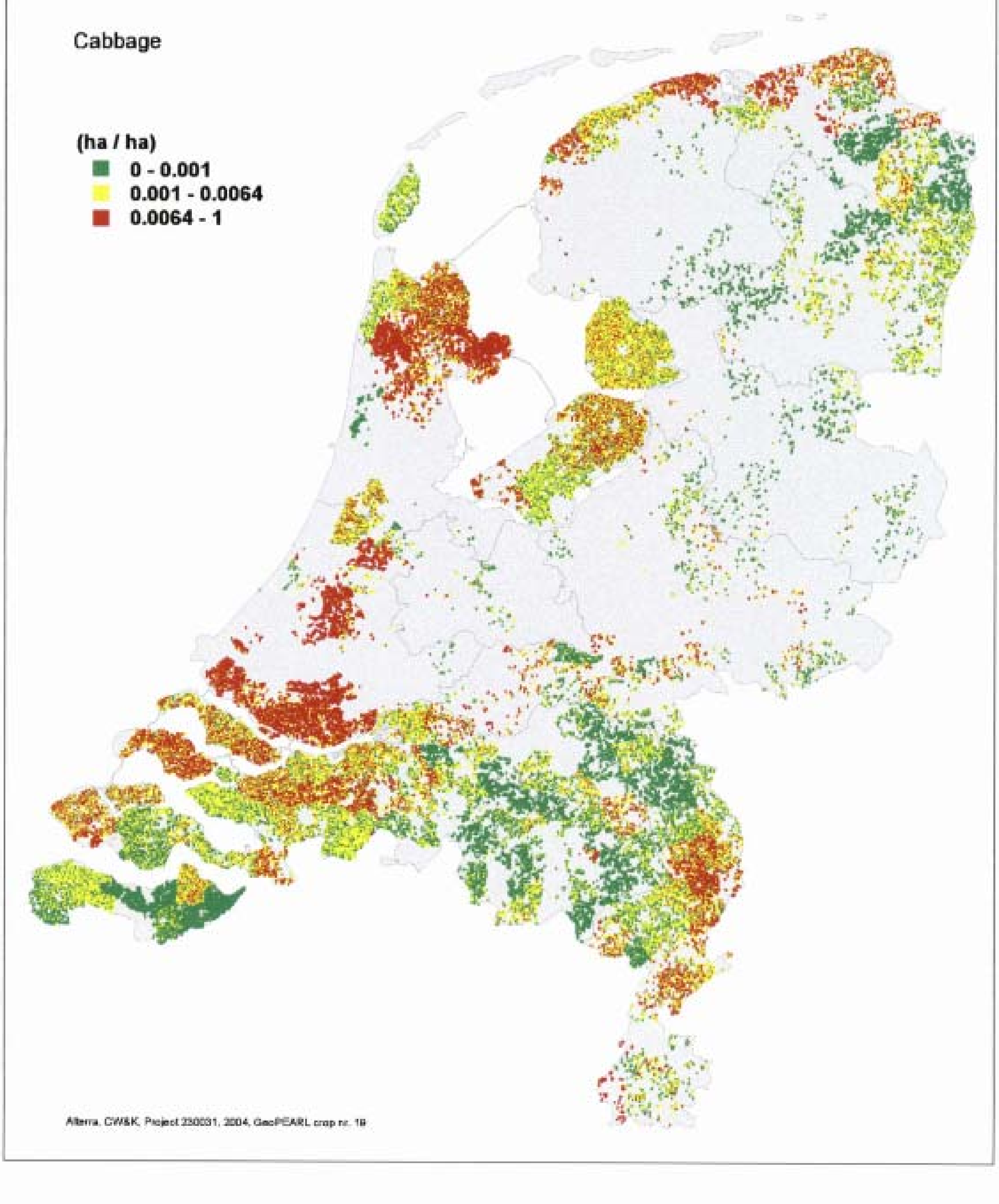

Green manuring
(ha / ha)
0 - 0.002
0.002 - 0.007
0.007 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 15

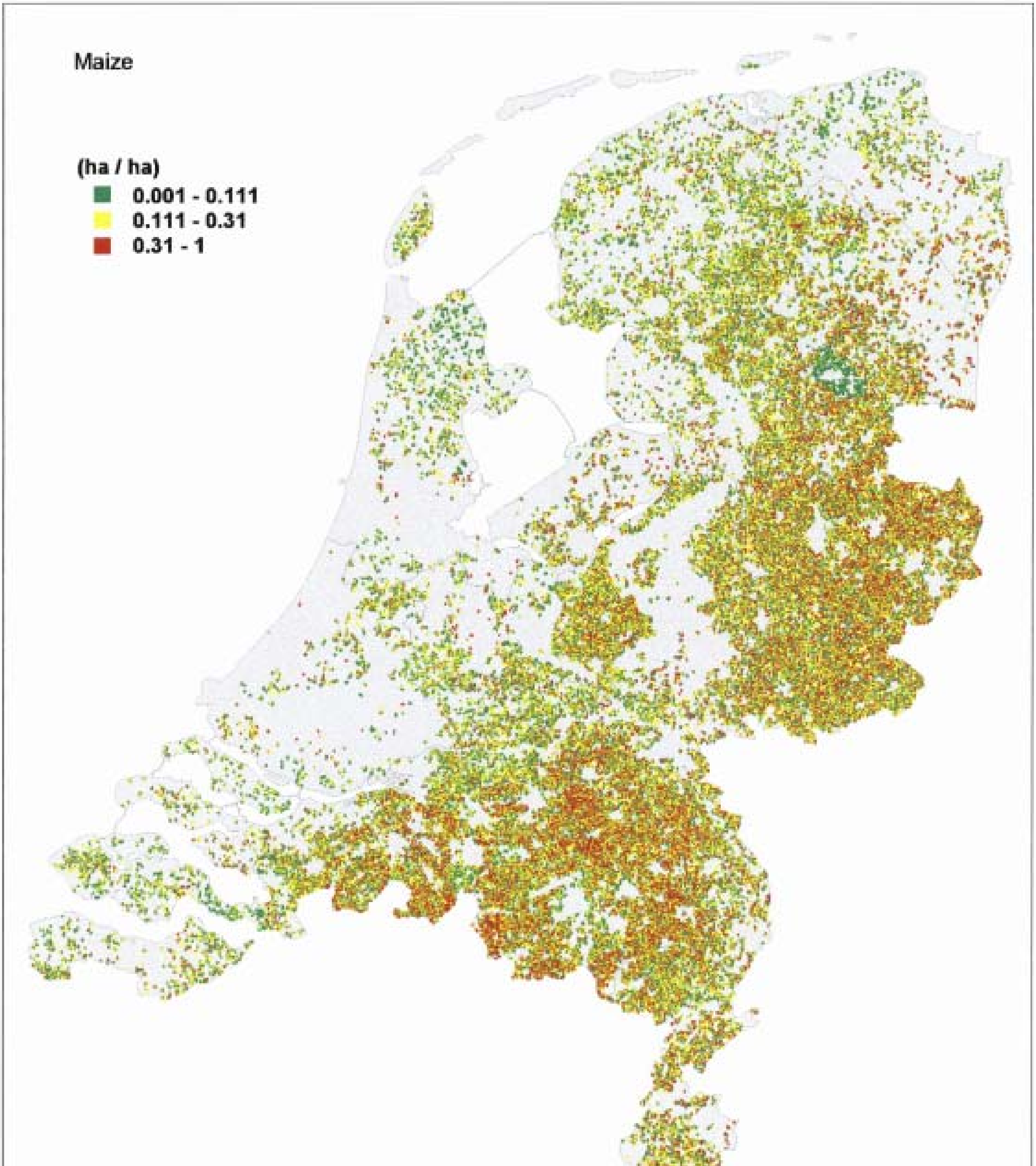


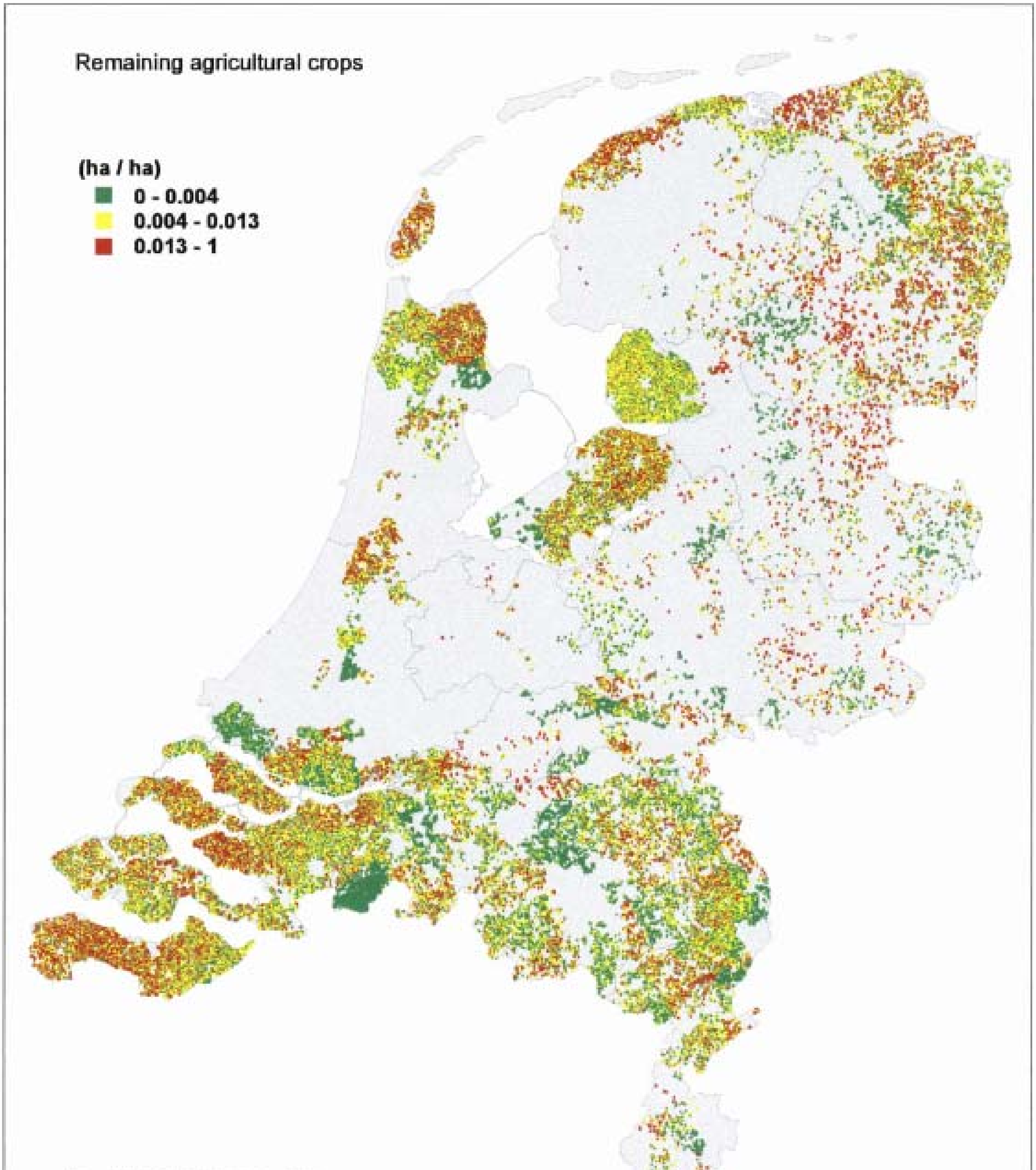
Vegetables
(ha / ha)
0 - 0.006
0.006 - 0.027
0.027 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 16

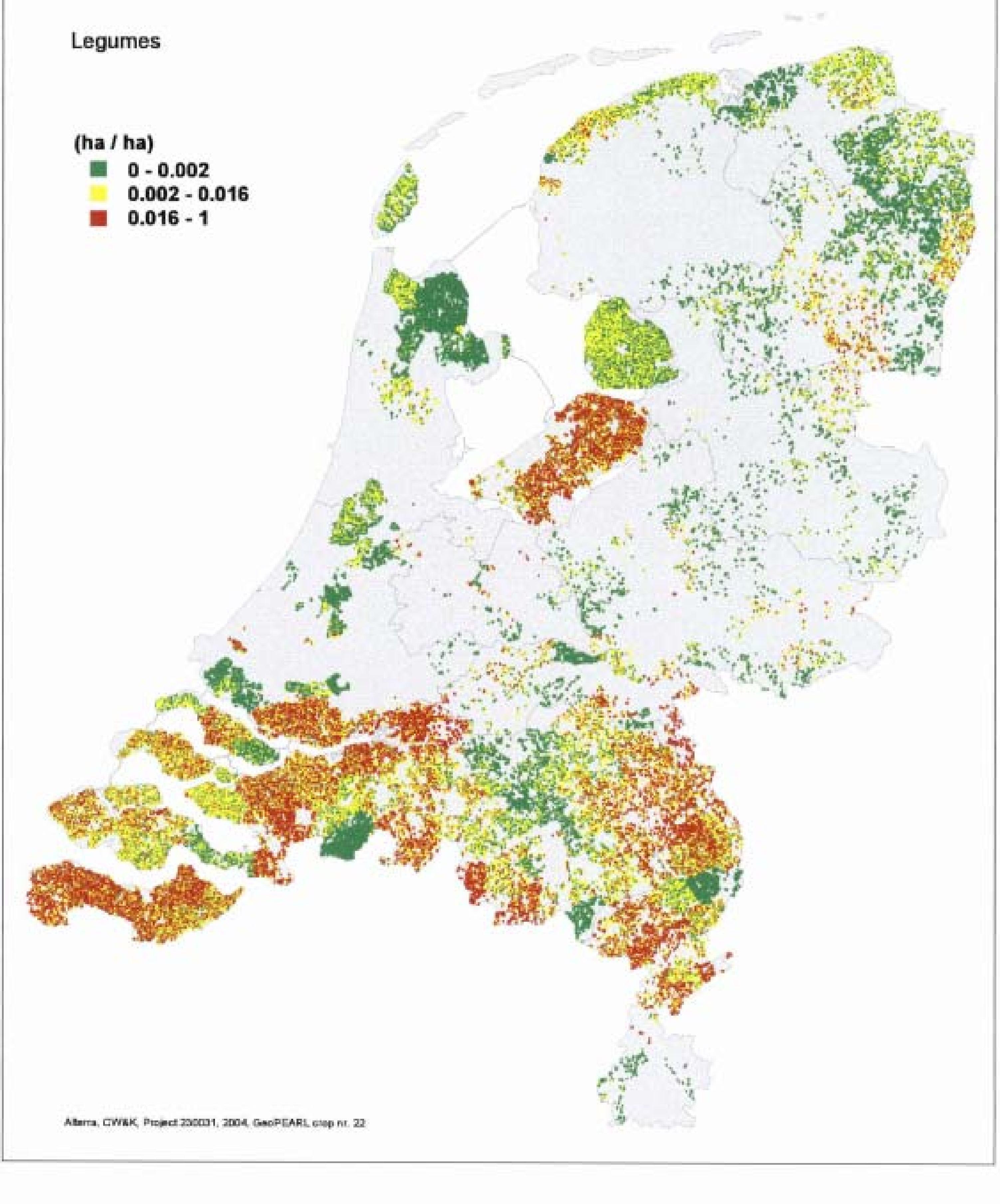

Cannabis
(ha / ha)
0 - 0.0003
0.0003 - 0.0028
0.0028 - 0.8143
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 17

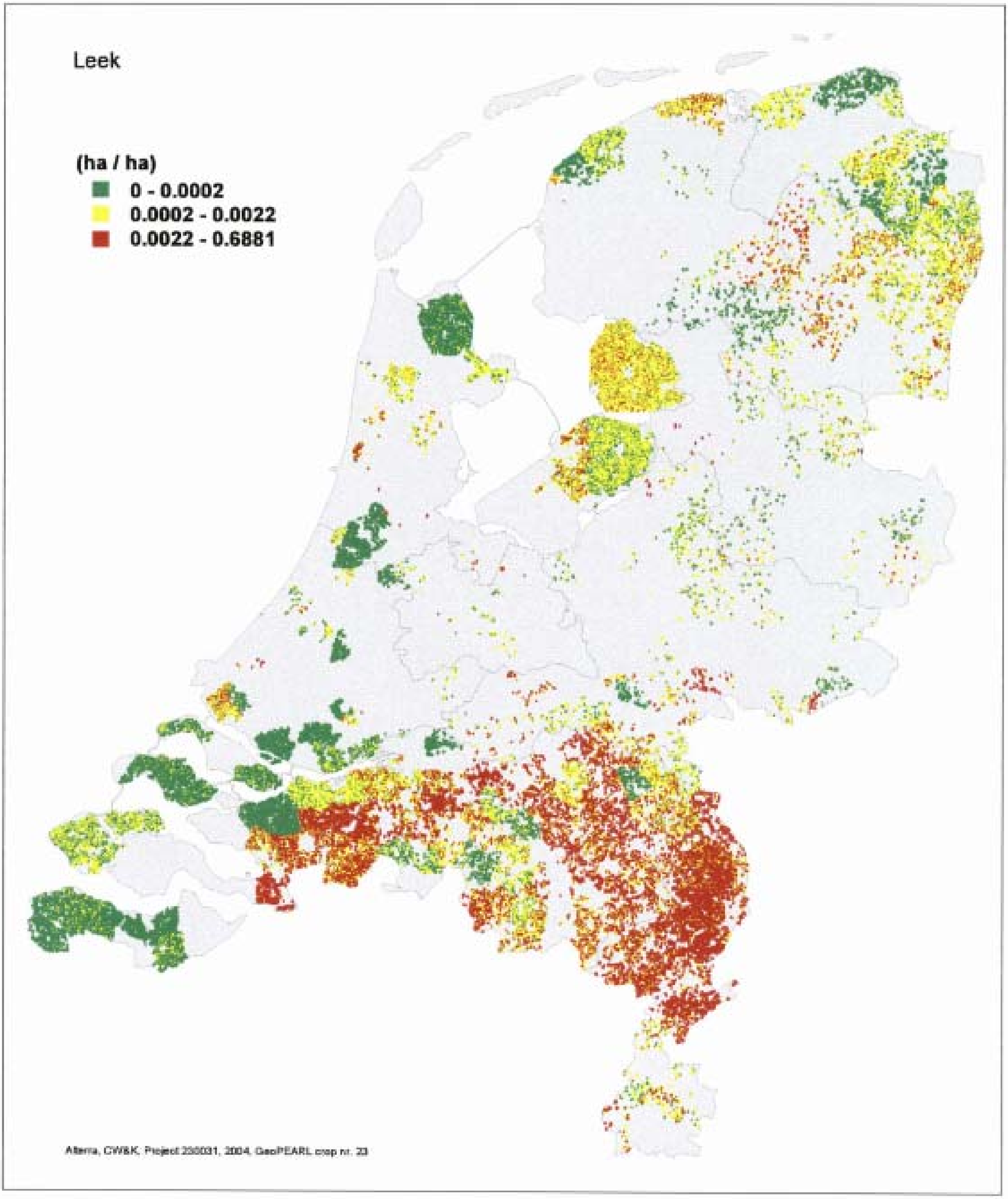

Silviculture
(ha / ha)
0 - 0.0003
0.0003 - 0.0014
0.0014 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 18

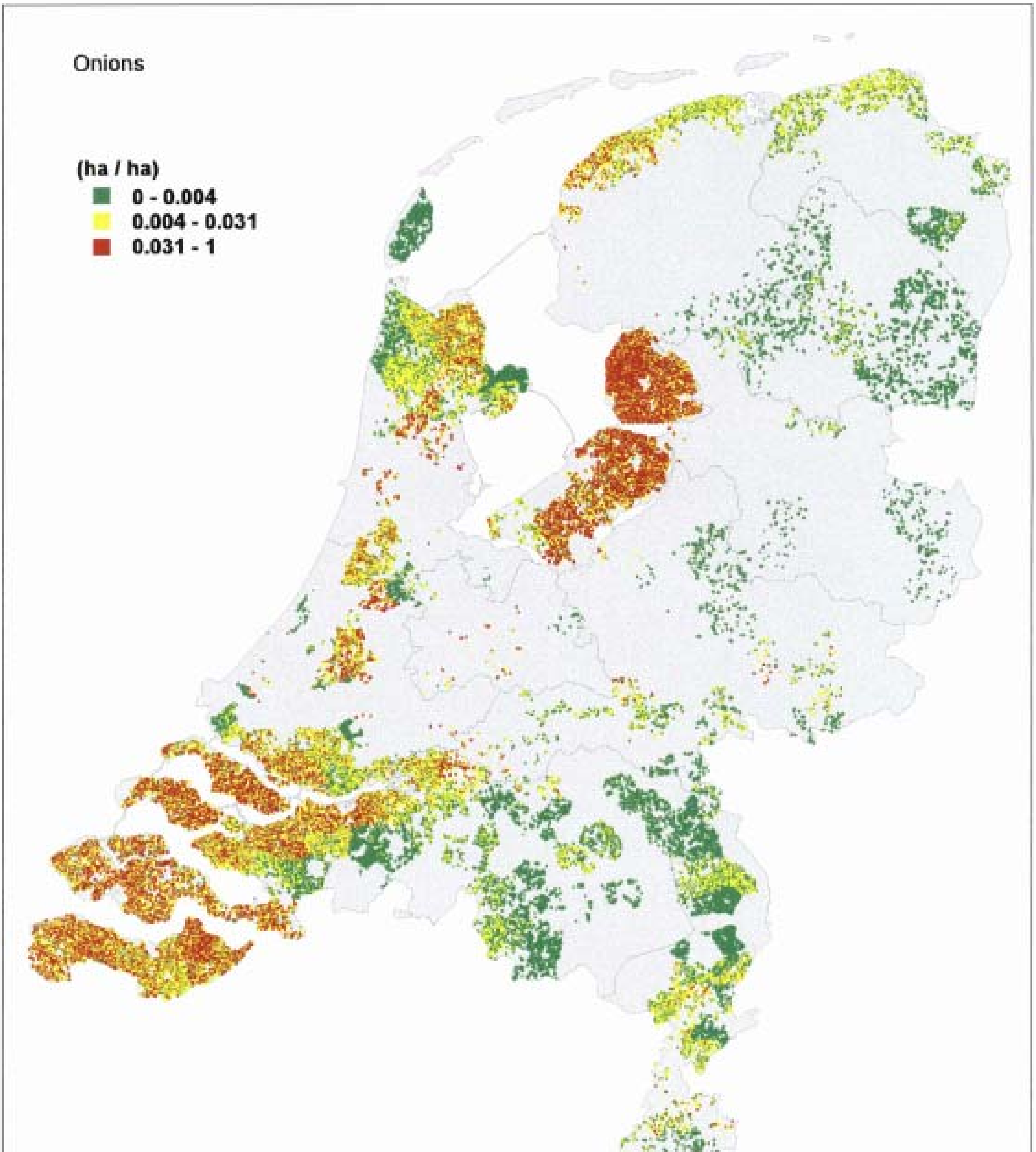

Cabbage
(ha / ha)
0 - 0.001
0.001 - 0.0064
0.0064 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 18

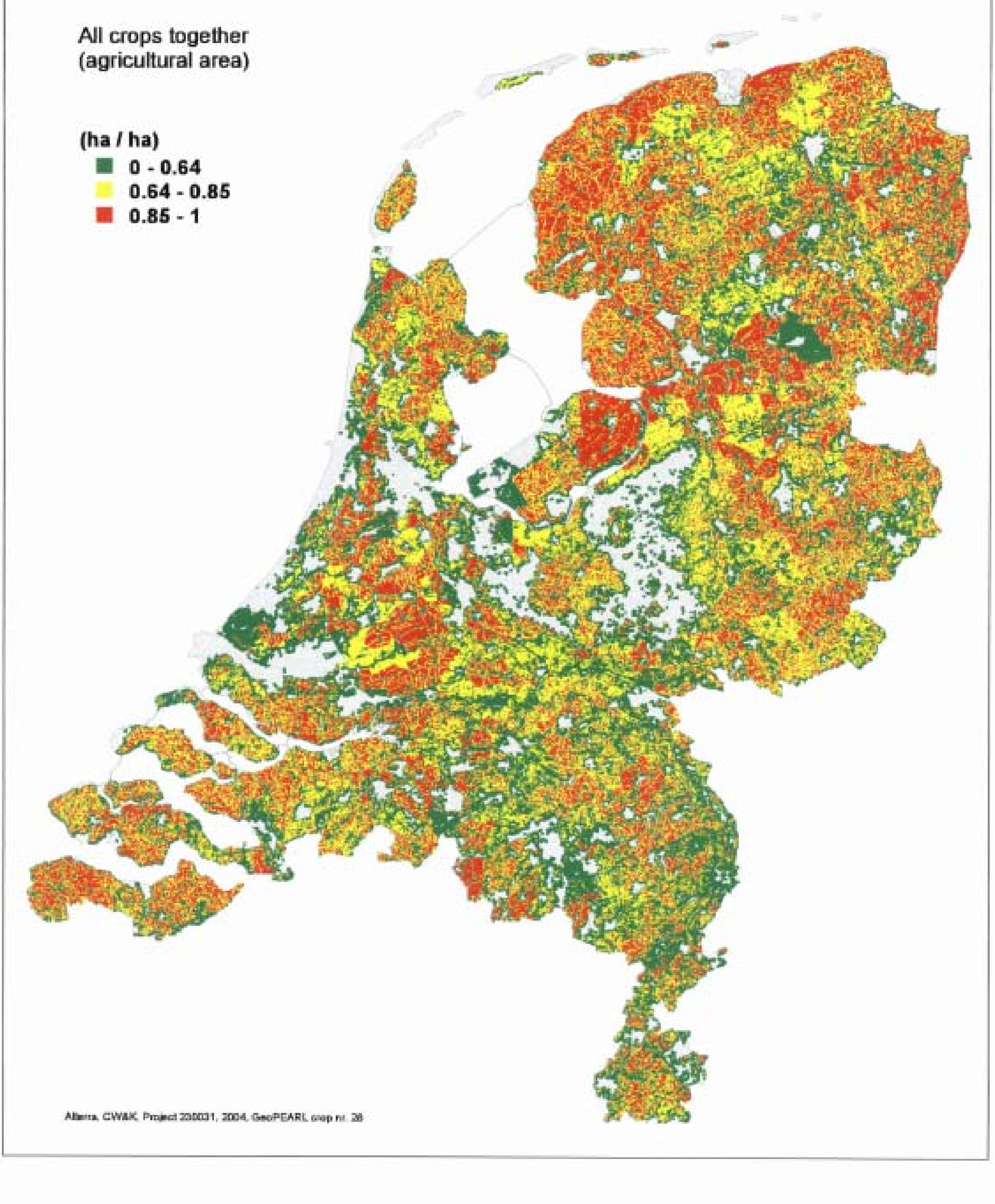

Maize
(ha / ha)
0.001 - 0.111
0.111 - 0.31
0.31 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 20


Remaining agricultural crops
(ha / ha)
0 - 0.004
0.004 - 0.013
0.013 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 21


Legumes
(ha / ha)
0 - 0.002
0.002 - 0.016
0.016 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 22


Leek
(ha / ha)
0 - 0.0002
0.0002 - 0.0022
0.0022 - 0.6881
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 23


Onions
(ha / ha)
0 - 0.004
0.004 - 0.031
0.031 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 24


All crops together
(agricultural area)
(ha / ha)
0 - 0.64
0.64 - 0.85
0.85 - 1
Alterra, CW&K, Project 230031, 2004, GeoPEARL crop nr. 28