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Quantifying biomass production for assessing ecosystem services of riverine landscapes

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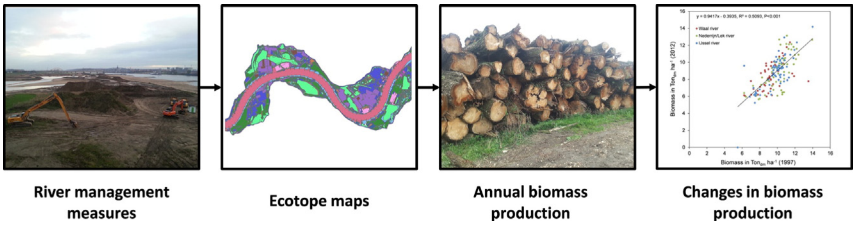
HIGHLIGHTS

- An approach for quantifying terrestrial biomass production of floodplains was developed.
- Quantification of spatiotemporal development of biomass production in floodplains along the Rhine River from 1997 to 2012.
- Biomass production of floodplains decreased due to land use changes and flood risk management.
- Relevant management measures were side channel construction, floodplain lowering and vegetation removal.

GRAPHICAL ABSTRACT



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ABSTRACT

Society is increasingly in need of renewable resources to replace fossil fuels and to prevent resource depletion. River-floodplain systems are known to provide important societal functions and ecosystem services to mankind, such as production of vegetative biomass. In order to determine the potential of harvesting vegetative riparian biomass, the capacity of river systems to produce such biomass needs to be determined. We developed a method for quantifying the spatiotemporal development of annual biomass production in river floodplains. Vegetation specific growth rates were linked to a landscape classification system (i.e., the Ecotope System for National Waterways). Biomass production was calculated for floodplains along the three Rhine River distributaries (i.e., the rivers Waal, Nederrijn-Lek and IJssel) over a 15 year period (1997–2012). During this period several large scale river management measures were undertaken to reduce flood risks and improve the spatial quality of the Rhine River as part of the Room for the River program. Biomass production decreased by 12%–16% from 1997 to 2012 along the three distributaries, which may be a side effect of flood mitigation. Almost 90% of the biomass produced was non-woody (e.g., grass/hay, reed, crops), which decreased along all three river distributaries due to the abandonment of production grasslands and the physical reconstruction of floodplains (e.g., creation of side channels). Woody vegetation, however, showed a slight increase during the 15 year period likely owing to vegetation succession from shrubs to softwood forest.

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1. Introduction

At present, the depletion of Earth's natural mineral and fossil resources is occurring at an alarming rate, highlighting the need for alternatives (Bentley, 2002; Sorrel et al., 2010; Höök and Tang, 2013). A shift in focus towards a more sustainable use of resources is required. River-floodplain systems are among the most important ecosystems to mankind, as they provide a range of valuable ecosystem services, such as water supply, flood mitigation, transport capacity and biomass (Tockner and Stanford, 2002; Wang et al., 2010; Nedkov and Burkhard, 2012; Large and Gilvear, 2014). Biomass may be used as a resource of carbon-rich materials (e.g., fibers and construction material) or as an alternative to fossil fuels. For instance, timber from riparian forests can be used to build houses or furniture, while reed from marsh lands can be used for thatching and building insulation. Biomass used for building also serves as a carbon sink, potentially storing carbon for many years (Fang et al., 2001; Binkley et al., 2002). Other biomass applications that may act as carbon sinks are biopolymers, bioplastics, textile and paper (Pervaiz and Sain, 2003; Mohanty et al., 2005). In addition, vegetation biomass of floodplains is important for nutrient retention (e.g., carbon, nitrogen) in floodplains as well as water retention in upstream riverine areas (Tufekcioglu et al., 2003; Van Stokkom et al., 2005).

A vital first step in quantifying ecosystem services is quantifying the systems' capacity to deliver these services (De Groot et al., 2010; Crossman et al., 2013; Villamagna et al., 2013; Schröter et al., 2014). So, valuation of the potential harvest of vegetative biomass from river floodplain systems requires the quantification of their capacity for biomass production. Once annual biomass increment values are established for the system, sustainable harvesting approaches can be developed in order to capitalize on biomass as a riverine ecosystem service. A river system's capacity to produce biomass is highly dependent on the types of vegetation present in the floodplain and their management (Baptist et al., 2004; Olde Venterink et al., 2006). For instance, the biomass produced annually on natural grasslands is lower than that of actively managed (e.g., fertilized) production grasslands (Aarts et al., 2005; Tolkamp et al., 2006). Tall and dense riparian vegetation increases the hydraulic roughness of the landscape, leading to increased flow resistance and potential flooding (Hupp, 2000; Tabacchi et al., 2000; Nienhuis and Leuven, 2001; Straatsma et al., 2009). River management authorities are responsible for ensuring flood safety, by, among other means, the management of riparian vegetation. Ensuring flood safety has become increasingly demanding from a management perspective. This is because river discharges are expected to increase in the near future, resulting in an increased chance of flooding of densely populated and economically valuable areas (Jansen et al., 1998; Van Stokkom et al., 2005; Straatsma et al., 2009). Floodplain reconstruction by means of dike relocation, the construction of side channels, floodplain lowering, and the removal of hydraulic obstructions is needed to increase the discharge capacity of river systems (Jansen et al., 1998; Silva et al., 2001; Van Stokkom et al., 2005; RVR, 2017). These measures in turn strongly affect the configuration of the riverine landscape and its vegetation.

The Room for the River (RfR) program was initiated in the Netherlands with two goals in mind: 1) to give the Rhine River more space in order to accommodate higher discharges, and 2) improve spatial quality. This program consisted of multiple floodplain reconstruction measures which caused major landscape changes in floodplains along the Rhine River distributaries in the Netherlands (Waal River, Nederrijn-Lek River and IJssel River) (Jansen et al., 1998; Silva et al., 2001; Van Stokkom et al., 2005; RVR, 2017). It was hypothesized that these landscape changes likely also reduced the biomass production potentials of the floodplains. For example, the construction of side channels reduces terrestrial floodplain surface area and thus the potential for production of vegetative biomass. To date, however, the biomass production capacity, as well as the spatiotemporal development of biomass production of these floodplains have not been quantified due to a lack of suitable indicators, empirical data and predictive models.

The goal of this study is to develop a method that will quantify the potential for terrestrial biomass production in riverine ecosystems. The aims are: 1) to develop an approach for quantification of various types of biomass in riparian ecosystems; 2) to quantify biomass production of riverine ecosystems by determining the yearly biomass increment for nine alluvial vegetation types; and 3) to determine how the biomass production changed across space and time in floodplains along the Rhine River distributaries in the Netherlands while undergoing riverine management measures and natural succession over a period of 15 years from 1997 to 2012.

2. Methods

2.1. Study area

The Rhine River enters the Netherlands at Lobith with a discharge ranging from 574 to 12,600 $m^3\ s^{-1}$ and an average discharge of 2300 $m^3\ s^{-1}$ calculated over the years 1901–2009 (Uehlinger et al., 2009). The Lower Rhine River bifurcates twice; the first bifurcation occurs at Pannerden where the Lower Rhine River splits into the Waal River and the Pannerdensch Kanaal. Following this, the Pannerdensch Kanaal bifurcates into the Nederrijn-Lek River and the IJssel River (Fig. 1A). In total the three distributaries and their floodplains comprise an area of circa 35,000 ha. During peak discharges in 1995 the risk of dike breaches along the Rhine River in the Netherlands was very high, requiring the evacuation of 250,000 people and causing an estimated US$ 1 billion economic damage to trade and industry (Silva et al., 2001; Van Stokkom et al., 2005). It was apparent that mitigating measures had to be taken in the light of expected future high discharge events (Middelkoop et al., 2001; Rijke et al., 2012).

2.2. Ecotope System for National waterways (ESN)

Input data for the biomass quantification approach (see Section 2.5 and Fig. 2) consisted of ecotope maps of the Rhine River distributaries. Since 1997, the river and adjacent floodplains in between the embankments of the Rhine River distributaries have been mapped regularly according to the Ecotope System for National waterways (ESN) (Rijkswaterstaat, 1998; Houkes, 2008). The ESN has been developed by the Directorate for Water Management of the Dutch Ministry of Infrastructure and Environment (Dutch: Rijkswaterstaat) to classify and to map riverine landscapes in the Netherlands. An ecotope is defined as: ‘a physically limited ecological unit, whose composition and development are determined by abiotic, biotic and anthropogenic aspects together’ (Rijkswaterstaat, 1998; Van der Molen et al., 2003). Ecotopes are homogeneous landscape units with specific geomorphological, hydro-morphological, ecological and land-use characteristics. In total 82 different ecotopes are distinguished covering the aquatic, riparian and terrestrial parts of the river-floodplain system. The area is mapped at a 1:10,000 scale, with a minimum mapping unit (MMU) of 20 by 20 m. The delineation of ecotopes was carried out using visual interpretation of false-color stereographic images and subsequent GIS overlay with inundation duration, management, water depth, substrate and salinity gradients (Van der Molen et al., 2000, 2003; Lorenz and Van der Molen, 2001; Bergwerff et al., 2003; Willems et al., 2007). The ecotope maps contain attributes, such as vegetation class, inundation frequency and management style, which enables the linking of ecotopes to (potential) ecosystem services of riverine landscapes (Koopman et al., 2017). Ecotope maps of the Dutch Rhine River distributaries are available from Rijkswaterstaat (www.rijkswaterstaat.nl) for the years 1997, 2005, 2008 and 2012.

2.3. Woody biomass production

Potential annual woody biomass increment was calculated for different types of riparian forests and shrubs. The increment was expressed in

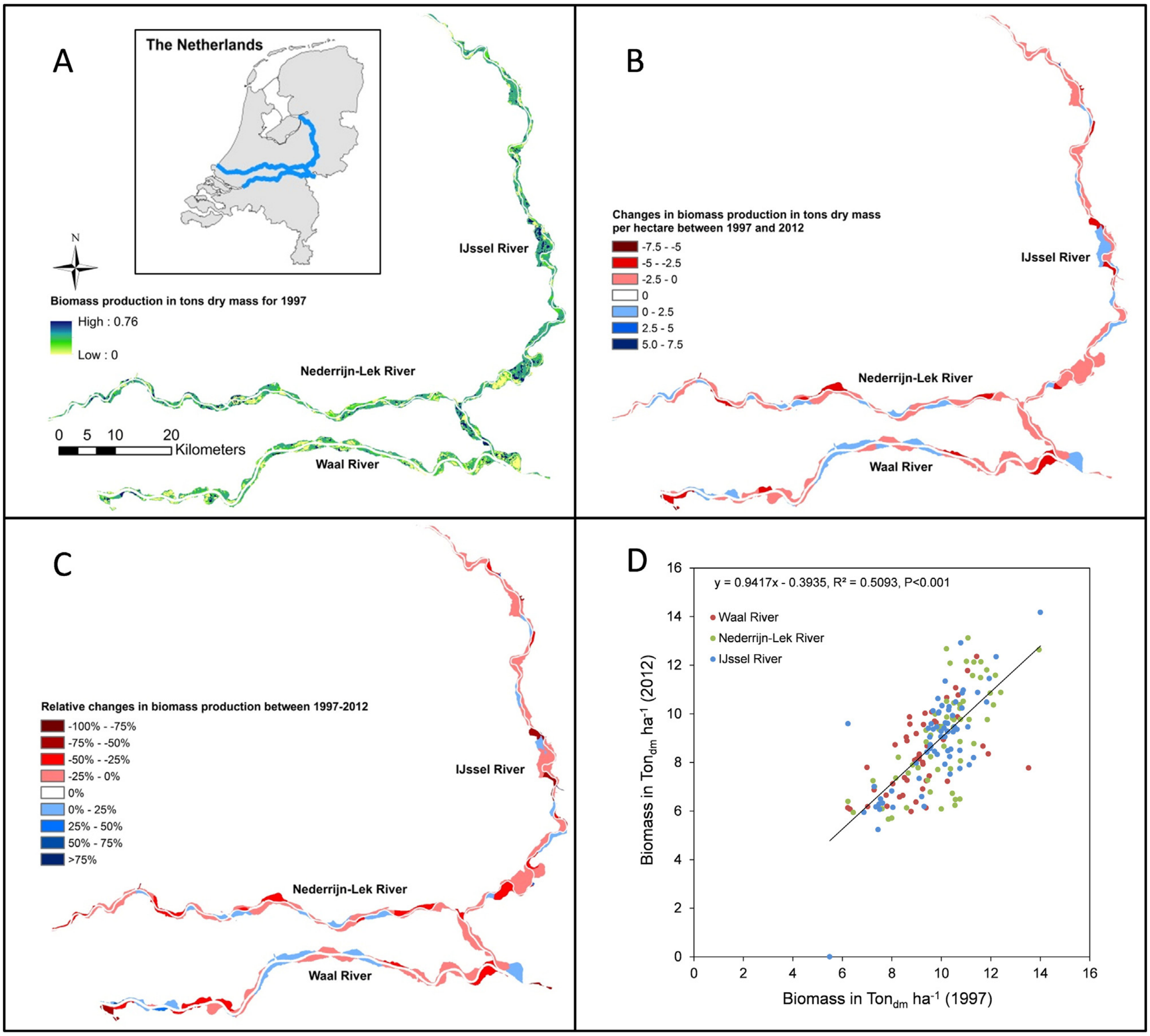


Fig. 1. Annual biomass production in 177 floodplains along the Rhine River distributaries. A) The biomass production per 0.04 ha (minimum mapping unit) in 1997. B) Differences in annual biomass production between 1997 and 2012. C) The relative changes in annual biomass production (%) between 1997 and 2012. D) Bivariate distribution of biomass production per hectare per floodplain. Linear regression analyses showed that the intercept was not significant ($P = 0.57$) whereas the slope was significant ($P < 0.001$).

tons of dry mass per hectare per year and calculated using the formula of Tolkamp et al. (2006):

$$B = G * BEF * C * V \quad (1)$$

where B is the annual woody biomass increment (ton$_{dm}$ ha^{-1} yr^{-1}), G is the increase in spindle wood (the wood of the stem including the bark) of the woody vegetation (m^3 ha^{-1} yr^{-1}), BEF is the biomass expansion factor that accounts for the branching of woody vegetation having a value of >1 (a mean BEF of 1.5 for deciduous tree species was used for all riverine woody vegetation types; Tolkamp et al., 2006), C is the conversion factor to dry matter (ton$_{dm}$ m^{-3}) (a mean conversion factor of 0.51 for deciduous tree species was used for all riverine woody vegetation types; Tolkamp et al., 2006), and V is the woody vegetation coverage of the ecotope (V was 1 for most vegetation types except reed which had a coverage of 0.75). Woody biomass consists of spindle wood, and top and branch wood. To determine the annual woody biomass produced by riparian forests and shrubs (ton$_{dm}$ yr^{-1}), the increment is multiplied with the surface area (S) over which the vegetation spans.

A distinction was made between the production of hardwood and softwood biomass, which have different characteristics (e.g., growth rates). Depending on vegetation type, different growth rates were used to calculate annual biomass production (Jansen et al., 1996; Stortelder et al., 2001; Probos, 2014). For shrubs, no distinction between hardwood and softwood could be made since only generic growth rates for riparian shrubs were available (see Supplementary Table SI1 for growth rates).

2.4. Non-woody biomass production

Non-woody biomass production in riverine areas consists of reed from marshes, herbaceous vegetation, and agricultural products such as hay and crops grown on production grasslands and arable land, respectively. The annual increment of non-woody biomass

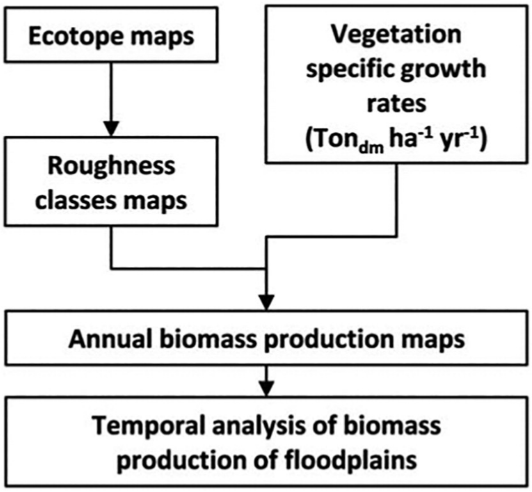


Fig. 2. Flowchart showing the approach for quantifying terrestrial biomass production of floodplains.

per hectare was multiplied with the surface areas of the grasslands, marshes, dry herbaceous vegetation and arable land (see Supplementary Table SI1 for specific growth rates retreived from: Anonymous, 1998; Aarts et al., 2005; Tolkamp et al., 2006; CBS, 2016). Maize is the most commonly grown crop on arable land in floodplains along the Rhine River distributaries (Jansen, 2009). Therefore, the average growth rate for maize was used to calculate crop biomass production.

2.5. Biomass calculation for the Rhine River distributaries

The biomass was calculated in a spatially explicit manner using the PCRaster-Python software (Schmitz et al., 2013). An overview of the biomass quantification approach is given in Fig. 2. Preprocessing consisted of aggregating ecotope classes into land cover classes based on similarity with respect to vegetation structure (Van Velzen et al., 2003). This was required because ecotope-specific biomass growth information was lacking. Ecotopes that contained similar vegetation structural characteristics were grouped into a single land cover class. These land cover classes are similar to the roughness classes used in hydraulic modelling since different vegetation types have specific roughness values (Van Velzen et al., 2002, 2003; Werner et al., 2005). The land cover classes represented the various types of usable biomass (e.g., grass/hay, reed, hardwood and softwood; Anonymous, 2015). Following this, annual woody and non-woody growth data (see Supplementary Table SI1) were linked to corresponding land cover classes and the biomass production per square meter of each class was calculated (Fig. 2). We rasterized the ESN shape files to a 20 m spatial resolution corresponding with the minimum mapping unit of 20 × 20 m. The total floodplain area was divided into 177 sections (i.e., floodplains), which are geographical units derived from the “Room for the River project”. Biomass production values were calculated for the four ESN mapping years (see Section 2.2), and subsequently aggregated over floodplain sections and river distributaries. A statistical analysis was performed to determine the changes in biomass production of river distributaries over the years using a one-way repeated measures ANOVA. A Bonferroni correction was applied to reduce the chance of a type I error. Independent variables were the four time steps (1997, 2005, 2008, 2012) and the dependent variable was annual biomass production (in ton$_{dm}$ ha^{-1}). In addition, a linear regression analysis was performed to determine the relationship between changes in biomass production of floodplain sections along the river distributaries in 1997 and 2012.

2.6. Landscape changes along the Rhine River distributaries

In order to explain changes in biomass production during the 15 year period, changes in land cover classes during this period were computed in a transition matrix. The matrix contained the surface area in hectares for each change in land cover between 1997 and 2012. Land cover classes either remained the same, or changed to other land cover class types due to either vegetation succession (Geerling et al., 2006; Makaske et al., 2011) or management measures (Silva et al., 2001; Baptist et al., 2004; Van Stokkom et al., 2005). The matrix's diagonal depicted the surface area that remained the same, while the off-diagonal cells showed the surface areas that changed.

2.7. Uncertainty in calculations

Vegetation growth rates are dependent on age and local abiotic factors (Jansen et al., 1996; Tolkamp et al., 2006). Specific data on these factors were lacking. Hence aggregated vegetation growth rate data were used for the vegetation types (Supplementary Table SI1). The uncertainty relating to the use of aggregated data was quantified by determining the standard deviation of the different vegetation growth rates used in this study (Supplementary Table SI1). Following this, the growth rate standard deviations were used as estimates for the minimum (mean minus one standard deviation) and maximum (mean plus one standard deviation) potential values of growth rate, which were subsequently used for calculating maximum and minimum biomass production. These maximum and minimum biomass values are depicted by the error bars in Fig. 3 and represent the variability in produced biomass due to the variability in growth rate.

3. Results

3.1. Biomass production

The annual production of biomass in the study area showed spatiotemporal variation (Figs. 1 and 3; Table 1; Supplementary Table SI2). Over the period 1997–2012, biomass production decreased in multiple floodplains (Fig. 1B, C and D). Decreases in total biomass production per floodplain ranged between 0.6% and 100%. In total 95 floodplains (54%) showed decreases in biomass production of between 0% and 25%, 34 floodplains had biomass production decreases of between 25% and 50%, 10 floodplains had decreases in biomass production of between 50%–75%. In two floodplains along the IJssel River and Nederrijn-Lek River biomass production decreased by between 75% and 100%, due to the removal of a softwood floodplain forest and reconstruction of a production grassland to stone substrate, respectively. The remaining 36 floodplains showed an increase in total biomass production in the 15 year period. 31 Floodplains showed increases in biomass production that ranged between 0 and 25%. Higher increases (>25%) were only found in floodplains along the Waal and IJssel Rivers (two and three floodplains, respectively). Four of the highest increases ranged between 25% and 75% and one increased by 216% (Fig. 1C).

The average biomass produced per hectare per floodplain decreased between 0 and 7.5 ton$_{dm}$ ha^{-1} in some floodplains, but increased in some other floodplain sections by 0 to 5 ton$_{dm}$ ha^{-1} (Fig. 1B, D). In 138 floodplains (78%) along the three distributaries the biomass production decreased between 0 and 5 ton$_{dm}$ ha^{-1} (Fig. 1D). The highest decreases in biomass production (5 to 7.5 ton$_{dm}$ ha^{-1}) were found in one floodplain along the IJssel River and one floodplain along the Waal River. A total of 36 floodplains showed an increased production of between 0 and 2.5 ton$_{dm}$ ha^{-1} in 2012 compared to 1997. Only one floodplain section along the IJssel River showed a higher increase in biomass production (i.e., between 2.5 and 5 ton$_{dm}$ ha^{-1}).

Across all three distributaries, the total biomass and non-woody biomass production showed average decreases of 12–16% and 14–19%,

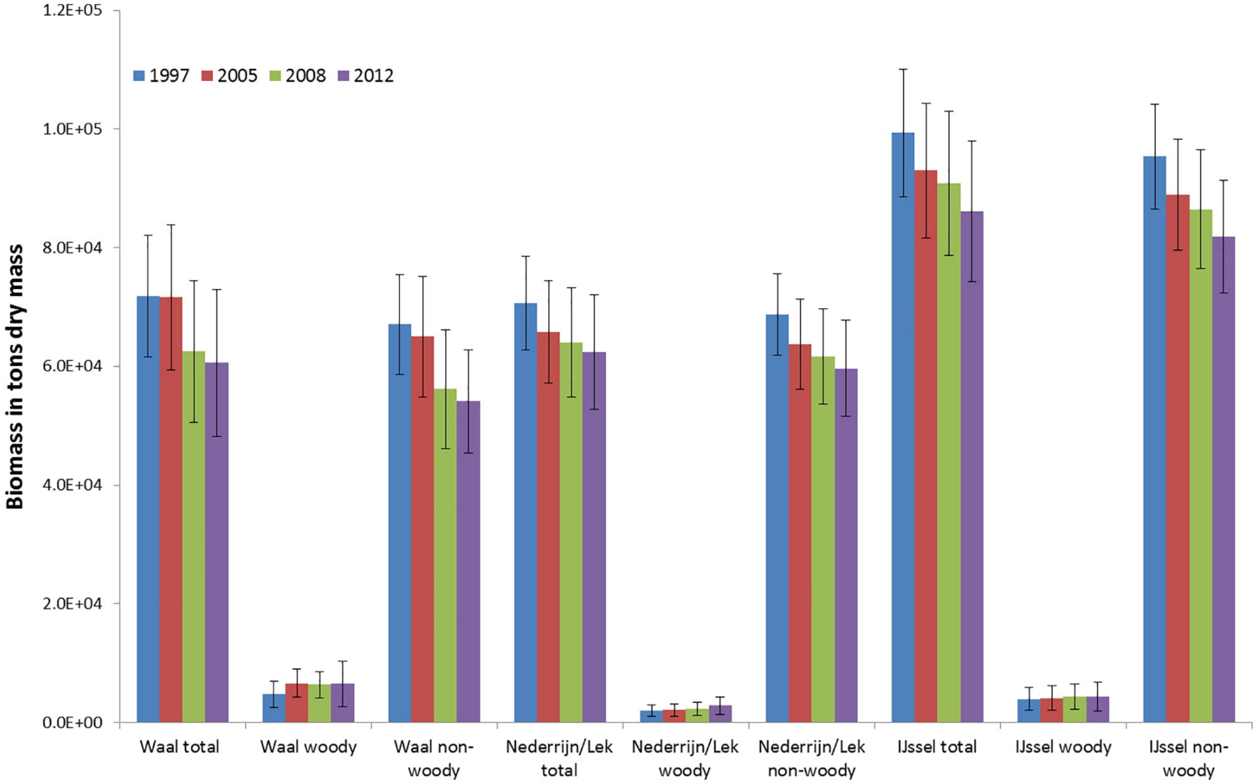


Fig. 3. The total, woody, and non-woody biomass production of 177 floodplains along three Rhine River distributaries (i.e., Waal River, Nederrijn-Lek River and IJssel River). Error bars represent the variability in biomass due to variability in growth rates (based on standard deviation).

respectively, during the 15 year period. This decrease was the highest in floodplains along the Waal River. The average biomass produced per hectare significantly decreased between 1997 and 2012 along all three distributaries, with the highest decrease occurring along the Nederrijn-Lek River (Table 1). Floodplains along the IJssel River produced the highest amount of biomass of all distributaries in all four years investigated (Figs. 1A and 3). These floodplains had the highest total surface area of non-woody vegetation compared to the non-woody surface areas in floodplains along the Waal River and Nederrijn-Lek River (Supplementary Table SI3). Woody biomass production of the three distributaries was low compared to non-woody biomass, but increased by 10–37% between 1997 and 2012. The floodplains of the Waal River produced the most woody biomass of all distributaries across all four years. Woody biomass production along the Waal River increased from 1997 to 2005 but decreased slightly afterwards. Woody biomass production along the Nederrijn-Lek River was the lowest of the three distributaries, but showed an increase in production across the entire 15 year period. The floodplains along the IJssel River showed a marginal increase in woody biomass production from 1997 to 2012 (Fig. 3; Supplementary Table SI3). Most of the woody biomass production along the three distributaries was softwood originating from softwood forests and to a smaller extent from softwood shrubs. Hardwood production was low compared to softwood production (0.6–1.2% vs. 2.0–9.9% of the total production). The highest production of hardwood biomass was found in floodplains along the IJssel River (Supplementary Table SI2).

The production of grass/hay and crops accounted for ≥78% of the total biomass production in each year and distributary, except for the Waal River in 2012. The production of dry herbaceous vegetation and reed was low compared to other non-woody biomass types (Supplementary Table SI2).

3.2. Uncertainty of biomass calculations

Variability in growth rates of plants, shrubs and trees resulted in variability in the calculated biomass production over 15 years that ranged from $\pm 7.9 \cdot 10^3$ ton$_{dm}$ for the Nederrijn-Lek River in 1997, to $\pm 1.4 \cdot 10^4$ ton$_{dm}$ for the Waal River in 2012 (Fig. 3). The variability of woody biomass production ranged from $\pm 1.0 \cdot 10^3$ ton$_{dm}$ for the Nederrijn-Lek River in 1997, to $\pm 3.8 \cdot 10^3$ ton$_{dm}$ for the Waal River in 2012. The variability in woody biomass production was sometimes equal to, or even higher than 50% of the average production. The variability of non-woody biomass production ranged from $\pm 6.9 \cdot 10^3$ ton$_{dm}$ for the Nederrijn-Lek River in 1997, to $\pm 1.0 \cdot 10^4$ ton$_{dm}$ for the Waal River in 2005 (Fig. 3).

3.3. Landscape changes along the Rhine River distributaries

During the 15 year period studied, land cover classes altered in several floodplains due to vegetation succession or floodplain reconstruction measures. In total, $2.4 \cdot 10^3$ ha of vegetation land cover classes altered as a result of vegetation succession. The land cover classes that had the largest changes in surface area due to succession were production grassland and natural grassland, which transformed into $6.1 \cdot 10^2$ and $4.3 \cdot 10^2$ ha of dry herbaceous vegetation, respectively (Table 2).

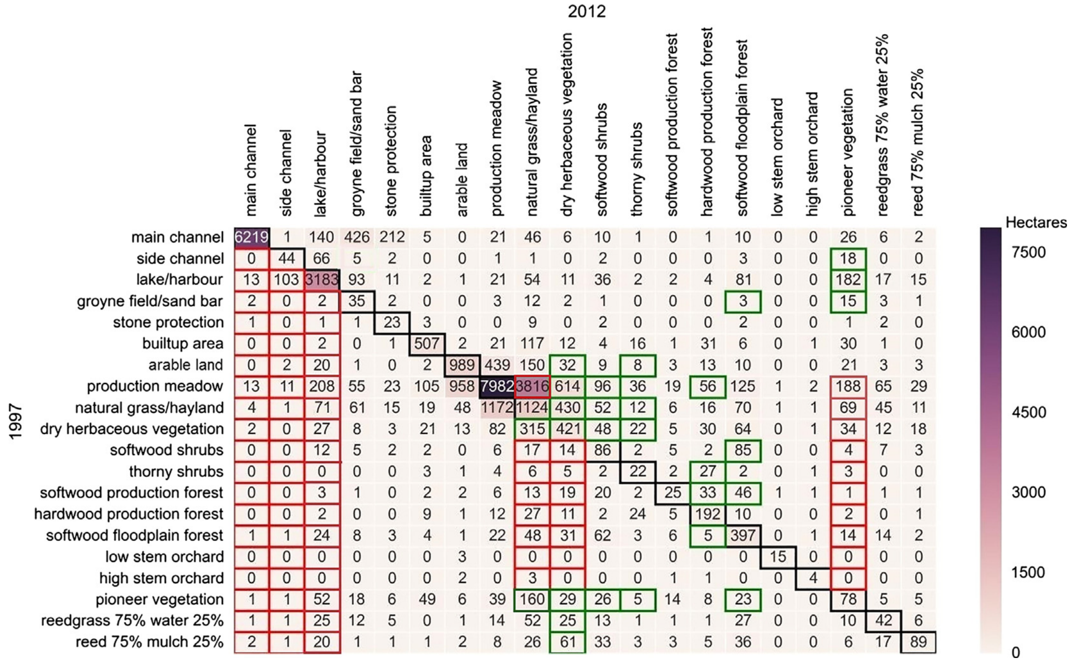
Reconstruction measures transformed a total of $4.7 \cdot 10^3$ ha to other land cover classes (13% of the total surface area of the Rhine River). Most of these transformations concern small surface areas compared to

Table 1
The average annual biomass production per hectare (ton$_{dm}$ ha^{-1}) in 177 floodplains along the three Rhine River distributaries. Letters indicate significant differences according to one-way repeated measures ANOVA, $\alpha = 0.05$.

Distributary	1997	2005	2008	2012	1997–2012 (%)*
Waal River	9.2^a	8.7^b	8.5^b	8.3^b	−9.7
Nederrijn-Lek River	10.1^a	9.2^b	9.0^b	9.1^b	−10.2
IJssel River	9.8^a	9.3^b	9.2^b	8.8^c	−9.7

* Relative difference in biomass production per hectare over the period 1997–2012.

Table 2
Transition matrix showing transitions of land cover classes into other land cover classes from 1997 to 2012 for the whole study area. Numbers indicate the surface transition in hectares. Green boxes indicated transitions through vegetation succession. Red boxes indicate transitions due to management measures. Other transitions are caused by agricultural changes or classification errors.



1997 \ 2012	main channel	side channel	lake/harbour	groyne field/sand bar	stone protection	builtup area	arable land	production meadow	natural grass/hayland	dry herbaceous vegetation	softwood shrubs	thorny shrubs	softwood production forest	hardwood production forest	softwood floodplain forest	low stem orchard	high stem orchard	pioneer vegetation	reedgrass 75% water 25%	reed 75% mulch 25%
main channel	6219	1	140	426	212	5	0	21	46	6	10	1	0	1	10	0	0	26	6	2
side channel	0	44	66	5	2	0	0	1	1	0	2	0	0	0	3	0	0	18	0	0
lake/harbour	13	103	3183	93	11	2	1	21	54	11	36	2	2	4	81	0	0	182	17	15
groyne field/sand bar	2	0	2	35	2	0	0	3	12	2	1	0	0	0	3	0	0	15	3	1
stone protection	1	0	1	1	23	3	0	0	9	0	2	0	0	0	2	0	0	1	2	0
builtup area	0	0	2	0	1	507	2	21	117	12	4	16	1	31	6	0	1	30	1	0
arable land	0	2	20	1	0	2	989	439	150	32	9	8	3	13	10	0	0	21	3	3
production meadow	13	11	208	55	23	105	958	7982	3816	614	96	36	19	56	125	1	2	188	65	29
natural grass/hayland	4	1	71	61	15	19	48	1172	1124	430	52	12	6	16	70	1	1	69	45	11
dry herbaceous vegetation	2	0	27	8	3	21	13	82	315	421	48	22	5	30	64	0	1	34	12	18
softwood shrubs	0	0	12	5	2	2	0	6	17	14	86	2	5	2	85	0	0	4	7	3
thorny shrubs	0	0	0	0	0	3	1	4	6	5	2	22	2	27	2	0	1	3	0	0
softwood production forest	0	0	3	1	0	2	2	6	13	19	20	2	25	33	46	1	1	1	1	1
hardwood production forest	0	0	2	0	0	9	1	12	27	11	2	24	5	192	10	0	0	2	0	1
softwood floodplain forest	1	1	24	8	3	4	1	22	48	31	62	3	6	5	397	0	1	14	14	2
low stem orchard	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	15	0	0	0	0
high stem orchard	0	0	0	0	0	0	2	0	3	0	0	0	1	1	0	0	4	0	0	0
pioneer vegetation	1	1	52	18	6	49	6	39	160	29	26	5	14	8	23	0	0	78	5	5
reedgrass 75% water 25%	1	1	25	12	5	0	1	14	52	25	13	1	1	1	27	0	0	10	42	6
reed 75% mulch 25%	2	1	20	1	1	1	2	8	26	61	33	3	3	5	36	0	0	6	17	89

the changes caused by vegetation succession, except for the conversion of production grasslands to natural grasslands. This 'grassland' conversion comprised almost 82% of the surface area affected by all reconstruction measures. The remaining conversions due to reconstruction measures comprised $8.5 \cdot 10^2$ ha and included the digging of side channels and the removal of woody vegetation to increase discharge capacity (conversion of woody vegetation into pioneer vegetation, grassland or herbaceous vegetation; Table 2).

3.4. Biomass production changes on a floodplain scale

The 'Stokebrandsweerd' is a floodplain located along the IJssel River near the city of Zutphen. This floodplain underwent floodplain reconstruction and management measures between 1997 and 2012. As part of these measures, a side channel was excavated in a production grassland (increase in the side channel and lake/harbor land cover classes), while management converted agricultural land and production grassland into natural grassland (Table 3, Supplementary Fig. SI1). This caused decreases in the production of crops and grass from production grasslands. Biomass from natural grasslands increased slightly, but this was not sufficient to replace the losses resulting from the reduction in production grassland. While both softwood and hardwood shrubs increased in surface area, floodplain forests were harvested causing an overal decline in woody biomass production (Table 3, Supplementary Fig. SI1). The total surface area of the 'Stokebrandsweerd' floodplain decreased by 19%, and the terrestrial surface area decreased by 27%, causing a decrease in total biomass production of 33%.

4. Discussion

4.1. Relevance to ecosystem services assessment and river management

Annual biomass production potential of all floodplains along the three Rhine River distributaries in the Netherlands was estimated for a

Table 3
Landscape changes in the 'Stokebrandweerd' floodplain along the IJssel River from 1997 to 2012 and the resulting changes in biomass production. Surface areas of land cover classes are given in hectares (ha) and the produced biomass in tons dry mass (ton_{dm}).

Land cover class surface area in ha	1997	2012	Biomass production in ton_{dm}	1997	2012
Side channel	–	0.7	–	–	–
Lake/harbor	5.3	8.0	–	–	–
Groyne field/sand bar	–	0.3	–	–	–
Stone protection	–	3.4	–	–	–
Builtup terrain	4.0	0.7	–	–	–
Agricultural land	3.9		Crops	74.0	
Production grassland	78.6	52.9	Grass (production)	845.9	568.8
Natural grassland	15.0	17.3	Grass (natural)	93.3	108.0
Dry herbaceous vegetation	2.1	3.7	Dry herbaceous vegetation	13.0	22.9
Softwood shrubs	0.1	1.2	Softwood (shrubs)	0.2	1.9
Hardwood shrubs	–	0.3	Hardwood (shrubs)		0.5
Hardwood forest	4.4	0.3	Hardwood (forest)	20.0	1.3
Softwood forest	3.2	2.8	Softwood (forest)	35.5	26.4
High stem orchard	0.5	–	–	–	–
Pioneer vegetation	–	3.2	–	–	–
75% reed, 25% water	0.5	0.2	Reed	2.1	1.1
Total surface area	117.7	95.1	Total biomass production	1083.8	730.8

15 year period. During this period, Room for the River projects were implemented to increase the discharge capacity of the river system and improve its spatial quality (Jansen et al., 1998; Silva et al., 2001; Van Stokkom et al., 2005; RVR, 2017). In this article we showed how these river management measures affected the river system's potential for delivering biomass as an ecosystem service. At present, our method is the most comprehensive approach for quantifying biomass production at a large spatiotemporal scale, such as that of the Rhine River distributaries over 15 years. Quantifying the system's capacity for producing biomass is a necessary first step in determining the flow and eventual use of biomass as an ecosystem service (De Groot et al., 2010; Crossman et al., 2013; Villamagna et al., 2013; Schröter et al., 2014). Our results serve as a valuable input for riverine ecosystem services assessment, or as an input for life cycle analyses of biomass use for energy production (Heller et al., 2003).

4.2. Uncertainties

In addition to the uncertainty in growth rates, the classification error of the ESN maps is also a source of uncertainty. The accuracy of the 2005 ESN map was assessed at 69% for eight aggregated vegetation classes (Knotters and Brus, 2013). Explanations for this relatively low accuracy are difficulties in distinguishing certain vegetation types on the basis of aerial photographs, distinguishing the growth and succession of vegetation during the time between taking the photographs and collecting ground truth data, variability in river discharge (different water levels during mapping), and errors made during fieldwork (Knotters and Brus, 2013). In addition, the size of the MMU of the ESN did not match the point observations used for validation. A random classification error does not strongly affect the total biomass production at the scale of a river reach because the low and high production classes cancel each other out. However, a random error does affect the transition matrix of the land cover classes because a misclassified polygon will display as a change in land cover. Straatsma et al. (2013) showed that the uncertainty in hydromorphological and ecological modelling due to land cover classification errors in the Rhine branches has large local effect, but errors are smaller when they are aggregated to river reach scale. For example, the 68% confidence intervals of potential biodiversity scores, which are also derived from the ecotope map, varied between 10 and 15%. The ESN maps were still considered useful since they are the only landscape classification maps that describe the entire river-floodplain area at a level of detail of 20 × 20 m.

Modern satellite and airborne imagery allow biomass production estimates at finer spatial resolutions than 20 × 20 m across the globe (Kerr and Ostrovksy, 2003; Ayanu et al., 2012). However, as yet, such images do not contain the same information present in the ecotopes of the ESN maps (e.g., flooding frequencies and management) (Van der Molen et al., 2003). Moreover, the ESN maps are easily scalable and allow back casting over a period of 15 years to 1997, a time when the current imagery techniques were not available (Ayanu et al., 2012). These attributes make the ESN maps suitable for use in linking and quantifying highly divergent riverine ecosystem services and their potential trade-offs (Koopman et al., 2017). In addition, the ESN is used for other policy analyses and scientific research supporting integrated river management (Van der Molen et al., 2003; De Nooij et al., 2004; Straatsma et al., 2009; Straatsma et al., 2017).

The growth rate of trees and shrubs depends on age and growth form classes which are determined by local abiotic factors (Jansen et al., 1996). Unfortunately, the ESN does not include data on the age of ecotopes and height of vegetation (used to determine growth classes), which limits calculations of age and growth form class specific annual biomass production. Hence, we used aggregated data from different riparian areas for softwood vegetation and assumed that this data was representative for vegetation along the three Rhine River distributaries. We were unable to find similar data for hardwood vegetation, which forced us to use highly aggregated data from different environments and age and growth form classes. Only limited data was available for riparian shrubs growing in floodplains across the Netherlands, which meant that no distinction could be made between hardwood and softwood shrubs. Hence, the growth rate of riparian shrubs in general was attributed to both softwood and hardwood shrubs in order to estimate shrub biomass production. Despite the variability, we believe the data used were valid as they have also been used in other ecosystem services assessments for policy making such as the European and National Atlases Natural Capital (ANCs) and ECOPLAN (ANK, 2017; ECOPLAN, 2017; Remme et al., 2017). The variability in biomass growth rates due to aggregation of data from different locations and environments may be reduced if more ecotope specific data becomes available.

4.3. Effects of land-use changes, riverine management measures and succession on biomass production in floodplains along the Dutch Rhine River distributaries

Climate change and increased runoff due to urbanization are expected to increase the peak discharge of rivers in the future (Middelkoop et al., 2001; Du et al., 2012). In view of this, flood mitigation will become increasingly important. The floodplain reconstructions that occurred between 1997 and 2012 aimed to increase the peak discharge capacity of the Rhine River from 15,000 to 16,000 $m^3\ s^{-1}$, and to enhance the spatial quality of the riverine area (Jansen et al., 1998). Our hypothesis was confirmed, as the land use changes and management measures that aimed to realize the 1000 $m^3\ s^{-1}$ increase in discharge capacity (Rijkswaterstaat, 2000; Van Stokkom et al., 2005) during this period coincided with a decrease in total biomass production by 12 to 16% in floodplains along all three Rhine River distributaries. This assumes that the various river management measures applied led to the removal or conversion of vegetation. Non-woody biomass decreased by $3.6 \cdot 10^4$ $ton_{dm}\ yr^{-1}$ in total for all three Rhine River distributaries. In contrast, the total woody biomass production for the three distributaries slightly increased by $3.0 \cdot 10^3$ $ton_{dm}\ yr^{-1}$ during the 15 year period. Woody vegetation only covered 7 to 10% of the area, and was not removed to the same degree as the non-woody vegetation during the implementation of river management measures. This is beneficial to the production of woody biomass but could also positively influence floodplain riparian biodiversity. Straatsma et al. (2017), for instance, demonstrated an increase in biodiversity due to floodplain reconstruction measures in the same area over the period 1997–2012.

In some floodplains the total biomass production decreased while the biomass production per hectare increased. For example, the total production in a floodplain along the IJssel River decreased by 2.6% while the production per hectare increased by 0.1%. This was caused by a reduction in surface area of 4%, while the relative surface area of vegetation types with higher growth rates such as crops increased by 4.3%.

Between 1997 and 2012 many privately owned production grasslands in floodplains along the Rhine River distributaries were sold to various nature conservation organizations. In most cases, these organizations abandoned intensive agricultural activities in favor of naturally grazed grasslands which facilitated riverine biodiversity and landscape quality and reduced maintenance costs (Tables 2, 3; Supplementary Figure SI1; Nienhuis et al., 2002). This resulted in a reduction of the biomass production of these grasslands by a factor of almost two. Due to succession, some production grasslands changed into dry herbaceous vegetation, also causing a reduction in biomass production of almost two (Supplementary Table SI1; Aarts et al., 2005; Tolkamp et al., 2006). The succession driven changes of natural grasslands into dry herbaceous vegetation did not affect biomass production, as biomass production rates for these land cover classes are similar (Supplementary Table SI1).

The lowering of floodplains increased water storage and conveyance capacity in several of the studied floodplains (Van Stokkom et al., 2005).

The required vegetation removal in these floodplain sections caused a decrease in biomass production, e.g., softwood forests have a higher biomass production than pioneer vegetation or grasslands (Table 2). Side channels were dug in several floodplains such as the 'Stokebrandsweerd' floodplain along the IJssel River (Jansen et al., 1998; Van Rooij and Van Wezel, 2003; Van Stokkom et al., 2005; Lambermont, 2005). In most cases, production grassland was converted into side channels in these floodplains (Tables 2, 3; Supplementary Figure SI1). Conversely, dike relocation increased the surface area of some floodplains leading to local increases in biomass production. In total, 486 ha of terrestrial biomass producing surface area were transformed to aquatic surface area, while elsewhere, terrestrial biomass producing surface area increased by 124 ha. Therefore, measures resulted in a net decrease in biomass producing surface area leading to a lower overall biomass production (Figs. 1 and 3).

Vegetation affects the roughness value of the floodplain and, therefore, the discharge capacity. Olde Venterink et al. (2006) showed that willow woodland has a lower roughness than reed beds. However, depending on its density, height, and water depth, woody vegetation can feature a higher hydraulic roughness than non-woody vegetation (Van Velzen et al., 2002; Werner et al., 2005). In order to reduce roughness in some floodplains, vegetation was removed (Rijkswaterstaat, 2000). This may have been visible in some floodplains where woody vegetation was converted to pioneer vegetation or grasslands (Table 2). In other floodplains, vegetation succession was allowed to proceed, which resulted in a net increase in woody biomass production (Fig. 3; Table 2).

The results of this study show that land-use changes, river management measures and succession affect the biomass production of floodplains. Depending on the targets set by riverine management, choices have to be made that achieve the correct balance between functions, such as discharge capacity, and biomass related ecosystem services (e.g., CO_2 sequestration; Schulp et al., 2008; Nabuurs et al., 2013). Our study provides input data for the quantification of vegetative biomass related ecosystem services and the analysis of potential service tradeoffs (e.g., carbon sequestration (carbon credits; European Union, 2017) vs. flood mitigating services (flood damage costs; De Moel and Aerts, 2011).

5. Conclusions and recommendations

This study quantified the annual biomass production capacity of floodplains along the Rhine River distributaries at a large spatiotemporal scale. On average, the contribution of non-woody and woody biomass to total biomass production across the 15 year (1997–2012) time period amounted to 94% and 6%, respectively. The floodplains along the IJssel River showed the highest biomass production, both in total and per hectare. Floodplains along the Nederrijn-Lek River produced the least amount of total biomass, while floodplains along the Waal River featured the lowest production per hectare. Woody biomass production was highest in floodplains along the Waal River.

Total and non-woody biomass production decreased along all three distributaries from 1997 to 2012 (12–16% and 13–19%, respectively), while woody biomass production increased by 10–37%. Multiple flood protection measures carried out during this period led to the reconstruction of floodplains and the associated removal of vegetation or conversion of semi-terrestrial areas to aquatic ecotopes. The switch from intensively managed production grasslands to natural grasslands also caused a reduction in biomass production.

Vegetation age and local environmental conditions were not incorporated into the woody biomass calculations due to lack of data. Therefore, we recommend further research to determine species, age and height specific growth rates of shrub and forest ecotopes under various environmental conditions.

Our approach allows spatially explicit estimations of biomass production in floodplains which can serve as input to life cycle analyses of sustainable biomass use.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2017.12.044.

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