Revealing 35 years of landcover dynamics in floodplains of trained lowland rivers using satellite data

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Abstract
Lacking substantial erosive and sedimentation forces, regulated rivers allow their floodplains to become overgrown with forest, increasing the flood risk of the hinterland. In the Netherlands, floodplains have therefore been subjected to interventions, like clear cutting, lowering and creation of side channels, and management, consisting of grazing and mowing. However, the comprehension of how those activities influence landcover dynamics is lacking. The aim of this study is therefore to investigate long-term landcover dynamics of a regulated river system through the lens of remote sensing. What transitions between landcover classes can be observed? And how (if) do management and interventions impact succession and retrogression of landcover classes? The study area comprised the upstream part of the Dutch Rhine River, its three branches and five adjacent floodplains. Satellite data (LandSat 5 and 8), encompassing a 35-year period (1984–2018), were used for studying landcover dynamics. Landcover classification was based on seven classes: water, built-up area, bare substrate, grass, herbaceous vegetation, shrubs and forest. Retrogression was highest for the landcover classes obstructing water flow (shrubs, forest and herbaceous vegetation), succession was most frequent on bare substrate, and water and grass were the most stable landcover classes. The regulated nature of the system became apparent from the spatial and temporal cacophony of landcover dynamics which differ from those of natural meandering rivers. This study showed that satellite data are useful for analyzing the impact of human activities within floodplains of regulated rivers and may assist in floodplain management aimed at combining water safety and nature policies.

KEYWORDS
floodplains, Google Earth Engine, landcover dynamics, regulated rivers, river management, satellite data

INTRODUCTION

Floodplains of natural rivers are one of the world’s most distinct ecosystems (Tockner & Stanford, 2002). These rivers actively shape the vegetation composition of their floodplains by meandering through the landscape in which erosion removes vegetation and sedimentation provides areas with bare substrate to restart vegetation succession (Corenblit, Steiger, Gurnell, & Naiman, 2009; Corenblit, Steiger, Gurnell, Tabacchi, & Roques, 2009; Geerling et al., 2006). These landscaping processes create a diverse landscape with a variety of successional stages (Nanson & Beach, 1977). When rivers become channelized, fixed, or dammed riverine forces cease and floodplain
vegetation composition is shaped more dominantly by biological processes (Bornette, Tabacchi, Hupp, Pujjalon, & Rostan, 2008; Garofano-Gomez et al., 2017; Geerling et al., 2008), potentially leading to floodplains overgrown with forests (Ward, Tockner, Arscott, & Clare, 2002).

The disruption of the floodplain–river interaction and hence the massive development of shrubs and forests in floodplains may jeopardize flood safety by hampering water flow, which, during periods of high-water discharges, results in decreased water discharge capacity and therefore increased flood levels (Baptist et al., 2004). In the Netherlands, flood risk is reduced by actively managing vegetation development. However, as many of the Dutch floodplains are listed as natural areas with a legal status, the active management of vegetation may conflict with nature policies, as flood safety demands smooth areas, while natural areas thrive under high variety of vegetation structures brought about by different development stages. As such, both the river manager and various authorities responsible for nature have a keen interest in understanding large-scale dynamics of floodplain vegetation (Geerling, Duel, Buijse, & Smits, 2013).

Various management and intervention activities have been executed and have focused on flood safety and/or nature policies (Figure 1). The activities can be divided in two types: there are small-scale management activities which mostly affect the rate of succession and larger-scale interventions, which have a more disruptive character. The small-scale management activities are often ad hoc, have various forms and have remained largely undocumented. Examples of types of small-scale management are sowing bare sediments with seed mixtures to create “natural” grasslands to cut-off direct succession from bare soil to forest (softwood); grazing by horses and cattle at higher intensities to halt or limit succession and at lower densities for semi-natural landscaping; and beavers were reintroduced to enhance diversity in vegetation structure of woody vegetation (Pelser, Platteeuw, & Vulink, 2003; Sluiter, 2003). The larger-scale (1–5 km) interventions have been aimed at sand and clay extraction and have been deployed for nature rehabilitation purposes (Buijse et al., 2002). Examples are the removal of trees, shrubs and reed (Oosterloo & Otermann, 2016) and floodplain lowering (Geerling et al., 2008; Simons et al., 2001; Van Vuren et al., 2005).

The various management activities and interventions produced a patchwork of land covers of which the long-term (>10 years) large-scale dynamics in terms of succession, retrogression, and their spatial patterns are unknown. Therefore, the aim of this study is to investigate long-term landcover dynamics of a regulated river system through the lens of remote sensing. What transitions between landcover classes can be observed? And how (if) do management and interventions impact succession and retrogression of land cover classes? We show large-scale pattern dynamics and selected smaller scale examples of management and interventions related to succession and retrogression. In the discussion we focus on linking the observed pattern dynamics to known management policies and activities. As method we use the time series of Landsat 5 and 8 as available in Google Earth Engine which has been applied to river landscape changes (Donchys et al., 2016; Gorelick et al., 2017; Zurqani, Post, Mikhailova, Schlautman, & Sharp, 2018).

2 | DATA AND METHOD

The Rhine River enters the Netherlands with an average discharge of 2,217 m³/s (100 year averaged, www.waterinfo.rws.nl). Shortly after entering the Netherlands, the Rhine River splits into the Waal River and the Nederrijn River. A few kilometres downstream the first split, the IJssel River branches off from the Nederrijn River. The discharge is roughly divided in a ratio of 6:2:1 between the Waal, Nederrijn and IJssel, respectively (Ten Brinke, 2005). The Nederrijn is the only impounded branch. Since the late 1980’s the use of floodplains has shifted from mainly agriculture to more nature conservation (Baptist et al., 2004). This study encompassed three scales: the river scale, the branch scale and the floodplain scale (Figure 2). On floodplain scale, five floodplains were selected to cover a range of management intensities and interventions (Table 1). The branch scale comprises the floodplains adjacent to those branches and the river scale comprises all the floodplains.

The availability of ground truth data is a major challenge, but of high importance for vegetation and landcover classification by satellites and other remote sensing techniques. It is needed for training and validating the selected classification algorithm. In the Netherlands, floodplain vegetation surveys for the Rhine took place in 1997, 2005,
The maps are based on manual interpretation of 25 cm ground resolution stereographic true colour airborne images (Geerling, Vreeken-Buijs, Jesse, Ragas, & Smits, 2009). In these maps, floodplain land cover is grouped into 29 classes, like natural and production grasslands, orchards, natural and production forests, pioneer vegetation and several more classes. The automatic classification of satellite images allows for identification of a limited set of vegetation classes. Therefore, the 29 detailed landcover classes were lumped together into seven classes: water, built-up area, bare substrate, grass, herbaceous vegetation, shrubs and forest (Data S1). Landcover changes in (part of) this sequence are referred to as succession, changes in the reverse order are referred to as retrogression. These lumped classes were used as ground truth data in the classification procedure.

On Google Earth Engine, data from Landsat 5 and 8, with a spatial resolution of 30 x 30 m, were used to study the period 1984–2018. All cloud free images were used. For each year, a composite image was produced by creating a seasonal median of each band and subsequently those bands were stacked. Using multiple images allowed for a better distinction between classes because of class specific spectral changes caused by differences in seasonal growth of (agricultural) management. Next, areas on the vegetation mappings were selected that remained the same between 1997 and 2017. The selected areas were used for training and validation, for which stratified sampling was used: 1000 pixels were selected, of which 700 were randomly selected for training and 300 for validation. The training pixels of the seven landcover classes were used to train a random forest classifier algorithm. This classifier was chosen because of its accuracy for classifications (Belgiu & Dragu, 2016). The algorithm was based on 50 decision trees per class. This classification was then applied to the whole composite image.

The accuracy across each landcover class was expressed in precision and sensitivity. Precision was defined as the true positives compared to the sum of the true positives and the false positives for a class. Sensitivity was defined as the true positives compared to the sum of true positives and false negatives for a class. The training and validation of the Landsat data resulted in an average accuracy of 77%. The accuracy differed between the landcover classes, where water was classified with the highest precision and sensitivity and herbaceous, shrubs and forest were classified with the least precision and sensitivity (Data S2 and Data S3). The overall kappa coefficient, to correct for chance, amounted to 72%, with a minimum value of 60% in 2002 and a maximum value of 81% in 2018.

To reduce noise of year to year fluctuations due to misclassification or short-term vegetation changes all data points were clustered into seven equal cohorts of 5 years. The clustering was based on the 5-year median value per data point. The clustering obviously masked dynamics on smaller time scales but allowed for a

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**FIGURE 2** Overview of the study area. In blue the study area, of which the lowest branch is the Waal River, the middle branch the Nederrijn River and the vertical branch the UsSEL River. The red pins indicate the location of the five floodplains used as case studies: Blauwe Kamer (BK), Duursche Waarden (DW), Gamerensche Waarden (GW), Klompenwaard (KW), and IJsselordsche Polder (IJP). Satellite image: Google Earth (2018)

**TABLE 1** Information on the selected floodplains: their river, area, date of function conversion, former use, date of excavation and the current intensity of grazing or mowing

<table>
<thead>
<tr>
<th>Floodplain</th>
<th>River</th>
<th>Area (ha)</th>
<th>Conversion to nature</th>
<th>Former use</th>
<th>Excavation</th>
<th>Current grazing intensity (animal/ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blauwe Kamer (B)</td>
<td>Nederrijn</td>
<td>229</td>
<td>1984</td>
<td>Clay extraction, grass and hay fields</td>
<td>1991/1992</td>
<td>3.0, year-round</td>
</tr>
<tr>
<td>Duursche Waarden (D)</td>
<td>Ussel</td>
<td>406</td>
<td>1987</td>
<td>Clay extraction</td>
<td>1989, 2007</td>
<td>1.3 year-round</td>
</tr>
<tr>
<td>Klompenwaard (K)</td>
<td>Nederij and Waal</td>
<td>93</td>
<td>1999</td>
<td>Grass fields</td>
<td>1999, entire area</td>
<td>0.3, year-round</td>
</tr>
<tr>
<td>IJsselordsche Polder (IJP)</td>
<td>Ussel</td>
<td>65</td>
<td>Not converted</td>
<td>Still agriculture</td>
<td></td>
<td>Mowing</td>
</tr>
</tbody>
</table>
general impression of the landcover dynamics. The data were then used to compile an overview of the net changes in landcover composition on the three scales, the age composition of today’s vegetation (defined as the time a pixel solidly belonged to its present-day class) to deduce the turnover rate of the landcovers, and subsequently, each pixel was tracked to obtain information on how frequent pixels changed into another landcover class to quantify the degree of change. Note that a forest pixel may counter-intuitively show succession, as it may start as forest, changes into bare substrate (retrogression) and returns to forest again (succession). For water it is similar, but then for retrogression as a water pixel may start as water, change into bare substrate (succession) and return to water again (retrogression). Additionally, per pixel a trendline was fitted through the seven cohorts as indication for the rate of succession and retrogression.

3 | RESULTS

3.1 | Changes in landcover

In all three branches grass was the most dominant landcover (>50% on average), followed by water (>10% on average). Subsequent shares of landcover differed between the branches (1859 ha on river scale). Also the area with forest (182 ha) and built-up (40 ha) decreased on river and branch scale with the exception of built-up area in the Waal branch. On river scale, the landcovers of herbaceous vegetation, water bare substrate and shrubs all increased, 1,012, 941, 91 and 36 ha, respectively. The Nederrijn and Waal branches showed, however, a decrease in shrub landcover.

**FIGURE 3** Mean land cover composition (hectare) on all three scales and in 5-year median cohorts of landcover composition (hectare) for the five floodplains over the period 1984–2018.
Landcover composition was more diverse and dynamic on floodplain scale (Figure 3). Considering the 35-year period, grass dominated in IJsseloordsche Polder, Duursche Waarden, Klopmenwaard and Gamerensche Waarden, while herbaceous vegetation dominated Blauwe Kamer (but only just). The decreasing trend in grass area found on river and branch scale was also apparent on floodplain level, except for IJsseloordsche Polder where all landcover classes were rather stable. For the four other floodplains, the area with water increased, as did the herbaceous vegetation and bare substrate. Shrubs decreased only in Gamerensche Waarden and forest in Blauwe Kamer and Duursche Waarden. Built-up area decreased only in Blauwe Kamer and Gamerensche Waarden.

3.2 | Age composition

The changes in landcover composition were temporally non-equidistant on any of the three scales (Figure 4). Grass, water, built-up and forest were the oldest (most stable) landcovers, while shrubs, herbaceous vegetation and bare substrate were younger. For example, in general around 70% of today’s grass landcover has been present since 1984–1988. The shrub landcover existed mostly (ca. 80%) of vegetation younger than 15 years. On floodplain scale, the age composition of the landcover classes was more variable than on river and branch scale.

3.3 | Succession, retrogression and stability

On all levels, retrogression was higher than success and stability for herbaceous vegetation, shrubs and forest (Figure 5). On floodplain level there were two exceptions. Herbaceous vegetation did show higher stability than retrogression in Blauwe Kamer and in Duursche Waarden. Forest dynamics were dominated by stability instead of retrogression. On all levels, stability was highest for water and grass. Again, two exceptions were observed on floodplain level: retrogression of grass instead of stability dominated Blauwe Kamer and succession of grass dominated stability in Gamerensche Waarden. Succession was, on all levels, highest for built-up landcover as it started to become overgrown, expect for Blauwe Kamer and IJsseloordsche Polder where built-up area remained mostly stable. Bare substrate showed mixed dynamics: succession was most dominant on river scale, for the Waal and Ussel branches and in Gamerensche Waard and IJsselooordsche Polder. In Duursche Waarden retrogression and succession were balanced and in Klopmenwaard stability dominated over retrogression and succession dynamics.

3.4 | Landcover dynamics

Changes in landcover were brought about by a variety of transitions. For example, grass could develop into shrub and subsequently retrogress into herbaceous vegetation, or it could develop into herbaceous vegetation and then into forest (Data S4, database is available by contacting the first author). Even though numerous potential changes were observed, principal links between landcovers could be identified. On river and branch scale, bare substrate developed mostly into grass and herbaceous vegetation, grass into herbaceous vegetation and bare substrate, herbaceous vegetation into grass and shrubs, shrubs into herbaceous vegetation and forest, and forest into shrubs and herbaceous vegetation (Data S5). These changes between landcovers were also identified on floodplain scale, but there were differences. The more rigorously excavated floodplains (Gamerensche Waarden and Kloopenwaard) showed a strong tendency of the vegetated landcover classes turning into bare substrate. In IJsselooordsche Polder grass could change...
into another vegetation class, but most of the initial grass landcover returned back to grass.

3.5 Spatial dynamics

Seen on an aerial view, areas could be highlighted with high rates of succession and regression and areas with stable land cover dynamics over the 35-year study period. For some floodplains, like Klompenwaard, high succession rates are present in the whole floodplain, while in others those higher succession and regression rates are only present in some areas of the floodplains, like in Duursche Waarden, Blauwe Kamer and Gamerensche Waard. In those three floodplains, and the whole of IJsselooordsche Polder, there are also areas with almost stable to stable land covers (Figure 6).

4 DISCUSSION

When comparing age composition (Figure 4) and landcover dynamics (Figure 5) to natural flowing rivers (e.g. Geerling et al., 2006; Marston et al., 1995), the regulated nature of the floodplains of the branches...
of the Dutch Rhine River is illustrated clearly. The studies of Marston et al. (1995) and Geerling et al. (2006) showed that water, bare substrate and grass landcovers are the most dynamic landcovers due to active alluvial processes. Shrub and forest landcovers were shown to be the most stable because those landcover classes are typically located in less active areas. In contrast, in the floodplains of the regulated Dutch Rhine River, water, grass and forest landcovers were the most stable landcovers and shrubs the least stable, signalling the absence of alluvial landscaping forces and the presence of other landscaping forces, like human management and interventions. In addition, clues on the presence of management and interventions were also given by the rates of succession and retrogression: the rate of succession was in general lower and the rate of retrogression higher than observed in the natural meandering Allier River (Geerling et al., 2006).

The strong retrogression found in our study may be linked to the creation of side channels and/or floodplain lakes in Blauwe Kamer (Demon & Van Bussel, 1994), Duursche Waarden (Rijkswaterstaat, 1994), Gamerensche Waarden (Jans, 2004) and Klompenwaard (Schoor, Greijdanus, Geerling, Van Kouwen, & Postma, 2011). And, although being speculation, the relative high rate of succession in those four floodplains, compared to the rate of succession in IJsselooordsche Polder, which is still under an agricultural management regime, could be caused by the transition from agricultural to nature-oriented management. Interestingly though, is the effect of grazing intensity in the non-agricultural managed floodplains. Landcovers appeared more stable under lower grazing intensity than under higher grazing intensity. This is unexpected as in general higher grazing regimes are used to control vegetation development: fixating the landscape (Vulink, 2001). However, the actual effect of grazing on landscape dynamics may be more complex, as vegetation structure and how the landscape is used by grazers may play a role (Gill, 2006). Additionally, landscape characteristics such as soil moisture and vegetation productivity are found to interact with land cover changes and grazing intensities (Adler, Raff, & Lauenroth, 2001; Zheng, Li, Lan, Ren, & Wang, 2015).

To balance vegetation management between flood safety and nature policies, the information in Figure 6 could be helpful to managers by revealing how management and interventions spatially and

FIGURE 6  Aerial view of succession, retrogression and stability of the landcovers of the five floodplains. Areas with high rates of succession are indicated with red, those with high rates of retrogression with blue and the more stable areas as yellow. The white tube-like shape is a river branch of which the name is mentioned in the titles of the figures.
temporally steer landcover dynamics. Nowadays practice is to allow for as much natural landcover dynamics as possible. To do so, models on landscape dynamics (Baptist et al., 2004) and a real-time monitoring system of landcover composition based on satellite imagery have been used (Geerling et al., in preparation). However, the success of allowing as much space to landcover dynamics as possible for conserving riparian vegetation is to be questioned, as the habitat template of the floodplains has changed by regulation of the Dutch Rhine River and the continuous human-disturbance (Stella, Rodríguez-González, Dufour, & Bendix, 2013). Under those changed environmental conditions, competition between riparian and terrestrial species become more important, altering the composition and the ecological functioning of those floodplains (Corenblit et al., 2017).

Note that the accuracy of the classified images could have led to overestimation of landcover dynamics, especially between grass and herbaceous landcover and shrub and forest landcover. This effect was partly overcome by using 5-year cohorts. Although being in agreement with accuracies of other studies (Azzari & Lobell, 2017; Huang et al., 2017; Mitchell, Wilson, Tweedt, Mii, & James, 2016), the accuracy may be increased by adding radar data as input to the classifier (Joshi et al., 2016). Also, adding satellite data with higher spatial and temporal resolution improves accuracy, like Sentinel2 data, with a resolution of 10 × 10 m, or even commercial available higher accuracy satellites, like Spot, Triple Sat or Worldview 3.

5 | CONCLUSION

Satellite images proved useful in researching how long-term vegetation development is impacted by river regulation and human activities aimed at guaranteeing water safety and meet nature goals. The satellite imagery revealed that human management and interventions resulted in a cacophony of landcover dynamics. In natural flowing rivers, there are distinct areas of higher and lower landcover dynamics which can be explained by the course of the river. In the studied regulated river system, higher and lower landcover dynamics resulted from spatially diverse management and interventions, obstructing disclosure of large-scale natural landcover developments.

Compared to natural flowing rivers, management and interventions slowed down succession rates and increased retrogression rates for the more water obstructing landcover classes (shrubs, forest and herbaceous vegetation). The smoother landcover classes (water and grass) displayed slower rates of both succession and retrogression. The presented aerial views of dynamic and stable areas could be an aid in streamlining management and interventions to allow vegetation to develop as natural as possible on its current habitat template without jeopardizing water safety.

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DATA AVAILABILITY STATEMENT

The database is available through contacting the first author. Cleaned data are included as appendices.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of this article.

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