Field systems and later prehistoric land use: new insights into land use detectability and palaeodemography in the Netherlands through LiDAR, automatic detection and traditional field data

Arnoldussen S.; Verschoof-van der Vaart, W.B.; Kaptijn, E.; Bourgeois, Q.P.J.

Received: 21 March 2022 | Revised: 11 November 2022 | Accepted: 8 December 2022

DOI: 10.1002/arp.1891

RESEARCH ARTICLE

WILEY

Field systems and later prehistoric land use: New insights into land use detectability and palaeodemography in the Netherlands through LiDAR, automatic detection and traditional field data

Stijn Arnoldussen[1] | Wouter B. Verschoof-van der Vaart[2] | Eva Kaptijn[3] | Quentin P. J. Bourgeois[2]

[1]Groningen Institute for Archaeology, Groningen University, Groningen, Netherlands

[2]Faculty of Archaeology, Leiden University, Leiden, Netherlands

[3]Erfgoed Gelderland, Arnhem, Netherlands

Correspondence
Stijn Arnoldussen, Groningen University, Groningen Institute for Archaeology, Poststraat 6, 9712 ER, Groningen, Netherlands.
Email: s.arnoldussen@rug.nl

Abstract

This paper discusses how the use of AI (artificial intelligence) detected later prehistoric field systems provides a more reliable base for reconstructing palaeodemographic trends, using the Netherlands as a case study. Despite its long tradition of settlement excavations, models that could be used to reconstruct (changes in) prehistoric land use have been few and often relied on (insufficiently mapped) nodal data points such as settlements and barrows. We argue that prehistoric field systems of field plots beset on all sides by earthen banks—known as Celtic fields—are a more suitable (i.e. less nodal) proxy for reconstructing later prehistoric land use.

For four 32.25 km^2 case study areas in different geogenetic regions of the Netherlands, prehistoric land use surface areas are modelled based on conventional methods and the results are compared to the results we obtained by using AI-assisted detection of prehistoric field systems. The nationally available LiDAR data were used for automated detection. Geotiff DTM images were fed into an object detection algorithm (based on the YOLOv4 framework and trained with known Dutch sites), and resultant geospatial vectors were imported into GIS.

Our analysis shows that AI-assisted detection of prehistoric embanked field systems on average leads to a factor 1.84 increase in known surface areas of Celtic fields. Modelling the numbers of occupants from this spatial coverage, yields population sizes of 37–135 persons for the case study regions (i.e. 1.15 to 4.19 p/km^2). This range aligns well with previous estimates and offers a more robust and representative proxy for palaeodemographic reconstructions. Variations in land use coverage between the regions could be explained by differences in present-day land use and research intensity. Particularly the regionally different extent of forestlands and heathlands (ideal for the (a) preservation and (b) automated LiDAR detection of embanked field systems) explains minor variations between the four case study regions.

KEYWORDS
artificial intelligence, Celtic fields, later prehistoric field systems, LiDAR, palaeodemography

1 | INTRODUCTION

1.1 | Problem definition

Based on settlements, funerary sites and object depositions recovered, it is clear that various and geologically distinct regions within the present-day Netherlands were inhabited between 2000 BCE and 50 BCE (the Bronze and Iron Age periods; e.g. Arnoldussen & Fokkens, 2008; Harsema, 2005; Schinkel, 2005). Despite this, archaeologists have struggled to use this data for reliable reconstructions of land use and palaeodemography (cf. Nikulka, 2016, esp. 72–73; 92–95; Roymans & Kortlang, 1999, esp. 36–40; Wolthuis & Arnoldussen, 2015). This means that important issues such as social cohesion (cf. Arnoldussen, 2008, 66 note 1; Gerritsen, 2003, esp. 109–111), resilience to ecological change (cf. Jongste & van Zijverden, 2007; Kluiving et al., 2015; van Zijverden, 2016, esp. 30–33; 133), agricultural sustainability (cf. Gerritsen, 2003, esp. 172–178) and cultural changes affected by or attributed to palaeodemographic parameters (i.e. migration, mobility and (over)population[1]) presently lack models applicable beyond the often small-case research areas of the studies cited here. This issue is of course not limited to the Low Countries, and for other areas of the North–West European basin, archaeologists similarly struggle with the construction and evaluation of palaeodemographic models of later prehistory (ranging in scale from local case studies to pan-European models[2]). In this paper, we will however focus on the palaeodemography of the Netherlands, due to the high-quality datasets available and its long-standing history of archaeological research of its settled landscape (e.g. Arnoldussen & Fokkens, 2008; Fokkens & Roymans, 1991).

Yet, for an area with such a long-standing archaeological research tradition into later prehistoric settlement, the lack of recent and refined palaeodemographic models and insights into changes in land use intensities is striking and problematic. Seeing as the later prehistoric periods here saw significant changes in settlement modes,[3] funerary traditions,[4] subsistence base[5] and material culture,[6] our understanding of the ways in which palaeodemography and land usage affected such themes is limited. This is because traditional approaches towards reconstructing diachronic changes in population estimates have mostly relied on singular datasets, that is site distributions, be it settlements,[7] funerary sites[8] or combinations of these[9] mapped or recorded as point-based data (rather than as surface polygons; i.e. these are nodal data). Moreover, the territories and population densities thus proposed have been established for small well-studied and ideally well-defined study regions (Figure 1, left: Louwe Kooijmans, 1995, 420 fig. 4) but have been extrapolated to the Netherlands at large without much critical reflection (cf. Harsema, 1980, 32; Gerritsen, 2003, 239; Louwe Kooijmans, 2005, 698; Figure 1, right).

Whereas such attempts are to be commended for their daring approach and for addressing the issue, to begin with, there are evident issues that affect their reliability. These comprise map formation processes (sensu Fokkens, 1998, 54–60), differences in research intensities and subsequent issues of representativity. For example, Bourgeois (2013, 40) has estimated that 68%–73% of prehistoric barrows may be lacking from the archaeological record, putting the few excavated (less than several hundreds; cf. Theunissen, 1999, 57) Bronze Age barrows in perspective. Many have been lost due to heathland reclamation, village construction and agricultural activities (Bourgeois, 2013, 50). The number of Bronze Age settlement sites presently known through excavations for the entirety of the Netherlands amounts to less than 150 (cf. Fokkens & Arnoldussen, 2008, fig. 1, already an underrepresentation viz. the barrows), and an incomplete inventory for the Iron Age lists 523 sites (for *c.* 60% of the surface area, not corrected for an inhabitable surface in prehistory), suggesting that for the 3,000 years of the Dutch Bronze Age and Iron Age, *c.* 1,000 settlements are known for 34,870 km^2 (*c.* 0.03 settlement/km^2) which again seems an unrealistic underrepresentation of prehistoric realities. Similarly, establishing past occupation durations of settlements is hampered by difficulties in establishing (a) absolute dates, (b) possible contemporaneity of houses and (c) overall later prehistoric settlement longevity.[10] For prehistoric field systems, the previously difficult dating of their banks has benefitted much from the introduction of OSL dating of sediments directly (cf. Arnoldussen, 2018; Nielsen & Dalsgaard, 2017). Compensating for the above skewness and poor representativeness of mostly nodal data is difficult, but in this paper, we propose that prehistoric field systems may be a more reliable data source—in itself but also in complementary approaches—to reconstruct (agricultural) land use in the past. In this, we do not focus on land use intensity as defined by Erb et al. (2013, 466 tab. 1: input, outputs and changes in system properties) as these require a much finer temporal framework but rather aim to reconstruct (cumulative, resultant) surface coverage for key types of landscape usage such as settlement activities or agricultural fields systems.

[1] Cf. Arnoldussen, 2008, 464–466; Kootker et al., 2018; Roymans & Kluiving, 2012; Spek, 2004, 140–141; van Gijn & Waterbolk, 1984; Waterbolk, 1959.
[2] E.g. Feeser et al., 2019; Kristiansen, 2018; Müller & Diachenko, 2019; Nikulka, 2016; Zimmermann et al., 2009.
[3] Cf. Fokkens & Roymans, 1991; Fokkens, 2005; Gerritsen, 2008; Waterbolk, 1982.
[4] Cf. Bourgeois, 2013; Fontijn, 1996; Hiddink, 2003; Lohof, 1994.
[5] Cf. Bakels, 2009; Brinkkemper & Van Wijngaarden-Bakker, 2005; van Amerongen, 2016.
[6] Cf. Butler & Fokkens, 2005; van der Broeke, 2005.
[7] E.g. Arnoldussen, 2008, 464–466; Gerritsen, 2003, 212; 215; Schinkel, 1998, 161–183.
[8] E.g. Kooi, 1979, 167–179; Gerritsen, 2003, 212.
[9] E.g.Louwe Kooijmans, 1995, 419–420; Spek, 2004, 141; Waterbolk, 1995.
[10] Cf. de Vries, 2021, 90; Fokkens, 2019; Jongste, 2008; Schinkel, 2005.

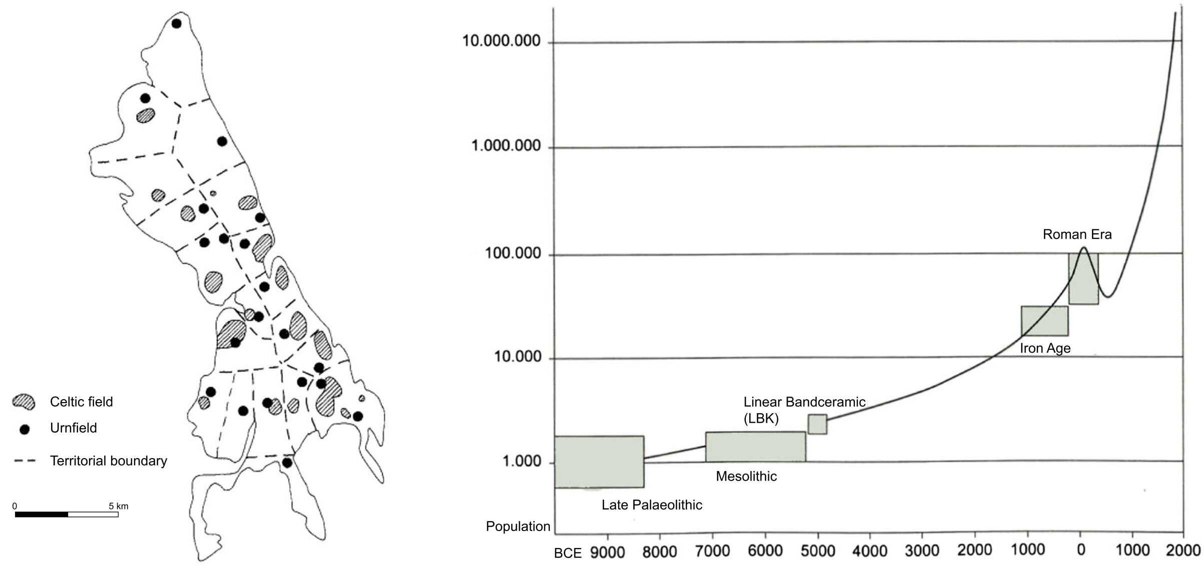

FIGURE 1 Left: Traditional method of palaeogeographic modelling for a well-defined area (near Emmen; from Louwe Kooijmans, 1995, 430 fig. 4). Right: Extrapolation of long-term population dynamics in the prehistory of the Netherlands (from Louwe Kooijmans, 2005, 697 fig. 3.11). [Colour figure can be viewed at wileyonlinelibrary.com]

1.2 | Research aim

The overall research aim is to test whether AI-assisted mapping of Celtic fields and using their surface area as input for palaeo-demographic modelling works better than traditional approaches that use human (expert) interpretation and nodal proxies such as settlements. We argue that there are several benefits to using prehistoric field systems as base data for reconstructions of prehistoric land use. First, being the locus of subsistence farming for local communities (Arnoldussen, 2018; Arnoldussen & van der Linden, 2017), these sites form strong proxy indicators for human presence in the landscape. Whereas archaeologists assume—and can partly prove—that habitation took place *within* these field systems in later prehistory (cf. Arnoldussen & de Vries, 2014, 2017), even if no excavations have taken place the rhythms and tasks of unmechanized agriculture presuppose habitation within economically suitable distances (here assumed to be <5 km). Second, excavations of embanked prehistoric field systems known as *raatakkers* in Dutch (Celtic fields) have shown that these were very stable (long-term) landscape structures, existing for centuries and perhaps to and over a millennium in some cases (between *c.* 1,200 BCE and AD 200 as shown by AMS and OSL dates of banks and fields[11]). Third, such prehistoric field systems have a substantial surface area (in our dataset, 205 ha on average [st. dev. = 115 ha]; Figure 2) and will have spanned up to several km^2 in prehistory. This means that—unlike geographically modest sites such as settlements or urnfields (or nodal sites such as barrows and deposition locations)—prehistoric field systems have a better chance of leaving a persistent presence in the landscape, despite being subject to detrimental forces such as urban sprawl, later agricultural usage or reclamation. Fourth, the methods of discovery for sites of this type do not have their roots in antiquarian traditions[12] —that are often nodal in approach and destructive in nature but rather are the results of an early example of 'remote sensing': aerial photography[13] gave a first impetus to the prospection of such sites, followed by a second push with the introduction, refinement and availability of LiDAR imagery.[14]

The identification and mapping of such later prehistoric field systems using LiDAR data have thrived in the last 5 years. Local heritage enthusiasts often scour freely available images and manage to recognize these (and other) archaeological sites[15] and in heritage management frequently LiDAR analyses or re-appraisals are commissioned to map or evaluate such sites.[16] Moreover, citizen science projects have proven very helpful in harnessing the interpretive power and enthusiasm of citizen researchers in mapping projects in the Central Netherlands (Veluwe and Utrechtse Heuvelrug; Lambers et al., 2019; Kaptijn et al., forthcoming).

Lastly, recent years have seen major advances in the use of (semi-) automated detection methods—with a clear trend towards the use of machine learning and deep learning approaches (Bickler, 2021; Fiorucci et al., 2020)—to detect different archaeological objects[17] in remotely sensed data (see Verschoof-van der Vaart, 2022 for an overview). Up to now, these methods have mainly been developed to

[11]AMS: Accelerator Mass Spectrometry, OSL: Optically Stimulated Luminescence, see Arnoldussen, 2018 for details of dating.

[12]Unlike with barrows, cf. Bourgeois, 2013, 3; Theunissen, 1999, 42–43.

[13]Brongers, 1976; Curwen & Curwen, 1923; von Frijtag Drabbe, 1947.

[14]E.g. Affek et al., 2022; Arnold, 2020; Devereux et al., 2005; Hesse, 2010, 2013; Humme et al., 2006; Meylemans et al., 2015.

[15]E.g. Janssen & Verhart, 2010; Wortelboer, 2014.

[16]E.g. Creemers et al., 2011; Jager, 2008, 2011; Meylemans et al., 2015; Oude Rengerink, 2004; Spek et al., 2009.

[17]In the field of Computer Vision the term 'feature' refers to the properties of an image, while an 'object' refers to real-world entities (Traviglia et al., 2016).

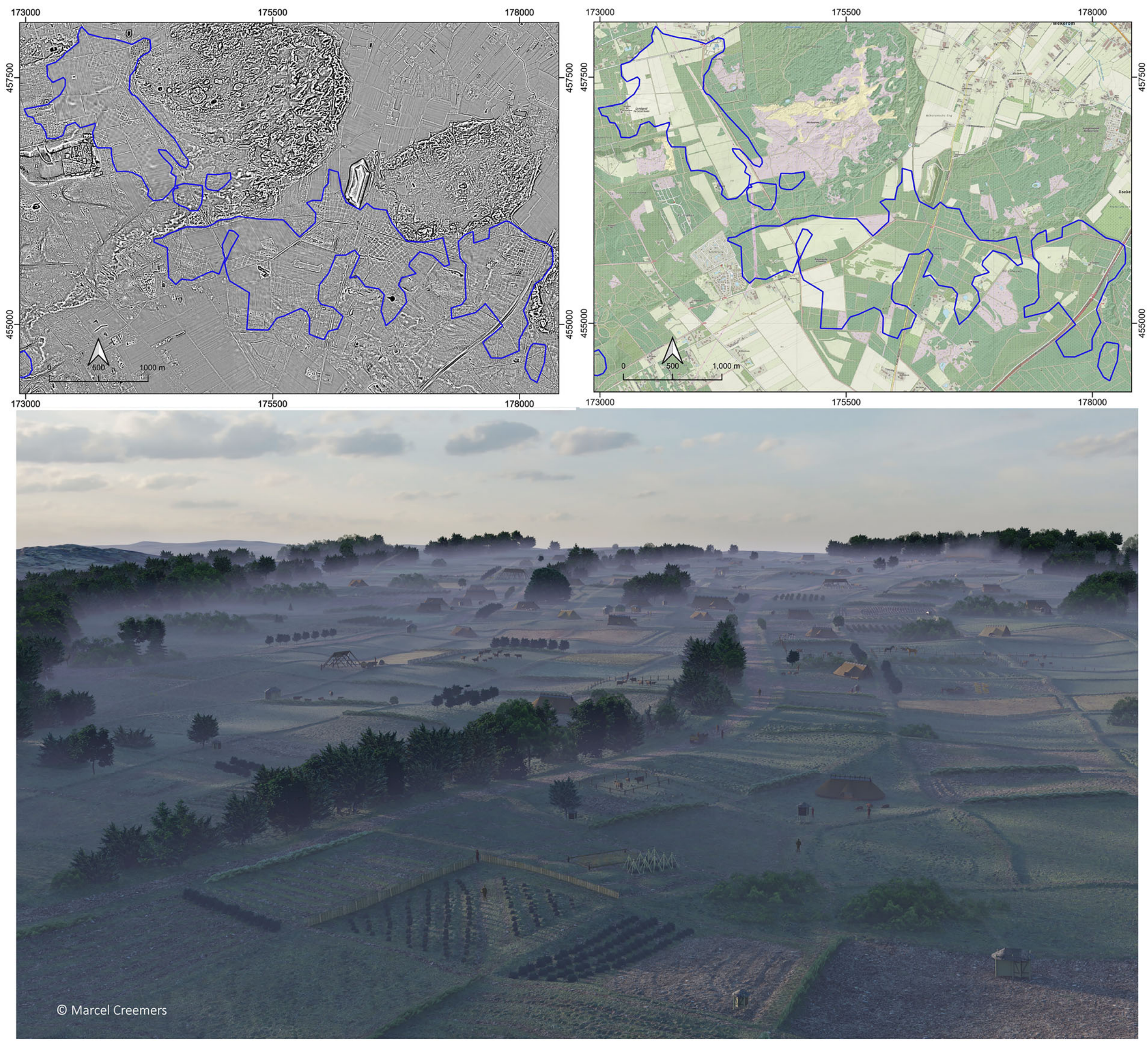

FIGURE 2 Top left: Example of the vast surface area of later prehistoric field systems known as raatakkers (Celtic fields; blue) near the hamlets of Lunteren and Wekerom (cf. Arnoldussen & Scheele, 2014), spanning areas of up to 1.9 km^2. Top right: The same Celtic fields (blue) on a current topographical map, showing forest in dark green, agricultural fields in light green and drift sand in grey. Bottom: Artist's reconstruction of an active raatakker system north of Elst (Utrecht) by Marcel Creemers (CC-BY-NC). [Colour figure can be viewed at wileyonlinelibrary.com]

detect compact, discrete objects, such as barrows and relict charcoal hearths (Davis, 2021; Traviglia & Torsello, 2017). However, several studies have been able to detect more complex, large-scale landscape patterns, such as field systems and roads using automated approaches.[18] For instance, Verschoof-Van der Vaart and Lambers (2021) were able to detect Celtic fields in the southern Netherlands using deep learning. In that study over 3 km^2 of Celtic field were detected in an area that was assumed to be devoid of these field systems, which contributed to major new insights into the structuring of the landscape in later prehistory (Verschoof-Van der Vaart & Lambers, 2021).

[18]Herrault et al., 2021; Olivier & Verschoof-van der Vaart, 2021; Verschoof-van der Vaart & Landauer, 2021; Verschoof-van der Vaart et al., 2020.

Therefore, in this study, a combination of automated and manual approaches is used to detect and map Celtic fields in the LiDAR data from four study areas, which differ in geology, current land use and archaeological research intensity, in the Netherlands (Figure 3). The results of these mapping efforts are used to estimate population sizes for the four study areas. Subsequently, these are compared to palaeo-demographic estimates based on settlement site data.

In Section (2), the study areas and the current state of archaeological knowledge are introduced, followed by an overview of the mapping methodology. In Sections 3 and 4, the results of the mapping effort and land use intensity estimation based on field systems will be presented, discussed and compared to other estimates based on settlement data. The paper finishes with general remarks on the methodology used (Section 5).

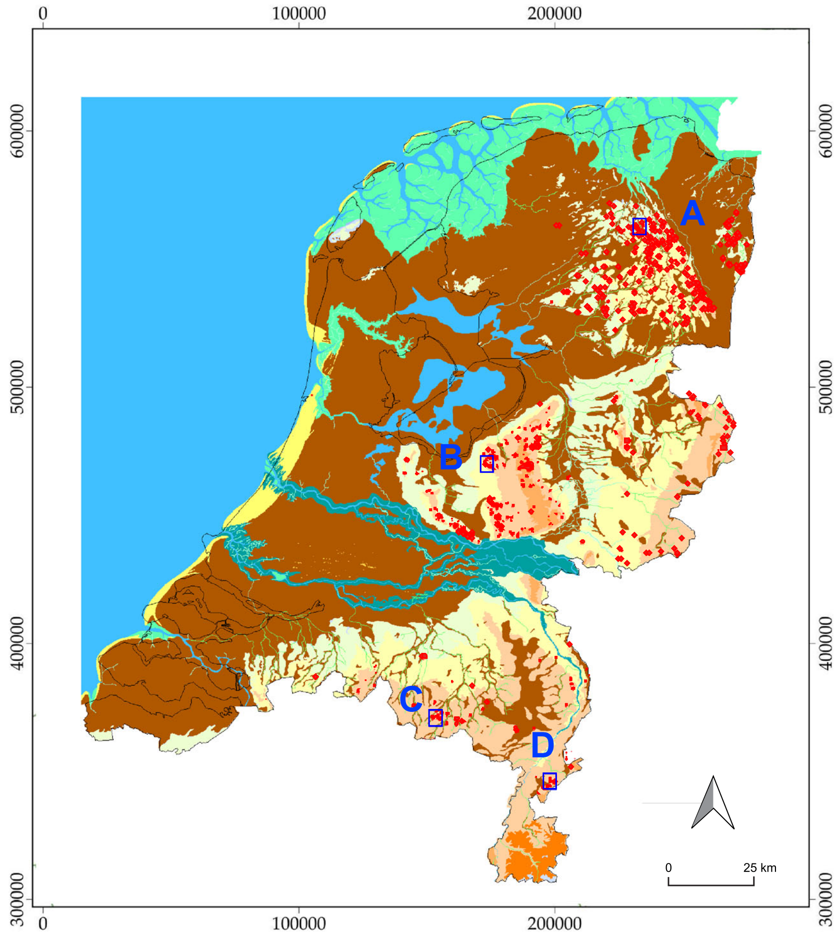

FIGURE 3 The four study areas (black), from top to bottom: (A) Zeijen, (B) Putten, (C) Riethoven and (D) Posterholt, on a palaeogeographical map of the Netherlands around 1500 BCE (after: Arnoldussen et al., 2011, red polylines indicate tentative Celtic field locations. Coordinates in Amersfoort/RD New, EPSG: 28992). [Colour figure can be viewed at wileyonlinelibrary.com]

2 | MATERIALS AND METHODS

2.1 | Study areas

For this research, four separate areas in different parts of the Netherlands were selected (Figure 3; Table 1). In the following, these areas will be designated by a letter (e.g. A and D).

In terms of geogenetic setting, the Zeijen (A) and Putten (B) regions have been shaped mostly during Saalian glaciation (*c*. 370–130 kA BP; de Mulder et al., 2003, 197; 338), during which in the former boulder–clay plateaus delimited by erosion valleys were formed (Rappol, 1984; Rappol & Kluiving, 1992, 75–76; Van Smeerdijk et al., 1995, 453) and in the latter sediments of the precursors to the contemporary Rhine and Meuse rivers were mixed and pushed up (de Mulder et al., 2003; van der Meer et al., 1985). In both the Zeijen and Putten regions, a thin (<2 m) aeolian sand deposit of Weichselian Age (115–10 kA BP; de Mulder et al., 2003, 206; 349) may locally cover parts of the Saalian period reworked sediments.[19] The same sediment, Weichselian coversand, forms the main constituent of the Riethoven study area (C), which locally overlies older Meuse precursor fluvial sediments (de Mulder et al., 2003, 323; 349) and is cross-cut by stream and brook valleys (Gerritsen, 2003, 17–18; de Mulder et al., 2003, 350). Coversand undulations, stream valleys and river dunes—often overlying older Meuse terraces and meanders (de Mulder et al., 2003, 327; 348)—characterize the Posterhold study area (D) landscape.

For the four case study areas, there are marked differences in archaeological research intensity and in the attention given to issues of land use and palaeodemography. The Zeijen study area (A) has seen targeted excavations from 1918 onwards (also of field systems, albeit that their true nature was not recognized until 1940; van Giffen, 1940). Yet, even for this region, models of palaeodemography and land use were applied that were essentially extrapolated from other parts of Drenthe (Kooi, 1979, 173–174). Based on reconstructions of urnfield populations, Kooi (1979, 174) assumed population densities of 3–4 persons per km^2. For the other three study areas, archaeological research has been anecdotal and focussed on barrows (e.g. Gerritsen, 2003, 296; van Giffen et al., 1971) or settlements (e.g. Slofstra, 1991; Willems, 1981). These early projects targeted visible and recognizable entities such as barrows (Bourgeois, 2013; Theunissen, 2006) and chance finds of settlements. It was not until the introduction of developer-led archaeology that more diverse locations were more systematically

[19] Castel & Rappol, 1992, 119; De Mulder et al., 2003, 206–210; Oude Rengerink, 2004; Van der Meer et al., 1985.

TABLE 1 Main geological and archaeological characteristics of the four case study areas

Case study area	A	B	C	D
Dutch grid sheet	12bz1	32fn1	57bn1	68en2
Region name	Zeijen	Putten	Riethoven	Posterholt
Geogenesis	Saalian Boulderclay plateau with Weichselian coversand, interspersed with stream valleys	Saalian-period dislocated riverine sediment, with local coversand covers and dry valleys	Middle Pleistocene Meuse sediments covered by Weichselian coversand and interspersed with sandy/loamy brook valleys	Pleistocene and Holocene Meuse river sediment, interspersed with Weichselian coversand elevations
Regional palaeodemography available?	Kooi, 1979; Wolthuis & Arnoldussen, 2015	n.a.	Gerritsen, 2003	n.a.
Key archaeological references	Jager, 2008; Spek et al., 2003, 2009; van der Sanden, 2018; van Es, 1958; van Giffen, 1918, 1936, 1940; Waterbolk, 1977, 1985	van Giffen et al., 1971; Bourgeois, 2013	Gerritsen, 2003; Lascaris, 2004; Slofstra, 1991; van de Glind, 2013; Verhoeven, 2004	Willems, 1981; van Hoof, 2000
Main method of field system prospection	Aerial photography (Brongers, 1976) and LiDAR (AHN2/3; Jager, 2008)	Aerial photography (Brongers, 1976) and LiDAR (AHN2/3; Kooistra & Maas, 2008)	Aerial photography (Milkowski, 1985)	Automated LiDAR detection (Verschoof-Van der Vaart & Lambers, 2021)

investigated.[20] For the Putten (B) and Posterholt (D) regions, no models of land use or palaeodemography were ever constructed. For the Riethoven area (C), Gerritsen (2003, 121–122) postulated that—based in part on four other micro-regions studied (*op.cit*., 205 fig. 5.2)—later prehistoric population densities ranged from 2 to 5 persons per km^2.

With respect to strategies and sizes of field systems recovered in prior research, the four study areas also exhibit strong differences (Table 2). Excavations of field systems only occurred in the Zeijen region (Arnoldussen, 2012; Arnoldussen & van der Linden, 2017 for references), and most field systems mapped with aerial photography were also found in this region (Brongers, 1976, 133–134; Map 3 M-N). Human-interpreter-based identification of field systems appears modest: up to a maximum of five field systems per area were mapped this way (average = 29.2 ha; st. dev. = 35.14 ha).

2.2 | Archaeological inventory

In order to evaluate the results of this research, for all four study areas additional spatial data on settlements, funerary sites and deposition locations were collected. The basis for this inventory was the national Dutch archaeological database Archis3 (https://archis.cultureelerfgoed.nl/), from which data with a start and/or end date between the Bronze Age (2000–800 BCE) and Iron Age (800–12 BCE) were retrieved. In addition, the national Dutch repository Dans-EASY (https://dans.knaw.nl/nl/data-stations/archaeology/) was queried for excavated settlements from these periods. Also, several research datasets such as on Bronze Age and Iron Age settlements (Arnoldussen, 2008), and Celtic fields (*Erfgoed gezocht*; Kaptijn et al., forthcoming) were integrated. This resulted in a series of GIS tables often comprising multiple entries for a single set of coordinates (for example, larger excavations are represented by multiple listings for their constituent features and finds).

Here, we render explicit in what ways these additional layers are used in our analysis. First, only one record for a deposition site was listed in Archis3. This concerned the possible offerings placed in the 'Bolleveen' peat near Zeijen (van Giffen, 1950; Zeiler, 2005). As the relations between object deposition and settlement patterns are often unclear,[21] and none such sites could be listed for the three other study areas, these data points/site types were excluded from further analyses.

The dataset on settlements equally poses challenges. For three regions settlement excavations are known.[22] In addition to these certain later prehistoric settlements—known through excavation—vast numbers of entries in Archis3 are known that could—but not by definition—pertain to settlement sites. Amongst such listings in

[20] E.g. Bongers & Jelsma, 2012; Hielkema, 2008; Parlevliet & Flamman, 2003; Van der Glind, 2013; Verhoeven, 2004.
[21] Cf. van Beek, 2001, 70–74; 93–96; Fontijn, 2005, 2007; Arnoldussen, 2008, 442–454
[22] A: Van Giffen, 1936, 1940, 1950; Jelsma, 2004; Hielkema, 2008, C: Slofstra, 1991; Lascaris, 2011; Van de Glind, 2013, D: Willems, 1982.

TABLE 2 Origin, counts and surface areas for field systems known from the case study regions prior to our investigation

Case study area	A	B	C	D
Region name	Zeijen	Putten	Riethoven	Posterholt
Field systems known (archaeology) and surface area	Zeijen–Noordseveld (30.49 ha in van Giffen, 1939; 48.75 ha in Waterbolk, 1977)	n.a.	n.a.	n.a.
Field systems known from aerial photography & surface area	5 locations (est. 5 × 5 ha = 25 ha in Waterbolk, 1985, map 2), including Noordse veld	1 location (Krachtighuizen, Est. 5 ha; Archis wrnr 7,223)	1 location (est. 5 ha; Milikowski, 1985, fig. 4; Gerritsen, 2003, 168 tab. 4.11)	n.a.
Field systems known from human LiDAR recognition (AHN) and surface area	Zeijen–Noordseveld (71.68 ha; Spek et al., 2009, 27 afb 10c)	(4 locations, 272.2 ha; pers. com. V. Arnold; Kooistra & Maas, 2008, 2324 fig. 5)	(2 locations, 61.01 ha; pers. com. J. Bazelmans, T. Doesborg)	(4 locations, pers. com. T. Ernst, T Doesborg, 77.8 ha)
Totals (prior to this study)	6 locations, 98.81 ha	5 locations, 277.7 ha	2 locations, 61.01 ha	4 locations, 77.8 ha

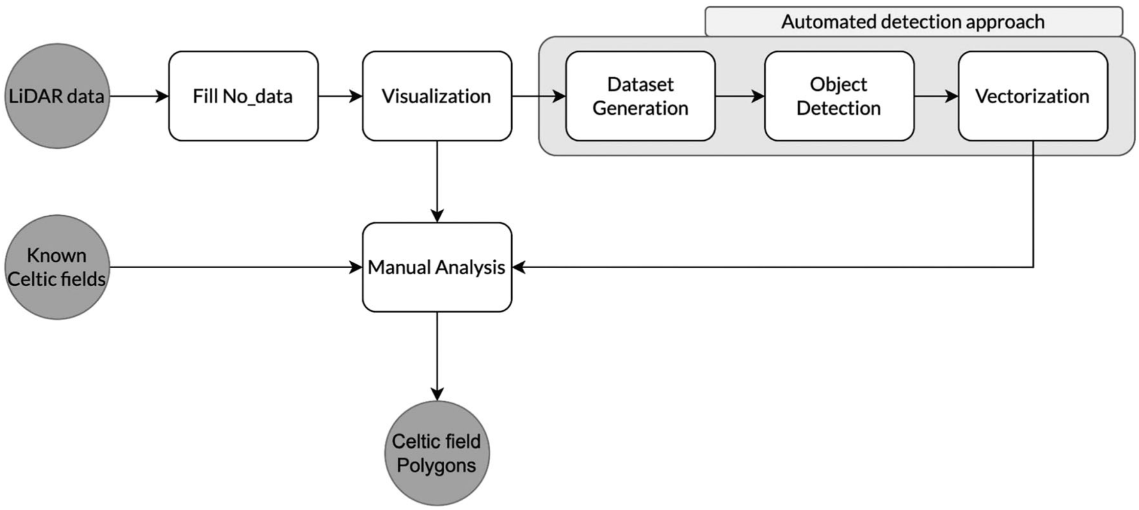

FIGURE 4 Schematic overview of the methodology used to annotate Celtic fields.

Archis3 are pottery fragments unequivocally datable to the period, flint artefacts and mentions of archaeological features such as ditches, fences and isolated postholes (without the certainty of a recognized later prehistoric house plan). In order to avoid entrenchment in strict (and arbitrary) criteria for what does—and what does *not*—constitute a probable, possible or tentative settlement site (cf. Arnoldussen, 2008, 66–69 for discussion), we opted for a landscape approach instead in which the totality of later prehistoric finds and features mentioned in Archis3 is used as the spatial input for a reconstruction of the late prehistoric 'settled landscape'. We define this as the zone in the landscape that—based on later prehistoric finds and features recovered—supported proven (excavated), probable, possible or tentative settlement sites.

Not only can we thus avoid discussion on the interpretative strength of each individual find in Archis3, but we can also bypass issues of data multiplication that originated from multiple artefacts and/or features being assigned to the same coordinate in Archis3. In the conversion of nodal (point) to polygon data, we have opted for a pragmatic 750 m buffer. This buffer reflects—but stays on the conservative side of—estimates based on the effective 'hailing distance' for neighbours in settlements (e.g. 150 m; Roberts, 1996, 24; Wesselingh, 2000, 20) and documented inter-house distances for Bronze Age (e.g. 53 m average; Arnoldussen, 2008, 328) and Iron Age (cf. Wolthuis & Arnoldussen, 2015, 174: max. 100 m) settlements and overall size estimates for later prehistoric hamlets (e.g. Fokkens, 1998, 141; Schinkel, 2005, 526). By using a cumulative 750 m buffer around possible settlement indicators, the settled surface area appears to be overestimated, but this deliberately functions as a counterweight to unquantifiable recovery biases.

2.3 | Human–computer mapping approach

In what follows, a combined human–computer strategy, as proposed and discussed by Verschoof-van der Vaart and Lambers (2021), was used to detect and map Celtic fields in LiDAR data from the four study areas (Figure 4). In such a strategy, automated detection is used in a supplementary role, next to manual analysis (see Section 4.2 for a discussion of human–computer strategies in practice). The automated detection is therefore not required to detect all Celtic fields areas and every plot therein, but rather it is used as an initial guide to detect new areas of Celtic field and give an initial estimation of their coverage, which can be used to ease the subsequent manual analysis. Consequently, the performance of the used method does not have to be high (see Verschoof-Van der Vaart & Lambers, 2021). This combination offers many opportunities for improving the investigation of remotely sensed data[23] and results in a more complete overview of the archaeology present and a gain in both quantitative and qualitative archaeological knowledge (Verschoof-Van der Vaart & Lambers, 2021).

For the automated and manual analysis, the third generation of Dutch LiDAR data (called *Actueel Hoogtebestand Nederland3* or AHN3) was used. This nationwide dataset has an average ground point density of 6–10 per sq m, a spatial resolution of 50 cm and a vertical and planimetric accuracy of 5 cm (van der Zon, 2013). The fourth generation (AHN4) is currently being made available on a nationwide level but is not available for all case study areas. The LiDAR data are freely available as an interpolated digital terrain model (DTM) from the online repository PDOK (Nationaal Georegister, 2021) in GeoTIFF tiles measuring 10,000 by 12,500 pixels (5 km by 6.25 km). Per study area, one of these tiles (31.25 km^2) was used (see Table 1 for the specific tiles used) and analysed in full. Prior to the analysis, the tiles were loaded into QGIS and a *Fill_nodata* processing tool was used to reduce the number of raster cells with no height data. Subsequently, the tiles were visualized with the simple local relief model visualization (Hesse, 2010) from the Relief Visualisation Toolbox 2.0 (Kokalj & Hesse, 2017). This visualization was chosen—based on earlier research on Celtic fields in Dutch LiDar Data (see Lambers et al., 2019)—as it very clearly represents slight elevations, such as the banks of Celtic fields.

Subsequently, an automated detection approach[24] was used to detect Celtic fields in LiDAR-derived DEM data. This method, developed by Olivier and Verschoof-van der Vaart (2021), consists of three parts: (1) a dataset generation part that uses geospatial information on the location of archaeological traces and LiDAR-derived DEM data to make cropped input images containing examples of archaeological traces of interest; (2) an object detection part, consisting of a convolutional neural network (CNN), that is a hierarchically structured algorithm consisting of multiple layers, which generally comprises a (image) feature extractor and classifier. In this case, the algorithm is used for object detection, where it has to predict the presence and location of an object, or a class of objects, in an image (Ball et al., 2017); and (3) a post-processing part that turns the results of the prior step (rectangular bounding boxes with a class and confidence score per input image) into geospatial vectors, directly usable in a GIS.

The object detection model used in this research, based on the YOLOv4 framework (Bochkovskiy et al., 2020), was previously transfer-learned[25] by Olivier and Verschoof-van der Vaart (2021) on a training dataset containing input images of LiDAR-derived DEM data from the Veluwe in the Netherlands, containing barrows, Celtic field and/or charcoal kilns. On a test dataset, this model reached an F1 score[26] of 0.82 for Celtic fields (Olivier & Verschoof-van der Vaart, 2021).

In this research, the LiDAR data from the case study areas were processed as described above and subsequently cut into input images of 500 by 500 pixels with 5% overlap in all directions. Subsequently, the pre-trained model from Olivier and Verschoof-van der Vaart (2021) was used to detect Celtic fields. The results were post-processed into geospatial vectors and loaded into QGIS.

The results of the automated detection and prior information on the location of Celtic fields (see Table 2) were used as the starting point of a manual analysis of the visualized LiDAR data. The manual analysis was performed by the second author, who has ample experience in analysing LiDAR data and considerable knowledge of the archaeology of the period. During the analysis elevation differentiation or histogram stretching (see Kokalj & Hesse, 2017) was used to enhance the contrast between archaeological features and the background. Every Celtic field area visible in the LiDAR-derived DEM data was annotated with a polygon. In the situation that the area was dissected by a modern topographic object (e.g. a road) two separate polygons were created. However, these two polygons were considered to belong to a single Celtic field complex.

3 | RESULTS

3.1 | Results of the mapping approach

Table 3 shows the results of the mapping approach conducted. Foremost, a substantial increase (average = 80 ha; st. dev. = 114.8 ha) in the area of Celtic fields can be observed. The largest increase can be observed in the Posterholt area (D; 113.2 ha), while the increase in the Riethoven area (C) is much more moderate (39.5 ha). The increase in area generally involves the extension of existing Celtic field systems, although additionally in every area 3–6 new locations were found (Figure 5). A cursory analysis of the automated detection results versus the known Celtic field locations shows that the majority of previously demarcated areas of Celtic fields in the different areas are detected, although this often involves not the full extent (i.e. all plots within the Celtic field). Well-defined Celtic fields are generally extensively detected while less conspicuous Celtic fields are only partially detected. This is in line with the results of the automated detection of Celtic fields performed by Verschoof-Van der Vaart and Lambers (2021) in the Midden Limburg area (the Netherlands).

[23]Bennett et al., 2014; Cowley, 2012; Trier & Piløw, 2012.

[24]The data generation scripts and the configuration files for the automated detection approach are available on: https://github.com/epsln/YOLOv4LiDAR.

[25]For the specific augmentations and modifications used for this model, see Olivier & Verschoof-van der Vaart, 2021, Table 2, "Modified model".

[26]The F1 score is a measure of a detection model's performance per class (Sammut & Webb, 2010). These measurements are normally restricted between 0 and 1, with higher values indicating a better performance.

TABLE 3 Results of the mapping approach per study area as compared to the prior known Celtic field areas

Case study area	Area old (ha)	Complexes	Area new (ha)	Complexes	Increase in percentage
A	81.3	5	160	8	96%
B	278.7	5	367.6	11	32%
C	61.2	2	100.7	6	65%
D	78.1	4	191.3	7	145%

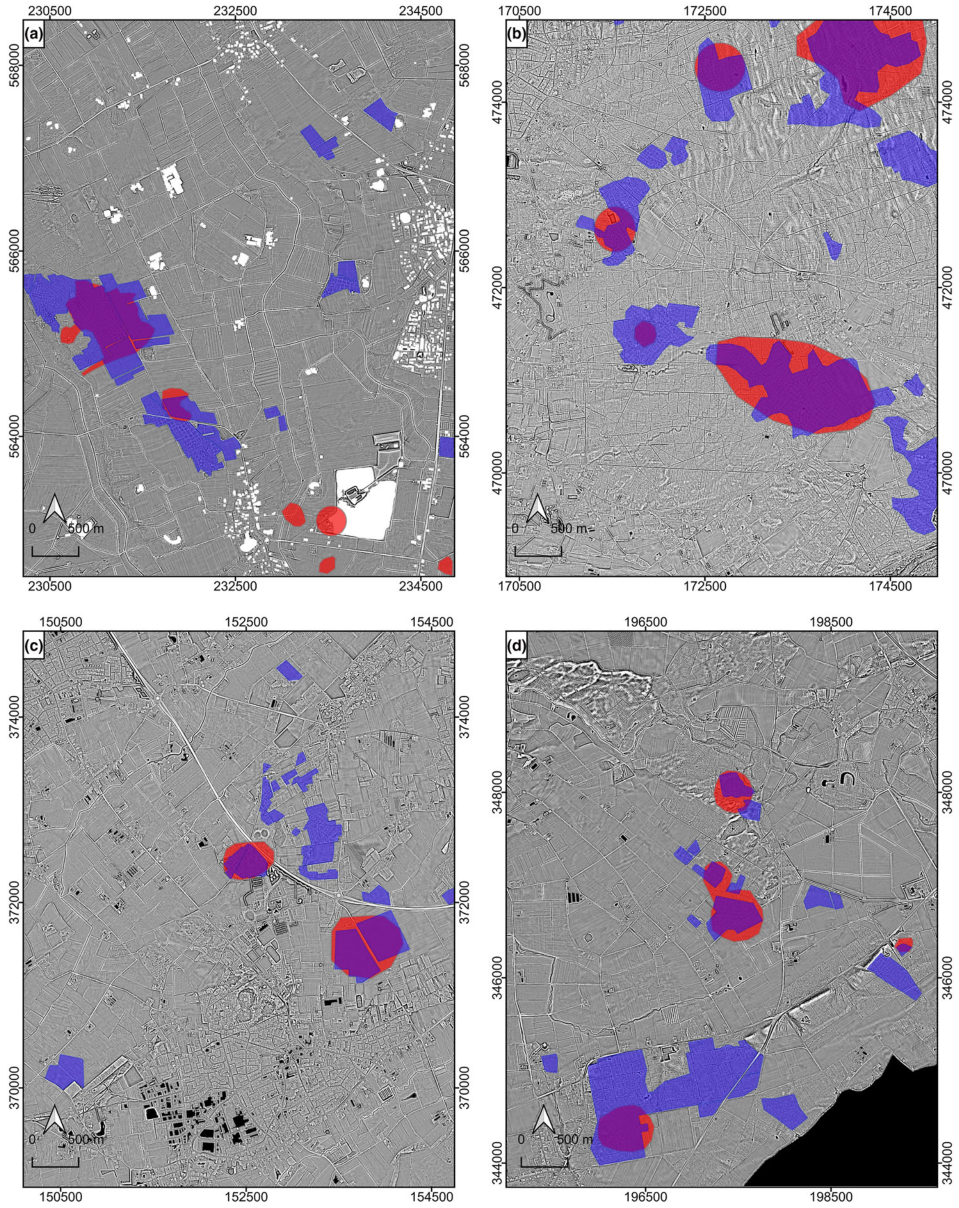

FIGURE 5 LiDAR-derived DEM data of the four study areas, visualized with simple local relief model (Hesse, 2010), showing the known Celtic field areas (red) and the results of the mapping approach (blue), overlap between the two is shown in violet (source of the elevation model: Nationaal Georegister, 2021; Coordinates in Amersfoort/RD new, EPSG: 28992). [Colour figure can be viewed at wileyonlinelibrary.com]

3.2 | Estimating land use intensity from field system data

Foremost, we should stress that the interpretative steps from field system coverage to land use intensities or demographic reconstructions are precarious but possible. If we treat prehistoric field systems as landscape structures rather than nodal points around which to draw Thiessen polygons of settlement territories,[27] we are much better equipped to appreciate their salience for prehistoric subsistence reconstructions. Inspired by New Archaeology's focus on models and calculations from the early 1960s onward, various archaeologists have

[27]Cf. Brongers, 1976, 67; Kooi, 1979, 173; Waterbolk, 1995, 15 Fig. 12; Louwe Kooijmans, 2005, 698 Fig. 31.2.

TABLE 4 Calculations and approximations of required arable sizes per person for Dutch later prehistoric agriculture

Ha required	Per	Remarks	Reference
7.69	Person	Celtic fields Emmen–Odoorn region	Brongers, 1976, 68
3.75	Person	Based on a three-course rotation	Kooi, 1979, 174–175
5	Person	Based on a two-course rotation	Kooi, 1979, 174–175
1.09–1.45	Person	6–8 p household with 10 animals	Fokkens, 1998, 144 tab. 27
0.98–1.32	Person	6–8 p household with 20 animals	Fokkens, 1998, 144 tab. 27
0.97–1.45	Person	10–15 p household with 10 animals	Fokkens, 1998, 144 tab. 27
9–18	Household	Based on Vaassen	Gerritsen, 2003, 177
1.28–2.57	Person	Based on Vaassen, assuming 7 p household	Gerritsen, 2003, 177
1.63–1.9	Person	6–7 p household, crop ratio 1:5, MBA-LIA average	Woltering, 2000, 350–351 tab. 22

tried to estimate the surface area of fields required by one household of subsistence farmers (Table 4). Based on Early Medieval crop yield and assumed agricultural regime (three- versus two-course rotation), Kooi (1979, 174–175) estimated an acreage of 3.75–5 ha arable per person. Fokkens (1998, 144 Table 27) drafted a quantitative model that—by variables of household and herd sizes and agricultural regime at hand (e.g. sod cutting, rotation schemes or stubble grazing)—estimated the arable (and fallow arable) for a 6–8 person household with 10 animals to be 8.7 ha (raised to 14.5 ha for a 10–15 person household and reduced to 7.9 ha for a 6–8 person household with a stronger livestock focus (20 animals; *loc.cit*.). Woltering (2000, 344 tab. 19; 350–351 tab. 22) estimated that a 6–7 person household would require between 7.2 and 17.6 ha of arable (11.4 ha average, for the Middle Bronze Age to Late Iron Age) based on the most pessimistic (1:5) grain yield ratio. Following the more detailed models of Fokkens and Woltering (Table 4), a range of 1–2.5 ha per person (or 10–40 persons per sq. km) seems a pragmatic and realistic approximation of required arable area in Dutch Later prehistory.

Whereas the above-modelled relations between required field system sizes *assume* or *imply* a correlation between habitation and arable,[28] there is solid footing for the spatial overlap (or integration) of habitation within Celtic field systems from the Early Iron Age onwards. At Hijken (Arnoldussen & de Vries, 2014), Peelo (Kooi & de Langen, 1987) and Westeinde (Arnoldussen & de Vries, 2017), Early Iron Age houses were excavated within Celtic field systems. For the Middle and Late Iron Age, Sellingen (van Giffen, 1939, 90), Vaassen (Brongers, 1976, 40–55), Wekerom (Arnoldussen & Scheele, 2014) and Hijken (Arnoldussen & de Vries, 2014) have similarly yielded house plans within the Celtic field confines (Figure 6).

If we are to approximate the correlation between field system plots and habitation, we should only take into account the plots that were effectively investigated at these sites (i.e. that show positive 'evidence of absence'). Using this strategy, Arnoldussen and De Vries (2017, 87) postulated that for sites where more than four plots were investigated (i.e. omitting investigations of insufficient size), an average ratio of house sites to field plots of 0.24 (st. dev. 0.12) seems plausible. As plot surface areas in Celtic fields are quite standardized (0.15 ha, st. dev. 0.03 calculated for Vaassen, Westeinde, Zeijen and Peelo), an average of 16 house sites for every 10 ha of field plots may be used as a crude approximation for Iron Age settlement densities within Celtic field systems. Depending on the essentially unknown estimate for the number of inhabitants of later prehistoric households (see Arnoldussen, 2008, 85–87 for a critical discussion), estimates of house-site longevity (*op.cit*., 88–92) and assumed contemporaneity (cf. Jongste, 2008, 105–107; Arnoldussen, 2008, 394; 464–465) numbers of house sites can with caution be used to crudely approximate later prehistoric habitation. For example, assuming a 6 person household and 50 years for farmhouse longevity, a 10 ha area of Celtic field may have supported 16 consecutive house phases over the duration of the (800 years) Iron Age period (i.e. 60 p km^2) or 5.33 settlement phases (each during 60 years, for a three house hamlet, at 96 year intervals) resulting in *c*. 7.2 persons per km^2. Averaging these extremes would mean that 33.6 p/km^2 (or 0.336 p/ha or 2.98 ha/person) appear plausible population densities for (within) Celtic fields. Using the results from our research, the later prehistoric population size can be estimated to range on average from *c*. 37 (case study area C) up to 135 (B; Table 5).

3.3 | Estimating land use intensity from 'settled landscape' data

In Section 2.2, we have argued that using data points tentatively indicative of later prehistoric settlements with a 750 m buffer provides a more representative measure of prehistoric land use intensities than excavated settlements alone. This moreover (a) solves the issue of research areas devoid of excavated later prehistoric settlements (i.e. area B: Putten), (b) bypasses discussions on the representativeness of singular finds as settlement proxies, (c) resolves point duplication issues (i.e. multiple records for one set of coordinates) and (d) acts as a counter-weight to recovery bias (i.e. underrepresentation) through overestimating the settled area as based on inter-house distances for the period. Whereas the buffer zones created provide an area of 'settled landscape' for each of the four case study areas (Table 6), any approximation of population sizes still relies on estimates of population densities. In Table 6, we

[28]Cf. Fockema Andreae, 1947, 292; Løvschal & Holst, 2014, 8; Oude Rengerink, 2004, 10.

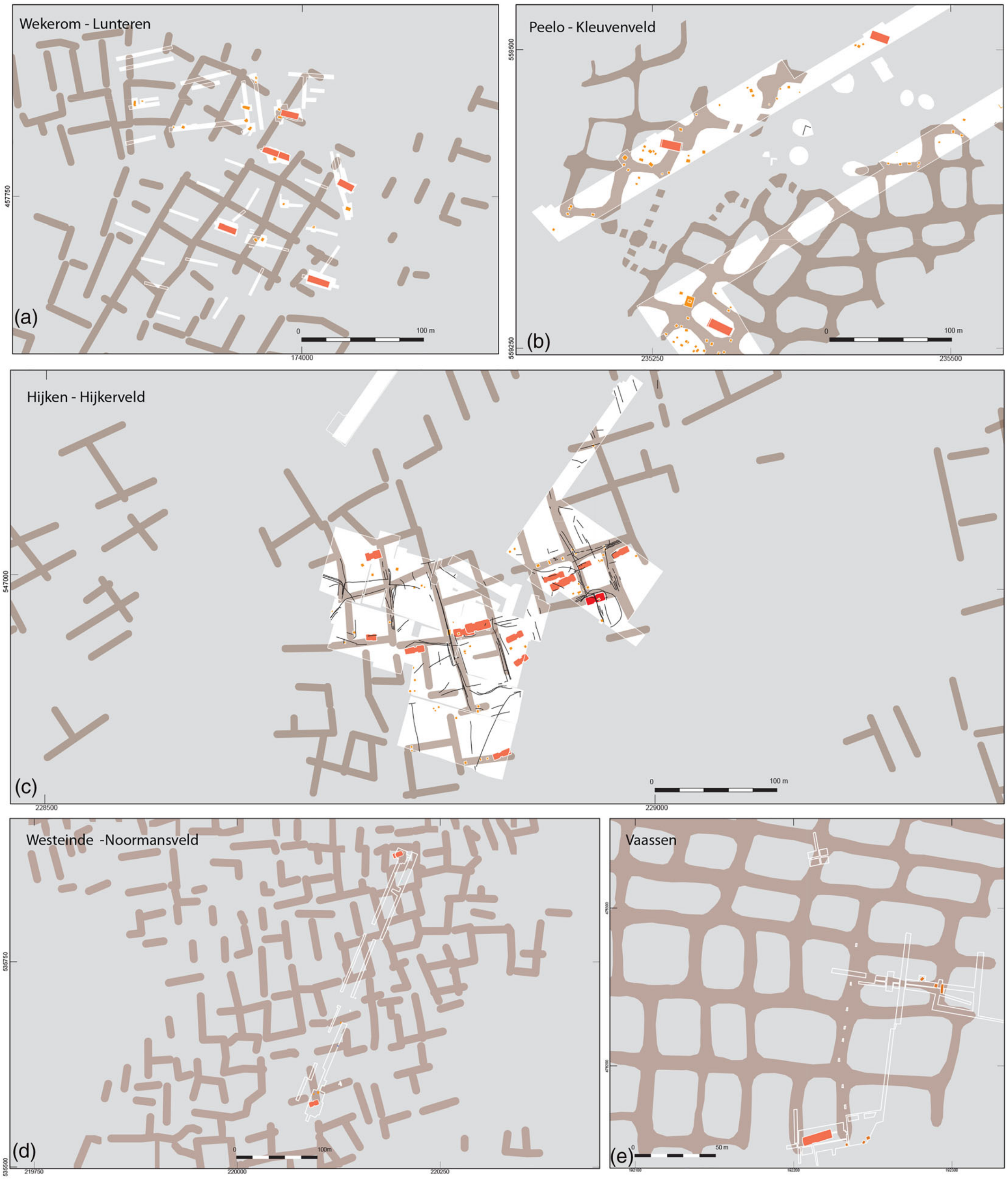

FIGURE 6 Overview of excavated Celtic fields with Iron Age habitation. (a) Wekerom–Lunteren: after Van Klaveren 1986; Arnoldussen & Scheele, 2014: 15 fig. 8), (b) Peelo–Kleuvenveld (after Kooi & de Langen, 1987; Kooi, 1979). (c) Hijken–Hijkerveld (after Harsema 1974; 1991: 23 fig. 2; Arnoldussen & de Vries, 2014: 101 fig. 12). (d) Westeinde–Noormansveld (after Arnoldussen & de Wit, 2018, 60 fig. 3.4.8.). (e) Vaassen (after Brongers, 1976, 44 fig. 4). White areas and outlines represent the excavated areas. The locations of reconstructed and observed Celtic field banks are depicted in halftone brown. Iron age houses and outbuildings are depicted in red, and the black polylines represent fence lines (note that for Peelo, Vaassen and Hijken barrows also present have been omitted from the plans). [Colour figure can be viewed at wileyonlinelibrary.com]

have used the population density estimate published by Gerritsen (2003, 221–222) of 2–5 persons per km^2 (figures ultimately based on urnfield data from the southern Netherlands) and Louwe Kooijmans' (2005, 698) estimate of 3–6 persons per km^2 (figures ultimately based on settlement data from the southern Netherlands; Schinkel, 2005, 524; 525 note 12). For the Northern Netherlands, Kooi (1979, 174) used urnfield data to postulate population densities of 3–4 persons per km^2, but as the maximum of this is lower than those quoted by Gerritsen or Louwe Kooijmans, these are not used here. Rather, again to steer bias towards a maximum size of the population, the population sizes were calculated using the upper figures quoted by Gerritsen or Louwe Kooijmans (5 and 6 p/km^2, respectively; Table 6).

Using the above parameters, the later prehistoric population size—based on the extent of the ‘settled landscape’—can be estimated to be between *c.* 100 and 140 persons in three regions (A, C and D).

TABLE 5 Estimates for population sizes based on the area of Celtic fields and population density estimates based on carrying capacity and habitation intensity; areas are presented in km^2 for easy comparison to with other estimates

Case study area	Area Celtic fields (km^2) based on prior research	Estimated population size based on carrying capacity (40 p/km^2)	Estimated population size based on habitation intensity (33.6 p/km^2)	Area Celtic fields (km^2) based on current research	Estimated population size based on carrying capacity (40 p/km^2)	Estimated population size based on habitation intensity (33.6 p/km^2)	Average estimated population size
A	0.8130	*c.* 33	*c.* 27	1.6000	*c.* 64	*c.* 54	*c.* 59
B	2.7870	*c.* 112	*c.* 94	3.6760	*c.* 147	*c.* 124	*c.* 135
C	0.6120	*c.* 25	*c.* 21	1.0070	*c.* 40	*c.* 34	*c.* 37
D	0.7810	*c.* 31	*c.* 26	1.9130	*c.* 77	*c.* 64	*c.* 70

TABLE 6 Estimates for population sizes based on the surface area estimate 'settled landscape' and population density estimates by Gerritsen (2003, 221–222) and Louwe Kooijmans (2005, 698, ref. to Schinkel, 2005, 524; 525 note 12)

Case study area	Area 'settled landscape (km^2 by buffer size)	Estimate of population size based on Gerritsen's 5p/750 m (Gerritsen, 2003, 221–222)	Estimate of population size based on Louwe Kooijmans' 6 p/750 m (Louwe Kooijmans, 2005, 698)
A	13.27 (500 m) 20.58 (750 m)	*c.* 103	*c.* 124
B	10.38 (500 m) 15.97 (750 m)	*c.* 80	*c.* 96
C	14.96 (500 m) 21.63 (750 m)	*c.* 108	*c.* 130
D	16.96 (500 m) 22.81 (750 m)	*c.* 114	*c.* 137

TABLE 7 Comparative overview of estimated population size based on a field system and 'settled landscape' data

Area	Estimate of population size based on field system data, in persons (min–max)	Estimate of population size based on 'settled landscape' data, in persons (min–max)
A	54–64	103–124
B	124–147	80–96
C	34–40	108–130
D	64–77	114–137

Only for region B (Putten) is the estimated population size smaller: *c.* 80–100 persons at any given time.

4 | DISCUSSION

4.1 | Comparing land use intensity based on different criteria

Table 7 lists the obtained estimates for population sizes in each of the four case study areas based on the two different approaches used here. While some variation is evident—and addressed below—we would like to emphasize that, firstly, all techniques yield results in the same order of magnitude. All population estimates range from 20 to 150 persons, whilst the maximum values spread considerably less (between 124 and 147 persons for each area). The maximum population density thus obtained (4.7 p/km^2; 147 persons over 31.25 km^2) aligns well with both national[29] and international[30] estimates for later prehistoric population densities. Yet, for both approaches and each case study area some variation in the estimates obtained is notable. With regards to the 'settled landscape' approach, the Putten area (B) has slightly lower estimates (<100) compared to the other areas. We suspect that this is an artefact of differences in present-day land use and housing and infrastructural development, in which the Putten region has an overrepresentation of forested estates and less built-up areas—which means that fewer developer-led projects were undertaken that could lead to new archaeological finds being reported. With settlements that comprise post-built structures and generally leave no surface scatters, prospective archaeology preceding such construction works is often instrumental in detecting settlement remains in such areas.

Similarly, the higher population numbers quoted for the Putten region based on field systems (Table 7) are also a side-effect of the present-day land use and its (positive) effect on the AI/LiDAR

[29]Gerritsen, 2003, 221–222; Louwe Kooijmans, 2005, 698.
[30]Müller & Diachenko, 2019, fig. 4; Nikulka, 2016, 227–250; Zimmermann et al., 2009, 377 fig. 8.

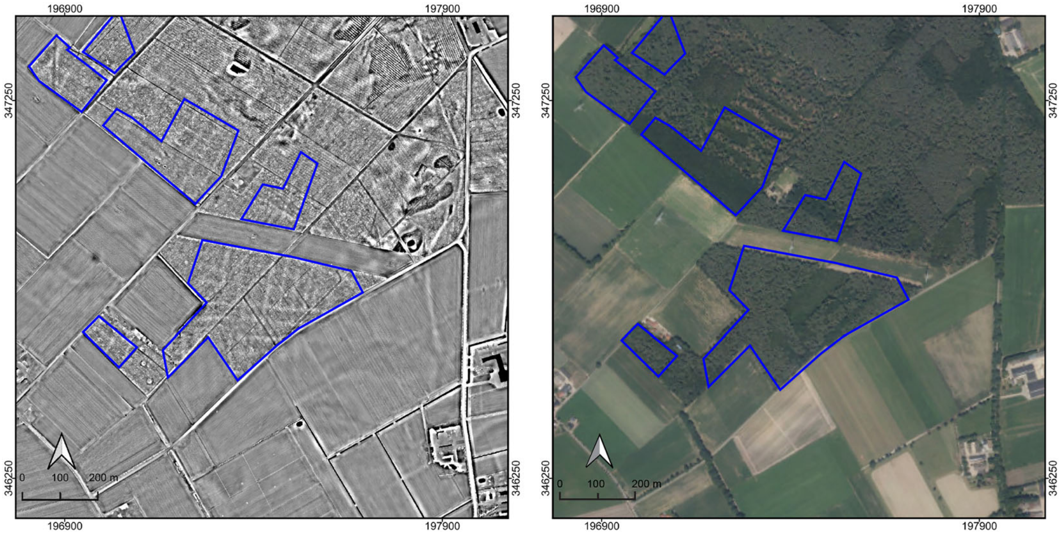

FIGURE 7 Left: Excerpt of LiDAR-derived DEM data from the Posterholt area (D), visualized with simple local relief model (Hesse, 2010). Right: Same area with a recent aerial photograph, clearly showing the visible Celtic field complexes (blue outlines) are delimited due to destruction by modern agriculture (source of the elevation model and photograph: Nationaal Georegister, 2021; Coordinates in Amersfoort/RD New, EPSG: 28992). [Colour figure can be viewed at wileyonlinelibrary.com]

detectability of Celtic fields. The higher area of forest and heathland in the Putten area (*c*. 68% surface area vs. max. 32% in the other areas) means it is innately better suited to the detection of phenomena such as Celtic fields.[31]

We are hesitant in favouring a single of the approaches used here and argue that a complementary use is probably the way forward. That being said, we would argue that the estimates derived from the Celtic field surface areas are more 'robust' or reliable due to the nature of the data at hand. This means that only for the Celtic field data, the surface areas used in the calculations are observed, rather than modelled—adding to their reliability. Nonetheless, in none of the case study regions did we map a Celtic field for which we are confident that the extent mapped is identical to its surface area in the past: all presently known Celtic fields are partly 'delimited' (destroyed or masked) by modern habitation, agricultural use or infrastructure (Figure 7; see also Figure 2). This means that the mapped area can only be taken to reflect a minimum extent. So, whilst we would—if pressed—argue that Celtic field coverage is the more reliable proxy, it evidently still is a significant underrepresentation of real prehistoric extents of these field systems. This could explain why in all areas except Putten (B), the maximum population values as obtained using the 'settled landscape' approach are on average a factor 2.3 times higher (1.93 [A], 3.25 [C] and 1.78 [D]). Whereas one might argue that the undated nature of Celtic fields is a problem here (cf. Arnoldussen, 2008, 11–18), the long-term approach taken to all datasets (settlement data, Celtic fields) means that we look at the cumulative pattern rather than the individual (dated) phenomenon—rendering this less of an important issue. Moreover, one should be mindful that the majority of the possible and plausible settlement sites are also not dated directly and that house contemporaneity is difficult to model. This means that our analysis cannot focus on the generational time-frames but should target the cross-generational or centennial scales in which the cultural landscape developed. We also recognize that each research area may have had its own internal historical development and that population densities may have fluctuated over the time period we investigate here. Yet, the later prehistoric cultural landscape fabric that was the cumulative outcome of these variable trajectories, and in particular the field systems—with their entwining of agricultural, economic, ritual and funerary usage—persisted over time as its most tangible, enduring, steering and widespread component.

4.2 | Human–computer strategies in practice

In this paper, automated detection was applied on a practical level—albeit in conjunction with manual analysis—to detect and map Celtic fields. The general use of automated detection in (every day) archaeological practice and prospection is rare,[32] although it is the aspiration of many research projects.[33] This general lack of incorporation has been attributed to the fact that on a technical level these approaches are still in a developmental stage with unsatisfactory results, while on a practical level the minimal requirements of these methods for specific activities remain undefined (Opitz & Herrmann, 2018). Indeed, if we look at the performance of the automated detection method in the current research the results are far from perfect. While within distinct (i.e. clearly visible) Celtic field complexes generally the majority of the plots are detected, in less conspicuous examples only a few or even none of the plots were found (Figure 8). Therefore the level of

[31]Cf. Kooistra & Maas, 2008, 2,324 fig. 5; Spek & Smeenge, 2021, 233 fig. 4.

[32]But see Verschoof-van der Vaart & Lambers, 2021.

[33]Cf. Kermit et al., 2018; Trier et al., 2018, Verschoof-van der Vaart, 2022.

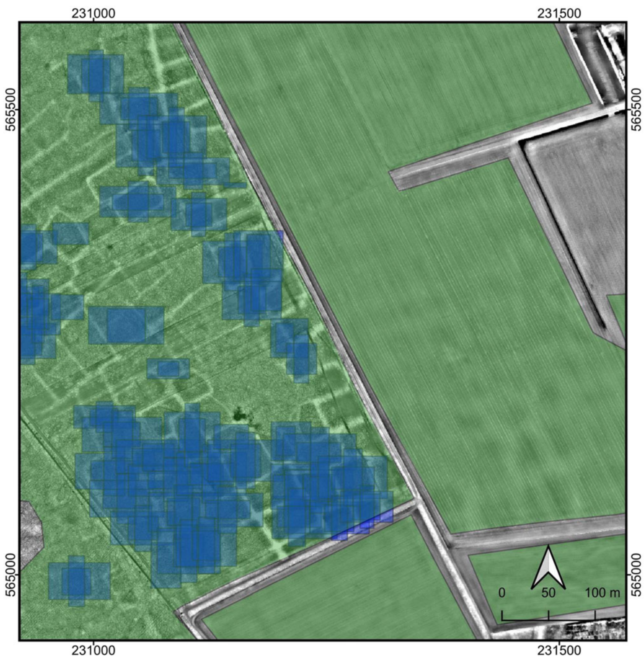

FIGURE 8 Excerpt of LiDAR-derived DEM data from the Zeijen area (A), visualized with simple local relief model (Hesse, 2010), showing detections made by the automated detection model (blue rectangles) and the manually annotated Celtic field areas (green areas; source of the elevation model: Nationaal Georegister, 2021; Coordinates in Amersfoort/RD New, EPSG: 28992). [Colour figure can be viewed at wileyonlinelibrary.com]

'completeness' (see Verschoof-van der Vaart & Lambers, 2021) varies between areas and complexes, which would be problematic if automated detection was used as the only source of information. Contrarily, when employing human–computer strategies, the level of competence and especially completeness of an automated detection tool does not have to be extremely high (also see Opitz, 2013) as the results are merely one of the multiple consulted data sources.

Using the results of the automated detection as a 'guide' in the manual analysis proved very effective and reduced the time needed to analyse the LiDAR-derived DEM data, even though the current research areas are relatively small. Of course, when the size of the research areas increases, the benefit of this strategy increases as well. In addition, the automated detection model pointed towards the presence of several new Celtic field complexes that were not known beforehand and might have been missed during manual analysis. Therefore, the problems surrounding the incorporation of automated detection can be largely overcome by using human–computer strategies, while also ensuring that the archaeological expert remains involved in the process (Verschoof-van der Vaart, 2022). Of course, with the development and implementation of better-performing automated detection methods, human involvement may decrease but should never be completely eliminated (see Traviglia et al., 2016).

5 | CONCLUSIONS

While the presence of Bronze and Iron Age people in the Netherlands is clearly attested by numerous finds in various regions, archaeologists have hitherto struggled to use this data for reliable reconstructions of land use and palaeodemography. Approaches to reconstructing population estimates have up to now mostly relied on either settlements, funerary sites or a combination thereof. In this article, we advocate the usage of prehistoric field systems, that is Celtic fields, as a reliable source for reconstructions of prehistoric land use.

In order to test this the surface area of later prehistoric land use of four study areas in the Netherlands was estimated based on the presence and coverage of Celtic fields. Subsequently, the obtained values were compared to estimates based on settlement site data. To map the Celtic fields a novel human–computer strategy was used, in which automated detection was applied in conjunction with manual analysis of LiDAR-derived DEM data. This approach can largely overcome the problems surrounding the incorporation of automated detection while also ensuring that the archaeological expert remains involved in the process.

The results of the mapping effort show a substantial increase in the area of Celtic fields in all study areas, ranging between circa 40 and 113 additional hectares of Celtic field discovered (an increase of factor 1.84 on average). The resulting land use intensity estimates show population sizes ranging between 34 and 147 persons for all case study areas. In comparison, the estimates based on settlement data range between 80 and 137. This shows that these estimates are in the same order of magnitude, with variation deriving from (a) differences in present-day land use and (b) (development-led) research intensity. Based on this a complementary use seems desirable, although we would argue that the estimates derived from field system data are more 'robust' or reliable due to the fact that these better represent the extent and scale of landscape usage compared to 'nodal' datasets such as settlement sites or funerary monuments often used.

Using a dataset of Dutch data not yet previously operationalized, we were able in this study to cross-regionally validate AI-assisted LiDAR mapping of prehistoric field systems and integrate the results in a methodological comparison of palaeodemographic modelling strategies. We thus presented a methodology that has proved its merit/effectiveness on a small scale, but whose value lies in the potential to easily scale-up to large areas, where human inspection/identification becomes impossible. At those scales, AI-assisted mapping becomes a necessity for efficient and effective mapping. We have shown that for regions that have low traditional archaeological research intensities (rendering traditional approaches based on nodal data less effective) but where prehistoric embanked field systems are detectable, reliable palaeodemographic estimates can still be determined. The main conclusions can thus be summarized as follows:

a. AI-assisted mapping of later prehistoric field systems proved to be a powerful tool for the identification of later prehistoric land use in areas where settlement data are scarce.

b. Palaeodemographic approximations based on field-system surface area yield usable results (i.e. ranging in the same order of magnitude as traditional approaches).
c. Buffer-based polygon methods for palaeodemographic approximations were shown to outperform nodal approaches (e.g. taking excavated settlements as proxies), as these proved less reliant on research intensity and thus better allowed inter-regional comparisons.
d. For the woodland- and heathland-dominated regions of NW Europe where field systems are preserved in forms detectable by LiDAR, AI-assisted detection algorithms are the main (i.e. fast, less subjective and reliable surface cover indications) strategies to determine later prehistoric landscape usage.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are openly available in Dataverse at https://dataverse.nl/, reference number https://doi.org/10.34894/L7WMNN.

ORCID

Stijn Arnoldussen https://orcid.org/0000-0002-5121-2738
Wouter B. Verschoof-van der Vaart https://orcid.org/0000-0002-1053-3009

REFERENCES

Affek, A. N., Wolski, J., Latocha, A., Zachwatowicz, M., & Wieczorek, M. (2022). The use of LiDAR in reconstructing the pre-World War II landscapes of abandoned mountain villages in southern Poland. *Archaeological Prospection*, *29*(1), 157–173. https://doi.org/10.1002/arp.1846

Arnold, V. (2020). Älter als die Römer? Bisher übersehene Spuren einstiger Beackerung unter Bayerns Wäldern. In J. Hamberger (Ed.). *Festschrift zur Ruhestandsversetzung von LWF-Präsident Olaf Schmidt* (Vol. 218, pp. 8–18). Zentrum Wald-Forst-Holz Weihenstephan.

Arnoldussen, S. (2008). *A living landscape. Bronze age settlement sites in the Dutch river area (c. 2000–800 BC)*. Sidestone press.

Arnoldussen, S. (2012). *Het Celtic field te Zeijen—Noordse veld: Kleinschalige opgravingen van wallen en velden van een laat-prehistorisch akkersysteem, Grondsporen* (Vol. 16). Groninger Instituut voor Archeologie.

Arnoldussen, S. (2018). The fields that outlived the Celts. The use-histories of Dutch later prehistoric field systems (Celtic fields or raakakkers). *Proceedings of the Prehistoric Society*, *84*, 303–327. https://doi.org/10.1017/ppr.2018.5

Arnoldussen, S., & de Vries, K. M. (2014). Of farms and fields: The Bronze Age and Iron Age settlement and Celtic field at Hijken - Hijkerveld. Palaeohistoria, 55/56 (2013/2014), 85-104.

Arnoldussen, S., & de Vries, K. M. (2017). A plan in place? Celtic field habitation at Westeinde (prov. Drenthe, the Netherlands). *Lunula Archaeologia Protohistorica*, *25*, 79–89.

Arnoldussen, S., & de Wit, M. J. M. (Eds.). (2018). *Westeinde–Noormansveld. Archeologisch onderzoek in een Drents Celtic field en tumulicomplex. Grondsporen* (Vol. 41). Groningen Instituut voor Archeologie.

Arnoldussen, S., & Fokkens, H. (2008). *Bronze age settlements in the low countries*. Oxbow books.

Arnoldussen, S., & Scheele, E. E. (2014). *De Celtic Fields van Wekerom: Kleinschalige opgravingen van wallen en velden van een laat-prehistorisch raatakkersysteem, Grondsporen* (Vol. 18). Groningen Institute of Archaeology (GIA).

Arnoldussen, S., & van der Linden, M. (2017). Palaeo-ecological and archaeological analysis of two Dutch Celtic fields (Zeijen-Noordse Veld and Wekerom-Lunteren): Solving the puzzle of local Celtic field bank formation. *Vegetation History and Archaeobotany*, *26*(6), 551–570. https://doi.org/10.1007/s00334-017-0625-z

Arnoldussen, S., Vos, P. C., Weerts, H. J. T., Lauwerier, R., & Brinkkemper, O. (2011). 1500 v. Chr. Nederland raakt overveend. In P. C. Vos, J. Bazelmans, H. J. T. Weerts, & M. J. van der Meulen (Eds.). *Atlas van Nederland in het Holoceen* (pp. 54–57). RCE/TNODeltares.

Bakels, C. C. (2009). *The Western European Loess Belt. Agrarian history, 5300 BC - AD 1000*. Springer.

Ball, J. E., Anderson, D. T., & Chan, C. S. (2017). Comprehensive survey of deep learning in remote sensing: Theories, tools, and challenges for the community. *Journal of Applied Remote Sensing*, *11*, 042609. https://doi.org/10.1117/1.JRS.11.042609

Bennett, R., Cowley, D., & De Laet, V. (2014). The data explosion: Tackling the taboo of automatic feature recognition in airborne survey data. *Antiquity*, *88*(341), 896–905. https://doi.org/10.1017/s0003598x00050766

Bickler, S. H. (2021). Machine learning arrives in archaeology. *Advances in Archaeological Practice*, *9*(2), 186–191. https://doi.org/10.1017/aap.2021.6

Bochkovskiy, A., Wang, C.-Y., & Liao, H.-Y. M. (2020). YOLOv4: Optimal speed and accuracy for object detection, arXiv:2004.10934. https://doi.org/10.48550/arXiv.2004.10934

Bongers, J. M. G., & Jelsma, J. (2012). Vries, Holtenweg (Gemeente Tynaarlo, Dr.). *Een Inventariserend Archeologisch Veldonderzoek*. De Steekproef bv.

Bourgeois, Q. P. J. (2013). Monuments on the horizon. The formation of the barrow landscape throughout the 3rd and 2nd millenium BC, Sidestone press, Leiden (PhD thesis).

Brinkkemper, O., & Van Wijngaarden-Bakker, L. (2005). All-round farming. Food production in the Bronze and Iron Age. In L. P. Louwe Kooijmans, P. W. van den Broeke, H. Fokkens, & A. L. van Gijn (Eds.). *The Prehistory of the Netherlands (II)* (pp. 491–512). Amsterdam University Press.

Brongers, J. A. (1976). Air photography and Celtic field research in the Netherlands, Nederlandse Oudheden, vol 6, Groningen (PhD. thesis).

Butler, J. J., & Fokkens, H. (2005). From stone to bronze. Technology and material culture. In L. P. Louwe Kooijmans, P. W. van den Broeke, H. Fokkens, & A. L. van Gijn (Eds.). *The prehistory of the Netherlands (I)* (pp. 371–399). Bert Bakker.

Castel, I. I. Y., & Rappol, M. (1992). Het Weichselien–Drenthe in de ijstijd. In M. Rappol (Ed.). *In de bodem van Drenthe* (pp. 117–132). Lingua Terrae.

Cowley, D. (2012). In with the new, out with the old? Auto-extraction for remote sensing archaeology. *Proceedings of SPIE*, *8532*, 853206–853206. https://doi.org/10.1117/12.981758

Creemers, G., Meylemans, E., Paesen, J., & De Bie, M. (2011). Laseraltimetrie en de kartering van Celtic Fields in de Belgische Kempen: Mogelijkheden en toekomstperspectieven. *Relicta Archeologie, Monumenten- en Landschapsonderzoek in Vlaanderen*, *7*, 11–36.

Curwen, E., & Curwen, E. C. (1923). Sussex Lynchets and their associated field-ways, Sussex archaeological. *Collections*, *64*, 1–65.

Davis, D. S. (2021). Theoretical repositioning of automated remote sensing archaeology: Shifting from features to ephemeral landscapes. *Journal of Computer Applications in Archaeology*, *4*(1), 94–109. https://doi.org/10.5334/jcaa.72

de Mulder, E. F. J., Geluk, M. C., Ritsema, I. L., Westerhoff, W. E., & Wong, T. E. (2003). *De ondergrond van Nederland*. Wolters-Noordhoff.

de Vries, K. M. (2021). Settling with the norm? Norm and variation in social groups and their material manifestations in (Roman) Iron Age (800 BC–AD 300) settlement sites of the northern Netherlands, Sidestone press, Leiden (PhD thesis).

Devereux, B. J., Amable, G. S., Crow, P., & Cliff, A. D. (2005). The potential of airborne LIDAR for detection of archaeological features under woodland canopies. *Antiquity*, *305*(79), 648–660.

Erb, K. H., Haberl, H., Jespen, M. R., Kümmerle, T., Lindner, M., Müller, D., Verburg, P. H., & Reemberg, A. (2013). A conceptual framework for analysing and measuring land-use intensity. *Current Opinion in Environmental Sustainability*, *5*(5), 464–470. https://doi.org/10.1016/j.cosust.2013.07.010

Feeser, I., Dörfler, W., Kneisel, J., Hinz, M., & Dreibrodt, S. (2019). Human impact and population dynamics in the Neolithic and bronze age: Multi-proxy evidence from north-western Central Europe. *The Holocene*, *29*(10), 1596–1606. https://doi.org/10.1177/0959683619857223

Fiorucci, M., Khoroshiltseva, M., Pontil, M., Traviglia, A., Del Bue, A., & James, S. (2020). Machine learning for cultural heritage: A survey. *Pattern Recognition Letters*, *133*, 102–108. https://doi.org/10.1016/j.patrec.2020.02.017

Fockema Andreae, S. J. (1947). Nederlandse rechtsoudheden op de akker. In H. E. van Gelder, P. Glazema, G. A. Bontekoe, H. Halbertsma, & W. Glasbergen (Eds.). *Een kwart eeuw oudheidkundig bodemonderzoek in Nederland. Gedenkboek A.E. van Giffen, Directeur van het Biologisch-Archaeologisch Instituut der Rijksuniversiteit te Groningen 1922–17 juni–1947* (pp. 289–298). J.A. Boom & Zoon.

Fokkens, H. (1998). *Drowned landscape. The occupation of the Western part of the Frisian–Drentian plateau, 4400 BC–AD 500*. Van Gorcum.

Fokkens, H. (2005). Mixed farming societies: synthesis. In L. P. Louwe Kooijmans, P. W. van den Broeke, H. Fokkens, & A. L. van Gijn (Eds.). *The prehistory of the Netherlands (I)* (pp. 463–474). Bert Bakker.

Fokkens, H. (2019). Hoe troep van de voorouders dateringen kan maken of breken. In S. Arnoldussen, E. A. G. Ball, J. van Dijk, E. Norde, & N. de Vries (Eds.). *Metaaltijden 6. Bijdragen in de studie van de metaaltijden*. Opgedragen aan Peter van den Broeke (pp. 175–184). Sidestone.

Fokkens, H., & Arnoldussen, S. (2008). Towards new models. In S. Arnoldussen & H. Fokkens (Eds.). *Bronze Age settlement sites in the Low Countries* (pp. 1–16). Oxbow Books.

Fokkens, H., & Roymans, N. (Eds.). (1991). *Nederzettingen uit de bronstijd en de vroege ijzertijd in de Lage Landen* (Vol. 13). Nederlandse Archeologische Rapporten. Rijksdienst voor het Oudheidkundig Bodemonderzoek.

Fontijn, D. (1996). Socializing landscape. Second thoughts about the cultural biography of urnfields. *Archaeological Dialogues*, *3*, 77–87. https://doi.org/10.1017/S1380203800000611

Fontijn, D. (2005). Giving up weapons. In M. Pearson & I. J. N. Thorpe (Eds.). *War, violence and slavery in prehistory* (pp. 145–154). Proceedings of a Prehistoric Society Conference at Sheffield University, Oxbow Books.

Fontijn, D. (2007). The significance of 'invisible' places. *World Archaeology*, *39*(1), 70–83. https://doi.org/10.1080/00438240601136462

Gerritsen, F. (2003). *Local identities. Landscape and community in the late prehistoric Meuse–Demer–Scheldt region, Amsterdam archaeological studies* (Vol. 9). Amsterdam University Press.

Gerritsen, F. A. (2008). Domestic times. Houses and temporalities in late prehistoric Europe. In A. Jones (Ed.). *Prehistoric Europe: Theory and practice* (pp. 143–161). Blackwell.

Harsema, O. H. (1980). *Drents boerenleven van de bronstijd tot de middeleeuwen, Museumfonds Publicatie* (Vol. 6). Drents Museum.

Harsema, O. H. (2005). Farms amongst Celtic fields. Settlements on the northern sands. In L. P. Louwe Kooijmans, P. W. van den Broeke, H. Fokkens, & A. L. van Gijn (Eds.). *The prehistory of the Netherlands (II)* (pp. 543–555). Bert Bakker.

Herrault, P. A., Poterek, Q., Keller, B., Schwartz, D., & Ertlen, D. (2021). Automated detection of former field systems from airborne laser scanning data: A new approach for historical ecology. *International Journal of Applied Earth Observation and Geoinformation*, *104*, 102563–102563. https://doi.org/10.1016/j.jag.2021.102563

Hesse, R. (2010). LiDAR-derived local relief models (LRM)—A new tool for archaeological prospection. *Archaeological Prospection*, *17*, 67–72. https://doi.org/10.1002/arp.374

Hesse, R. (2013). The changing picture of archaeological landscapes: Lidar prospection over very large areas as part of a cultural heritage strategy. In R. Opitz & D. Cowley (Eds.). *Interpreting archaeological topography: 3D data, visualisation and observation* (pp. 171–183). Oxford.

Hiddink, H. (2003). *Het grafritueel in de Late IJzertijd en Romeinse Tijd in het Maas-Demer-Scheldegebied, in het bijzonder van twee grafvelden bij Weert, Zuidnederlandse Archeologische Rapporten* (Vol. 11). Archeologisch Instituut Vrije Universiteit.

Hielkema, J. B. (2008). *Plangebied Donderen: Gemeente Tynaarlo (Drenthe): Een definitief archeologisch onderzoek*. RAAP Archeologisch Adviesbureau.

Humme, A., Lindenbergh, R., & Sueur, C. (2006). Revealing Celtic fields from LiDAR data using kriging based filtering. In H. G. Maas, D. Schneider (Eds.). Proceedings of the ISPRS Commission V Symposium, Dresden, 25–27 September 2006, (conference paper: http://www.isprs.org/proceedings/XXXVI/part5/), Dresden, pp. 1–5.

Jager, S. W. (2008). *Celtic fields in Zuid-Drenthe. Archeologisch vooronderzoek: Een inventariserend bureauonderzoek, RAAP Rapport* (Vol. 1731). RAAP bv.

Jager, S. W. (2011). *Celtic Fields ten Noorden van de 543.000-lijn in de Gemeente Midden-Drenthe, RAAP Rapport* (Vol. 2410). RAAP BV.

Janssen, M., & Verhart, L. B. M. (2010). Een Celtic field op de Steenheuvel bij Herkenbosch. *Jaarboek Heemkundevereniging Roerstreek*, *42*, 129–140.

Jelsma, J. (2004). *Een Inventariserend Archeologisch Veldonderzoek aan de Noordenveldweg/Norgerweg te Donderen*. De Steekproef.

Jongste, P. F. B. (2008). Living at Eigenblok. A Bronze Age settlement site in the Dutch river area. In S. Arnoldussen & H. Fokkens (Eds.). *Bronze age settlement sites in the Low Countries* (pp. 97–110). Oxbow books.

Jongste, P. F. B., & van Zijverden, W. K. (2007). The "Late Bronze Age problem" in the Rhine-Meuse delta (The Netherlands). Changes in climate or human interference in the hinterland? In H. Richard, C. Mordant, & M. Magny (Eds.). *Environnements et cultures à l'âge du Bronze en Europe occidentale* (pp. 343–355). CTHS.

Kaptijn, E., Bourgeois, Q. P.J., Verschoof-van der Vaart, W. B., Arnoldussen, S., & Lambers, K. (forthcoming). In search of Celtic fields: Results of the Heritage Quest project in the Netherlands and the potential of citizen science and LiDAR.

Kermit, M., Reksten, J. H., & Trier, D. (2018). Towards a national infrastructure for semi-automatic mapping of cultural heritage in Norway. In M. Matsumoto & E. Uleberg (Eds.). *Proceedings of the 44th computer applications and quantitative methods in archaeology conference (CAA 2016) at Oslo* (pp. 159–172). Archaeopress, Oxford.

Kluiving, S. J., Bekkema, M. E., & Roymans, N. G. A. M. (2015). Mass migration through soil exhaustion: Transformation of habitation patterns in the southern Netherlands (1000BC-500 AD). *Catena*, *132*, 139–150. https://doi.org/10.1016/j.catena.2014.12.015

Kokalj, Ž., & Hesse, R. (2017). *Airborne laser scanning raster data visualization: A guide to good practice*. Založba ZRC.

Kooi, P. B. (1979). Pre-Roman urnfields in the north of the Netherlands, Wolters-Noordhof, Groningen (PhD thesis).

Kooi, P. B., & de Langen, G. J. (1987). Bewoning in de vroege ijzertijd op het Kleuvenveld te Peelo, gem. Assen. *Nieuwe Drentse Volksalmanak*, *104*, 151–165.

Kooistra, M. J., & Maas, G. J. (2008). The widespread occurrence of Celtic field systems in the central part of the Netherlands. *Journal of Archaeological Science*, *35*, 2318–2328. https://doi.org/10.1016/j.jas.2008.03.007

Kootker, L. M., Geerdink, C., van den Broeke, P. W., Kars, H., & Davies, G. R. (2018). Breaking traditions: An isotopic study on the changing funerary practices in the Dutch iron age (800-12 BC). *Archaeometry*, *60*(3), 594–611. https://doi.org/10.1111/arcm.12333

Kristiansen, K. (2018). The rise and fall of Bronze Age societies in Thy, northwest Jutland. In J. H. Bech, B. V. Eriksen, & K. Kristiansen (Eds.).

Bronze age settlement and land-use in Thy, northwest Denmark (Vol. I, pp. 107–126). Aarhus University Press.
Lambers, K., Verschoof-van der Vaart, W. B., & Bourgeois, Q. P. J. (2019). Integrating remote sensing, machine learning, and citizen science in Dutch archaeological prospection. *Remote Sensing*, *11*(7), 794–794. https://doi.org/10.3390/rs11070794
Lascaris, M. (2004). *Verslag inventariserend veldonderzoek plangebied Kerkebogten, gemeente Eersel*. ACVU-HBS.
Lascaris, M. (2011). *Opgravingen in Eersel–Kerkebogten. Landschap en bewoning in de Bronstijd, IJzertijd, Romeinse tijd, Middeleeuwen en Nieuwe Tijd, Zuidnederlandse archeologische rapporten* (Vol. 44). Archeologisch Centrum Vrije Universiteit/Hendrik Brunsting Stichting.
Lohof, E. (1994). Tradition and change. Burial practices in the late Neolithic and bronze age in the North-Eastern Netherlands. *Archaeological Dialogues*, *1*, 98–118. https://doi.org/10.1017/S1380203800000167
Louwe Kooijmans, L. P. (1995). Prehistory or paradise? Prehistory as a reference for modern nature development, the Dutch case. *Mededelingen van de Rijks Geologische Dienst*, *52*, 415–424.
Louwe Kooijmans, L. P. (2005). Nederland in de prehistorie: Een terugblik. In L. P. Louwe Kooijmans, P. W. van den Broeke, H. Fokkens, & A. L. van Gijn (Eds.). *Nederland in de prehistorie* (pp. 695–720). Bert Bakker.
Løvschal, M., & Holst, M. K. (2014). Repeating boundaries: Repertoires of landscape regulations in southern Scandinavia in the Late Bronze Age and pre-Roman Iron Age. *Danish Journal of Archaeology*, *3*(2), 95–118. https://doi.org/10.1080/21662282.2014.990311
Meylemans, E., Creemers, G., De Bie, M., & Paesen, J. (2015). Revealing extensive protohistoric field systems through high resolution LIDAR data in the northern part of Belgium. *Archäologisches Korrespondenzblatt*, *45*, 197–213.
Milikowski, E. (1985). Archeologische luchtkartering van het gebied Eersel-Riethoven-Bergeijk in de Kempen. In J. Slofstra, H. H. van Regteren Altena, & F. Theuws (Eds.). *Het Kempenproject 2* (pp. 79–85). Stichting Brabants Heem.
Müller, J., & Diachenko, A. (2019). Tracing long-term demographic changes: The issue of spatial scales. *PLoS ONE*, *14*(1), 1–12. https://doi.org/10.1371/journal.pone.0208739
Nationaal Georegister. (2021). Publieke dienstverlening op de kaart (PDOK). https://www.pdok.nl/ [accessed on 07-03-2022].
Nielsen, N. H., & Dalsgaard, K. (2017). Dynamics of Celtic fields—A geoarchaeological investigation of Øster Lem Hede, Western Jutland, Denmark. *Geoarchaeology*, *32*, 414–434. https://doi.org/10.1002/gea.21615
Nikulka, F. (2016). *Archäologische demographie. Methoden, daten und bevölkerung der europäischen Bronze und Eisenzeiten*. Sidestone.
Olivier, M., & Verschoof-van der Vaart, W. B. (2021). Implementing state-of-the-art deep learning approaches for archaeological object detection in remotely-sensed data: The results of cross-domain collaboration. *Journal of Computer Applications in Archaeology*, *4*(1), 274–289. https://doi.org/10.5334/jcaa.78
Opitz, R. (2013). An overview of airborne and terrestrial laser scanning in archaeology. In R. Opitz & D. Cowley (Eds.). *Interpreting archaeological topography. Airborne laser scanning, 3D data and ground observation* (pp. 13–31). Oxbow Books, Oxford and Oakville.
Opitz, R., & Herrmann, J. (2018). Recent trends and long-standing problems in archaeological remote sensing. *Journal of Computer Applications in Archaeology*, *1*(1), 19–41. https://doi.org/10.5334/jcaa.11
Oude Rengerink, J. A. M. (2004). *Beheersgebied Wekeromse Zand: Aen inventariserend archeologisch onderzoek: Kartering en waardering Celtic fields*, *RAAP Rapport* (Vol. 1019). RAAP Archeologisch Adviesbureau.
Parlevliet, M., & Flamman, J. P. (2003). *Waterlaat 5, archeologisch onderzoek op het toekomstige bedrijventerrein 'Waterlaat 5', gemeente Bergeijk*, *AAC Rapport* (Vol. 11). AAC Projectenbureau.
Rappol, M. (1984). Till in southeast Drente and the origin of the Hondsrug complex, the Netherlands. *Eiszeitalter Und Gegenwart*, *34*, 7–27.
Rappol, M., & Kluiving, S. (1992). De landijsbedekking in de voorlaatste ijstijd. In M. Rappol (Ed.). *In de bodem van Drenthe* (pp. 71–115). Lingua Terrae.
Roberts, B. K. (1996). *Landscapes of settlement. Prehistory to the present*. Taylor & Francis Books Ltd.
Roymans, N., & Kortlang, F. P. (1999). Urnfield symbolism, ancestors and the land in the Lower Rhine region. In F. Theuws & N. Roymans (Eds.). *Land and ancestors. Cultural dynamics in the Urnfield period and the Middle Ages in the Southern Netherlands* (Vol. 4, pp. 33–61). Amsterdam University Press.
Roymans, N. G. A. M., & Kluiving, S. (2012). Soil degradation and shifting habitation patterns in the sand landscapes of the Southern Netherlands. In W. Bebermeier, R. Hebenstreit, E. Kaiser, & J. Krause (Eds.). *Landscape archaeology. Proceedings of the international conference held in Berlin, 6th–8th June 2012* (Vol. 3) (pp. 47–53). eTopoi.
Sammut, C., & Webb, G. I. (2010). *Encyclopaedia of machine learning*. Springer.
Schinkel, K. (1998). Unsettled settlement, occupation remains from the Bronze Age and the Iron Age at Oss-Ussen. The 1976-1986 excavations. *Analecta Prehistorica Leidensia*, *30*, 5–306.
Schinkel, K. (2005). Hamlets on the move. Settlements in the southern and central parts of the Netherlands. In L. P. Louwe Kooijmans, P. W. van den Broeke, H. Fokkens, & A. L. van Gijn (Eds.). *The prehistory of the Netherlands (II)* (pp. 519–542). Bert Bakker.
Slofstra, J. (1991). Een nederzetting uit de vroege ijzertijd op de Heesmortel bij Riethoven. In H. Fokkens & N. G. A. M. Roymans (Eds.). *Nederzettingen uit de bronstijd en de vroege ijzertijd in de Lage Landen* (Vol. 13, pp. 141–151). Rijksdienst voor het Oudheidkundig Bodemonderzoek.
Smeerdijk, D. G., Spek, T., & Kooistra, M. J. (1995). Anthropogenic soil formation and agricultural history of the open fields of Valthe (Drenthe, The Netherlands) in medieval and Early Modern Times. Integration of palaeoecology, historical geography and soil science. In G. F. W. Herngreen & L. van der Valk (Eds.). *Neogene and quaternary geology of North-West Europe. Contributions on the occasion of Waldo H. Zagwijn's retirement* (Vol. 52, pp. 451–479). Rijks Geologische Dienst.
Spek, T. (2004). *Het Drentse esdorpenlandschap: Een historisch-geografische studie*. Rijksdienst voor het Oudheidkundig Bodemonderzoek.
Spek, T., Groenman-van Waateringe, W., Kooistra, M., & Bakker, L. (2003). Formation and land-use history of Celtic fields in north-west Europe—An interdisciplinary case study at Zeijen, the Netherlands. *European Journal of Archaeology*, *6*(2), 141–173.
Spek, T., & Smeenge, H. (2021). Celtic fields en marke en malebossen. Enkele gedachten over hun landschapshistorische samenhang en een bijzondere prehistorische landschapstransitie. *Tijdschrift voor Historische Geografie*, *6*(3), 223–242. https://doi.org/10.5117/THG2021.3.001.SPEK
Spek, T., Snoek, M., van der Sanden, W. A. B., Kosian, M., van der Heijden, F., Theunissen, L., Nijenhuis, M., Vroon, H., & Greving, K. (Eds.). (2009). *Archeologische waardering van Celtic fields in Drenthe. Rapportage Archeologische Monumentenzorg* (Vol. 141). Rijksdienst voor het Cultureel Erfgoed.
Theunissen, E. M. (1999). Midden-bronstijdsamenlevingen in het zuiden van de Lage Landen. Een evaluatie van het begrip 'Hilversum-cultuur', Leiden University (PhD Thesis), Leiden.
Theunissen, E. M. (2006). Burial practices in the south of the Low Countries: The symbolic meaning of the Bronze Age barrow. In L. Šmedja (Ed.). *Archaeology of burial mounds* (pp. 150–162). University of West Bohemia, Department of Archaeology.
Traviglia, A., Cowley, D., & Lambers, K. (2016). Finding common ground: Human and computer vision in archaeological prospection. *AARGnews - Newsletter Aerial Archaeology Research Group*, *53*, 11–24.
Traviglia, A., & Torsello, A. (2017). Landscape pattern detection in archaeological remote sensing. *Geosciences*, *7*(4), 128–128. https://doi.org/10.3390/geosciences7040128

Trier, I. D., & Pilø, L. H. (2012). Automatic detection of pit structures in airborne laser scanning data. *Archaeological Prospection*, *19*(2), 103–121. https://doi.org/10.1002/arp.1421

Trier, I. D., Salberg, A.-B., & Pilø, L. H. (2018). Semi automatic mapping of charcoal kilns from airborne laser scanning data using deep learning. In M. Matsumoto & E. Uleberg (Eds.). *Oceans of data. Proceedings of the 44th Annual Conference on Computer Applications and Quantitative Methods in Archaeology* (pp. 219–231). Archaeopress, Oxford.

van Amerongen, Y. F. (2016). Wild West Frisia: The role of domestic and wild resource exploitation in Bronze Age subsistence, Sidestone press, Leiden (PhD thesis).

van Beek, R. (2001). Elp in perspectief. Een evaluatie en incorporatie van de verschillende aspecten van een bronstijd-cultuur, Leiden (Unpublishd MA thesis).

van de Glind, M. (2013). Bergeijk Waterlaat 6. Een nederzetting uit de ijzertijd, BAAC bv, Den Bosch.

van der Zon, N. (2013). *Kwaliteitsdocument AHN2*. Rijkswaterstaat.

van der Sanden, W. A. B. (2018). *Geschiedenis van Drenthe. Een archeologisch perspectief*. Koninklijke van Gorcum B.V.

van den Broeke, P. W. (2005). Blacksmiths and potters. Material culture and technology. In L. P. Louwe Kooijmans, P. W. van den Broeke, H. Fokkens, & A. L. van Gijn (Eds.). *The prehistory of the Netherlands (II)* (pp. 603–625). Bert Bakker.

van der Meer, J. J. M., Rappol, M., & Semeijn, J. N. (1985). Sedimentology and genesis of glacial deposits in the Goudsberg, Central Netherlands. *Mededelingen van de Rijks Geologische Dienst*, *39*(2), 1–29.

van Es, W. A. (1958). Een Versterkte Nederzetting te Vries. *Nieuwe Drentse Volksalmanak*, *76*, 50–66.

van Giffen, A. E. (1918). Begin van een onderzoek van 'de zogenaamde voormalige Romeinsche legerplaats en aangelegen grafheuvelveld te Zeijen. *Nieuwe Drentse Volksalmanak*, *36*, 135–175.

van Giffen, A. E. (1936). Een versterking naar Romeinsch patroon op het Noordscheveld bij Zeijen, Gem. Norg. *Nieuwe Drentsche Volksalmanak*, *54*, 123–129.

van Giffen, A. E. (1939). De zgn. heidensche legerplaats te Zuidveld bij Sellingen, gem. Vlachtwedde, Verslag Groninger Museum 1939, 86–93.

van Giffen, A. E. (1940). Nederzettingen, grafheuvels, leemkuilen en rijengrafveld tusschen Rhee en Zeijen, Gem. Vries. *Gem. Vries*., *Nieuwe Drentsche Volksalmanak*, *58*, 192–200.

van Giffen, A. E. (1950). De nederzettingsoverblijfselen in het Bolleveen en de versterking, de zgn. "legerplaats" aan het Witteveen op het Noordse veld, beide bij Zeijen, Gem. Zeijen. *Nieuwe Drentsche Volksalmanak*, *68*, 89–122.

van Giffen, A. E., Addink-Samplonius, M., & Glasbergen, W. (1971). Een grafheuvel te Putten. *Helinium*, *11*, 105–123.

van Gijn, A. L., & Waterbolk, H. T. (1984). The colonization of the salt marshes of Friesland and Groningen: The possibility of a transhumant prelude. *Palaeohistoria*, *26*, 101–122.

van Hoof, L. G. L. (2000). Filling black holes. Leven, sterven en deponeren in de metaaltijden van Zuid-Limburg, (unpublished Ma thesis), Leiden.

van Zijverden, W. K. (2016). After the deluge. A palaeogeographical reconstruction of Bronze Age West-Frisia 2000–800 BC, Sidestone, Leiden (PhD thesis).

Verhoeven, M. P. F. (2004). *Plangebied Kerkebogten, gemeente Eersel: een inventariserend archeologisch onderzoek*. RAAP BV.

Verschoof-van der Vaart, W. B. (2022). Learning to look at LiDAR. Combining CNN-based object detection and GIS for archaeological prospection in remotely-sensed data, Leiden University, Leiden (PhD thesis).

Verschoof-van der Vaart, W. B., & Lambers, K. (2021). Applying automated object detection in archaeological practice: A case study from the southern Netherlands. *Archaeological Prospection*, *29*, 1–17. https://doi.org/10.1002/arp.1833

Verschoof-van der Vaart, W. B., & Landauer, J. (2021). Using CarcassonNet to automatically detect and trace hollow roads in LiDAR data from the Netherlands. *Journal of Cultural Heritage*, *47*, 143–154. https://doi.org/10.1016/j.culher.2020.10.009

Verschoof-van der Vaart, W. B., Lambers, K., Kowalczyk, W., & Bourgeois, Q. P. J. (2020). Combining deep learning and location-based ranking for large-scale archaeological prospection of LiDAR data from the Netherlands. *ISPRS International Journal of Geo-Information*, *9*(5), 293–293. https://doi.org/10.3390/ijgi9050293

von Frijtag Drabbe, C. A. J. (1947). De luchtfoto in dienst van de archeologie. In H. E. van Gelder, P. Glazema, G. A. Bontekoe, H. Halbertsma, & W. Glasbergen (Eds.). *Een kwart eeuw oudheidkundig bodemonderzoek in Nederland. Gedenkboek A.E. van Giffen, Directeur van het Biologisch-Archaeologisch Instituut der Rijksuniversiteit te Groningen 1922–17 juni–1947* (pp. 491–496). J.A. Boom & Zoon.

Waterbolk, H. T. (1959). *Nieuwe gegevens over de herkomst van de oudste bewoners der kleistreken* (Vol. XI). Overdruk uit Akademiedagen N.V. Noord-hollandsche uitgeversmaatschappij.

Waterbolk, H. T. (1977). Opgravingen rond het Witteveen op het Noordse Veld bij Zeijen, gem. Vries (1949-1953). *Nieuwe Drentse Volksalmanak*, *94*, 5(177)–131(203).

Waterbolk, H. T. (1982). Mobilität von Dorf, Ackerflur und Gräberfeld in Drenthe seit der Latènezeit. *Offa*, *39*, 97–137.

Waterbolk, H. T. (1985). Archeologie. In J. Heringa, D. P. Blok, M. G. Buist, & H. T. Waterbolk (Eds.). *Geschiedenis van Drenthe* (pp. 15–90). Boom.

Waterbolk, H. T. (1995). Patterns of the peasant landscape. *Proceedings of the Prehistoric Society*, *61*, 1–36. https://doi.org/10.1017/S0079497X00003029

Wesselingh, D. A. (2000). Native neighbours: Local settlement system and social structure in the Roman period at Oss (the Netherlands). *Leiden (PhD Thesis)*. Leiden University.

Willems, W. J. H. (1981). Mariahoop, gem. Echt. IJzertijd nederzetting, Jaarverslag van de Rijksdienst voor het Oudheidkundig Bodemonderzoek 1983, 70.

Woltering, P. J. (2000). Occupation history of Texel, IV: Middle Bronze Age–Late Iron Age. *Berichten van de Rijksdienst voor het Oudheidkundig Bodemonderzoek*, *44*, 9–396.

Wolthuis, T. I., & Arnoldussen, S. (2015). IJzertijdbewoning: Een toetsing van de bewoningsmodellen voor locatiekeuze en demografie. In E. A. G. Ball & S. Arnoldussen (Eds.). *Metaaltijden 2. Bijdragen in de studie van de metaaltijden* (pp. 171–185). Sidestone press.

Wortelboer, R. (2014). Van Bronstijd tot moderne tijd. Een reis door de tijd aan de hand van lokale hoogteverschillen in de Hoorneboegse Heide bij Hilversum. *Archeologica Naerdincklant*, *2*(2014), 13–18.

Zimmermann, A., Hilpert, J., & Wendt, K. P. (2009). Estimations of population density for selected periods between the Neolithic and AD 1800. *Human Biology*, *81*(3), 357–380. https://doi.org/10.3378/027.081.0313

Zeiler, J. T. (2005). Vee uit het veen. *Archeozoölogisch onderzoek van botmateriaal uit het Bolleveen bij Zeijen (1e - 4e eeuw AD)*. ArcheoBone.

How to cite this article: Arnoldussen, S., Verschoof-van der Vaart, W. B., Kaptijn, E., & Bourgeois, Q. P. J. (2022). Field systems and later prehistoric land use: New insights into land use detectability and palaeodemography in the Netherlands through LiDAR, automatic detection and traditional field data. *Archaeological Prospection*, 1–18. https://doi.org/10.1002/arp.1891