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Producción de resina en el Noroeste de la Península Ibérica: metodología para la determinación del potencial productivo integrada en un sistema de apoyo a la decisión

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TESIS DOCTORAL

PRODUCCIÓN DE RESINA EN EL NOROESTE DE LA PENÍNSULA IBÉRICA: METODOLOGÍA PARA LA DETERMINACIÓN DEL POTENCIAL PRODUCTIVO INTEGRADA EN UN SISTEMA DE APOYO A LA DECISIÓN

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ACREMA
ADAPTACIÓN DE LA ACTIVIDAD RESINERA A MASAS DE PINO CON FINES PRODUCTORES DE MADERA
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A mis padres y abuelos, en
especial a Juan


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Óscar López Álvarez

PUBLICACIONES DERIVADAS DE ESTA TESIS

Esta tesis incluye es su cuerpo principal los siguientes artículos de investigación, correspondientes a los capítulos 4, 5 y 6, respectivamente:

López-Álvarez, Ó., Zas, R., & Marey-Perez, M. (2023). Resin tapping: A review of the main factors modulating pine resin yield. *Industrial Crops and Products*, *202*, 117105. https://doi.org/10.1016/j.indcrop.2023.117105 (Factor de Impacto, IF=5.6; Q1, posición 4/20 de *Agricultural Engineering*; Q1 posición 8/126 de *Agronomy*; 2023)

López-Álvarez, Ó., Zas, R., Martínez, E., & Marey-Perez, M. (2023). Resin yield response to different tapping methods and stimulant pastes in Pinus pinaster Ait. *European Journal of Forest Research*, *142*(6), 1281–1292. https://doi.org/10.1007/s10342-023-01590-9 (Factor de impacto, IF=2.6; Q1, posición 19/89 de *Forestry*, 2023)

López-Álvarez, Ó., Franco-Vázquez, L., & Marey-Perez, M. (2023). Base-age invariant models for predicting individual tree accumulated annual resin yield using two tapping methods in maritime pine (Pinus pinaster Ait.) forests in north-western Spain. *Forest Ecology and Management*, *549*, 121501. https://doi.org/10.1016/j.foreco.2023.121501 (Factor de impacto, IF=3.7; Q1, posición 6/89 en *Forestry*, 2023)

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RESUMEN

En esta tesis se presentan el flujo de trabajo y las metodologías empleadas para determinar el potencial productivo de resina de la especie *Pinus pinaster* Ait., integradas en un sistema de apoyo a la decisión. Los resultados obtenidos ofrecerán a los gestores forestales interesados en la explotación de este recurso no maderero la capacidad de estimar la producción de resina que potencialmente podrían obtener de sus parcelas, además de servir como herramienta en el proceso de toma de decisiones orientado a optimizar la gestión de los recursos forestales. Para el desarrollo de la herramienta se ha utilizado como área de estudio el noroeste de la Península Ibérica, estructurando el trabajo en cuatro fases. La primera consistió en la identificación de los principales factores que influyen en la producción de resina en base a la bibliografía disponible. A continuación se caracterizó la producción de resina en la zona de estudio, y se comparó con las producciones obtenidas en el centro de la Península Ibérica, empleando para ello variables propias del proceso extractivo, así como dasométricas y ambientales. Posteriormente se demostró, por primera vez, que es posible modelar el patrón de producción acumulada de resina a lo largo de la campaña de resinado; para ello se utilizaron la metodología de los modelos invariantes con la edad y la ecuación de Bertalanffy-Richards. Para estimar la producción de resina antes del inicio de la campaña, se implementó una metodología bietápica que incluyó técnicas de aprendizaje automático, y como variables predictoras la localización, las características dasométricas y otras propias del proceso extractivo. Finalmente, se creó el primer sistema de apoyo a la decisión integrado en una aplicación web, diseñado para predecir valores de la producción de resina, en el cual se integraron los modelos desarrollados a lo largo de esta tesis. Se espera que las funcionalidades que ofrece esta aplicación permitan la transferencia de conocimiento e I+D+I desde la academia a la sociedad, concretada en este caso en los gestores y propietarios forestales.

Palabras clave: *Pinus pinaster*, resina, productos forestales no madereros, sistema de apoyo a la decisión, modelización.


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RESUMO

Nesta tese preséntanse o fluxo de traballo e as metodoloxías empregadas para determinar o potencial produtivo de resina da especie *Pinus pinaster* Ait., integradas nun sistema de apoio á decisión. Os resultados obtidos ofrecerán aos xestores forestais interesados na explotación deste recurso non madeireiro a capacidade de estimar a produción de resina que potencialmente poderían obter das súas parcelas, ademais de servir como ferramenta no proceso de toma de decisións orientado a optimizar a xestión dos recursos forestais. Para o desenvolvemento da ferramenta utilizouse como área de estudo o noroeste da Península Ibérica, estruturando o traballo en catro fases. A primeira consistiu na identificación dos principais factores que inflúen na produción de resina en base á bibliografía dispoñible. A continuación caracterizouse a produción de resina na zona de estudo, e comparouse coas producións obtidas no centro da Península Ibérica, empregando para iso variables propias do proceso extractivo, así como dasométricas e ambientais. Posteriormente demostrouse, por primeira vez, que é posible modelar o patrón de produción acumulada de resina ao longo da campaña de resinado; para iso empregaronse a metodoloxía dos modelos invariantes coa idade e a ecuación de Bertalanffy-Richards. Para estimar a produción de resina antes do inicio da campaña, se implementó unha metodoloxía bietápica que incluíu técnicas de aprendizaxe automática, e como variables predictoras a localización, as características dasométricas e outras propias do proceso extractivo. Finalmente, creouse o primeiro sistema de apoio á decisión integrado nunha aplicación web, deseñado para predicir valores da produción de resina, no cal se integraron os modelos desenvolvidos ao longo desta tese. Agárdase que as funcionalidades que ofrece esta aplicación permitan a transferencia de coñecemento e I+D+I dende a academia á sociedade, concretada neste caso nos xestores e propietarios forestais.

Palabras clave: *Pinus pinaster*, resina, produtos forestais non madeireiros, sistema de apoio á decisión, modelización.

ABSTRACT

This thesis presents the process and methodologies used to determine the resin production potential of *Pinus pinaster* Ait. species, integrated in a decision support system. The results obtained will provide forest managers interested in the exploitation of this non-timber resource with the capacity to estimate the resin production that they could potentially obtain from their plots, as well as serving as a tool in the decision-making process aimed to optimise the management of forest resources. For the development of the tool, the northwest of the Iberian Peninsula was used as the study area, structuring the work in four phases. The first phase consisted of identifying the main factors influencing resin production based on the available literature. Next, resin production in the study area was characterised and compared with the production obtained in the centre of the Iberian Peninsula, using variables specific to the extraction process, as well as dasometric and environmental variables. Subsequently, it was demonstrated, for the first time, that it is possible to model the pattern of accumulated resin yield throughout the resin production campaign, using the methodology of base-age invariant models and the Bertalanffy-Richards equation. To estimate resin production before the start of the campaign, a two-stage methodology was implemented that included machine learning techniques, and location, dasometric characteristics and other variables specific to the extraction process as predictors. Finally, the first decision support system integrated in a web application was created, designed to predict resin production values, in which the models developed throughout this thesis were integrated. It is expected that the functionalities offered by this application will allow the transfer of knowledge and R+D+I from academia to society, in this case to forest managers and owners.

Keywords: *Pinus pinaster*, resin, non-timber forest products, decision support system, modelling.


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1 INTRODUCCIÓN

1.1 MOTIVACIÓN Y MARCO TEÓRICO DE LA TESIS

La preocupación por la conservación del medio ambiente, así como la lucha contra la despoblación rural, derivada en parte por la falta de oportunidades laborales, son dos de los ejes principales de las estrategias implementadas actualmente a nivel mundial. En 2015, la Organización de las Naciones Unidas (ONU) publicó la Agenda para el Desarrollo Sostenible (UN, 2015), la cual se trata de un plan de acción para la prosperidad del planeta y de las personas. En esta agenda se enumeran los Objetivos de Desarrollo Sostenible (ODSs), un compendio de metas que fueron adoptadas para que en 2030 esté garantizado el fin de la pobreza y la protección del planeta. Entre ellos, consideran estratégico crear oportunidades laborales para los jóvenes (ODS 8), la producción y consumo responsables (ODS 12), la acción por el clima (ODS 13) o la vida de los ecosistemas terrestres (ODS 15).

España no es ajena a estas preocupaciones, y es por eso por lo que desde hace años se han comenzado a implementar políticas alineadas con los ODSs. Una de las vías para lograr cumplir con estos objetivos es fomentar el desarrollo de sectores cuyas actividades principales valgan tanto para la fijación de población en estas áreas poblacional y económicamente deprimidas, como para preservar y valorizar de una manera sostenible el entorno natural. Es por eso por lo que el Ministerio para la Transición Ecológica y el Reto Demográfico se ha sumado a estas iniciativas y ha implementado planes y estrategias que abordan diferentes ámbitos temáticos como el fomento de una bioeconomía local sostenible, infraestructuras verdes y ecosistemas resilientes, o la neutralidad en carbono. Particularmente, el noroeste de la Península Ibérica es una de las zonas más afectadas por lo anteriormente mencionado, y a su vez que mayor superficie susceptible de desastres naturales, como incendios forestales, posee. Es por ello por lo que uno de los sectores que mejor encaja en estas estrategias y planes, ya que aúna cada una de las características requeridas y se trata de un sector fundamental para el desarrollo socioeconómico sostenible de áreas rurales y para la conservación de los bosques y su diversidad, es el sector forestal.

Dentro del sector forestal, existe un subsector que engloba a productos que forman parte de la riqueza natural y del patrimonio cultural europeo y mundial, y que, según el Instituto Forestal Europeo y la FAO, poseen un gran potencial para contribuir prácticamente a la totalidad de los ODSs, estos son los productos forestales no madereros (de ahora en adelante PFNMs). De entre todos ellos, existe uno que, debido a las particularidades de las masas forestales del noroeste de la Península Ibérica, podría llegar a formar parte del tejido forestal de esta región, así como a crear riqueza tanto social, como ambiental y económica. Este PFNM se trata de la producción de resina de pino.

Este producto empleado por las plantas del género *Pinus* como una de sus principales defensas frente a ataques externos, se trata de uno de los PFNMs que tiene más arraigo en el sur de Europa y particularmente en España. Además, se trata de una fuente de riqueza tanto social, como ambiental y económica. Es por ello por lo que el fomento de esta actividad derivará en una generación de puestos de trabajo de calidad relacionados con el medio natural, y por lo tanto de fijación de población en entornos rurales, así como brindará protección a los bosques, ya que es necesaria la presencia continuada de trabajadores en ellos, especialmente durante el periodo estival, época del año en el cual se centra el grueso del trabajo, y ayudará a avanzar hacia una neutralidad carbónica, ya que se trata de una materia prima que se puede emplear como sustituto de derivados del petróleo en diversos procesos industriales. Pero para que esta actividad se convierta en un instrumento eficaz frente a estos retos, se debe de generar conocimiento y proporcionar herramientas entorno a ella. Esto es necesario ya que, aunque se trate de uno de los PFNMs que más arraigo histórico tiene en determinadas zonas del sur de Europa, el avance científico y técnico dentro del sector es muy escaso.

Esta tesis presenta una metodología para la determinación del potencial productivo de producción de resina en masas de *Pinus pinaster* situadas en el noroeste de la Península Ibérica integrada en una aplicación web interactiva que sirve como un sistema de apoyo a la decisión. La metodología empleada para llevar a cabo esta tesis consta de cuatro fases: una primera fase en la que se comprueba el estado del arte de los trabajos científicos publicados hasta la fecha que contienen información relevante sobre los aspectos determinantes relacionados con la producción de resina; una segunda fase en la que se caracteriza la producción de resina en el noroeste de la Península Ibérica; una tercera en la que se modeliza como varía la producción de resina a lo largo del desarrollo de la campaña de resinado; y la cuarta en la que se modeliza la producción potencial de resina y se crea una aplicación web que sirva como sistema de apoyo a la decisión.

Las metodología y procedimientos que se presentan en el cuerpo de esta tesis, resumen los resultados obtenidos derivados de la investigación llevada a cabo durante los últimos tres años y que han pasado por un proceso de revisión por pares en revistas de alto impacto internacional. Cada uno de los capítulos representa un paso necesario para alcanzar el objetivo final de esta tesis, que es generar conocimiento entorno a la extracción de resina y proveer a los usuarios finales de herramientas y conocimiento que puedan aplicar en el día a día de sus explotaciones para así fomentar este tipo de aprovechamientos en el noroeste de la Península Ibérica.

1.2 JUSTIFICACIÓN DE LA UNIDAD Y COHERENCIA DE LA TESIS

La estructura básica de esta tesis doctoral está compuesta de nueve capítulos. El Capítulo 1 aporta una breve explicación de la motivación que llevo al doctorando a realizar la presente tesis, así como una perspectiva general del trabajo realizado. En el Capítulo 2 se presentan las hipótesis de partida, el objetivo principal de la tesis y los objetivos secundarios necesarios para alcanzar el objetivo final. En el Capítulo 3 se introducen de una manera breve los principales aspectos metodológicos empleados en cada uno de los cuatro capítulos subsiguientes. Estos capítulos se corresponden con los Capítulos 4, 5 y 6, y están formados por los textos publicados en revistas de alto impacto internacional. Asimismo, también se incluye el Capítulo 7, en el que se describe el proceso de creación del sistema de apoyo a la decisión. **Como bien se acaba de indicar, en los Capítulos del 4 al 6 aparecen las publicaciones que componen el compendio de publicaciones**.

En el **Capítulo 4 - *Resin tapping: A review of the main factors modulating pine resin yield*** se realiza una revisión bibliográfica de toda la bibliografía publicada hasta la fecha sobre los principales factores que influyen en la producción de resina, así como las técnicas que se están aplicando en la literatura actual para la modelización de la producción de resina. Dicha revisión también sirvió para detectar aquellas áreas de conocimiento relacionadas con la producción de resina que estaban menos desarrolladas y que tipo de carencias presentaban. Este capítulo ha sido publicado en la revista *Industrial Crops and Products* en 2023, esta revista está indexada en el Journal Citation Reports con un factor de impacto, IF, de 5.6 y pertenece al primer cuartil (Q1) de la categoría *Agricultural Engineering* (2023), y al primer cuartil (Q1) de la categoría *Agronomy* (2023).

En el **Capítulo 5 - *Resin yield response to different tapping methods and stimulant pastes in Pinus pinaster Ait*** se buscó caracterizar la producción de resina de *Pinus pinaster* en noroeste de la Península Ibérica frente a la zona más productiva de España, y comprobar la viabilidad del empleo de un nuevo método de resinado en envase cerrado, más apto para el clima del norte de España, frente al método tradicional de pica de corteza, empleado de manera tradicional en el centro de España y Portugal. Para esto, se realizó un análisis comparativo de la producción de resina en base a factores derivados del método de extracción, así como espaciotemporales que son moduladores de la producción. Para ello, se instaló una red de parcelas de ensayo sobre masas adultas en diferentes puntos de la geografía española en las que se emplearon dos métodos de extracción y dos tratamientos químicos estimulantes diferentes. Este capítulo ha sido publicado en la revista *European Journal of Forest Research* en 2023, esta revista está indexada en el Journal Citation Reports con un IF de 2.6 y pertenece al primer cuartil (Q1) de la categoría *Forestry* (2023).

En el **Capítulo 6 - *Base-age invariant models for predicting individual tree accumulated annual resin yield using two tapping methods in maritime pine (Pinus pinaster Ait.) forests in north-western Spain*** se ajusta por primera vez unos modelos capaces de predecir la producción de resina acumulada a lo largo de la campaña empleando como modelo base la ecuación de Bertalanffy-Richards, tanto para el método de extracción tradicional como para el método de pica circular mecanizada. Para obtener el ajuste óptimo se probaron cuatro ecuaciones base, que generaron ocho formulaciones de éstas diferentes para cada uno de los métodos de extracción, resultando en ambos casos la ecuación óptima la antes mencionada. Se trata del primer caso en el que se ajusta un modelo de esta naturaleza a la producción de resina, demostrando que el uso de estos modelos para predecir la producción final una vez se comienza la campaña son efectivos. Este capítulo ha sido publicado en la revista *Forest Ecology and Management* en 2023, revista está indexada en el Journal Citation Reports con IF de 3.7 y pertenece al primer cuartil (Q1) de la categoría *Forestry* (2023).

Los tres artículos antes mencionados, componen el cuerpo principal de la esta tesis doctoral, estando conectados entre ellos de una manera lógica, y siguiendo el hilo conductor de la investigación llevada a cabo con el fin último de cumplir los objetivos de dicha investigación.

En el **Capítulo 7 – *RESIM: Simulador de la producción de resina en proyectos de aprovechamiento resinero***, se creó la primera aplicación web interactiva capaz de dar estimaciones de la producción de resina en proyectos de aprovechamiento resinero en el noroeste de la Península Ibérica. Para la desarrollar esta aplicación web se siguió una metodología que consta de tres pasos: (i) desarrollo de los modelos de producción, (ii) desarrollo de los modelos de clasificación y (iii) implementación informática. Se trata de la primera vez que se crea una aplicación web interactiva accesible en formato libre capaz de predecir la producción de resina. Se espera que esta aplicación web sirva como una herramienta que incentive la puesta en marcha de aprovechamientos de este PFNM en el noroeste peninsular. Este capítulo se ha presentado en el Registro Central de la Propiedad Intelectual – EA0042017/Ministerio de Cultura con número de expediente 00765-02202427 como programa de ordenador.

Tras el cuerpo principal del documento y el capítulo dedicado a la elaboración de la aplicación web presentada en el Registro Central de la Propiedad Intelectual, en el Capítulo 8 se realizó una discusión general sobre los resultados obtenidos en cada uno de los capítulos 4, 5, 6 y 7, interrelacionándolos entre ellos, y mostrando que siguen un orden estructurado y lógico con los objetivos, haciendo que el lector los perciba como un todo.

Por último, en el Capítulo 9 se muestran las conclusiones generales obtenidas a partir de cada uno de los artículos, las principales contribuciones, y los avances derivados de esta investigación, que a su vez dan respuesta a cada uno de los objetivos establecidos al inicio de ésta. Además, en este apartado también se incluye el plan de futuro de esta investigación, del que parte ya está llevándose a cabo.

2 HIPÓTESIS Y OBJETIVOS

La producción de resina en el noroeste de la Península Ibérica se trata de una actividad relativamente reciente y que poco a poco se va expandiendo, es debido a ello que las técnicas y procedimientos óptimos para esta zona no están aún claros. A pesar de que este PFNM lleva cientos de años explotándose, el conocimiento generado a su alrededor es muy escaso. No existe un consenso general entre los investigadores sobre qué factores son los que modulan su producción, ni existen herramientas predictivas que se puedan emplear para obtener una estimación orientativa de la producción. Por lo tanto, en base a lo anterior y a lo expuesto en el Capítulo 1, las hipótesis de partida son las siguientes:

H1. Estudiar el estado del arte de las especies empleadas para la producción de resina, las características propias de los procesos extractivos, los factores que afectan a la producción o los modelos predictivos desarrollados hasta la fecha, ya que no son de fácil acceso.

H2. Caracterizar la producción de resina en el noroeste de la Península Ibérica respecto a la zona central de España, lugar donde este PFNM se producía históricamente, ya que es necesario para conocer el potencial productivo de esta zona.

H3. Explorar la manera de proveer de herramientas capaces de facilitar la gestión de las masas que están siendo resinadas para de esta manera incentivar y fomentar el aprovechamiento de este PFNM.

Una vez se han establecido las hipótesis de partida, **el objetivo principal de esta tesis es establecer una metodología para la determinación del potencial productivo de la producción de resina de *Pinus pinaster* en el noroeste de la Península Ibérica integrada en un sistema de apoyo a la decisión.** Para la determinación de este potencial productivo se ha seguido un flujo de trabajo definido, y para el que se fijaron los siguientes hitos intermedios, los cuales corresponden cada uno a una publicación en una revista internacional de alto impacto con revisión por pares y que componen el cuerpo principal del documento, así como con el Capítulo 7, en el que se desarrolla el sistema de apoyo a la decisión:

O1. Reunir en un único documento información relevante sobre los principales factores involucrados en la producción de resina y sus propiedades físicas y químicas en la bibliografía publicada hasta la fecha que sirva como punto de partida para investigaciones posteriores.
Tareas implicadas: establecer las principales especies de *Pinus* empleadas en la producción de resina y las regiones productoras, así como mostrar la evolución en los últimos años del número de publicaciones científicas; identificar los factores más influyentes en la producción de resina (genéticos, medioambientales, dendrométricos y fenotípicos); compilar las diferentes metodologías que se usan actualmente para extraer resina y su impacto en la producción y en la calidad de esta.
Abordado en: Capítulo 4 - *Resin tapping: A review of the main factors modulating pine resin yield.*

O2. Caracterizar la producción de resina en el noroeste de la Península Ibérica en la principal especie productora empleando diferentes métodos de extracción y pastas estimulantes.

Tareas implicadas: comparar en términos de producción de resina el método tradicional de la Península Ibérica o "pica de corteza" y el método de pica circular mecanizada; comparar la efectividad de las pastas estimulante Ethephon y ASACIF; estudiar como las variables dasométricas afectan a la producción de resina; estudiar la eficiencia durante el periodo de resinado de ambos métodos y pastas estimulantes.

Abordado en: Capítulo 5 - *Resin yield response to different tapping methods and stimulant pastes in Pinus pinaster Ait.*

O3. Modelizar la producción anual de resina una vez comienza la temporada de resinado con el fin de obtener una modelo que permita a los futuros interesados realizar una estimación de la producción al final de la campaña, pudiendo así optimizar y ajustar la duración de esta.

Tareas implicadas: evaluar la validez de la metodología de los modelos invariantes con la edad para modelizar la producción anual acumulada de resina en árboles individuales de *Pinus pinaster* en el noroeste de la Península Ibérica.

Abordado en: Capítulo 6 - *Base-age invariant models for predicting individual tree accumulated annual resin yield using two tapping methods in maritime pine (Pinus pinaster Ait.) forests in north-western Spain.*

O4. Crear un sistema de apoyo a la decisión que pueda ser empleado para la toma de decisiones en el establecimiento y gestión de explotaciones de resina de *Pinus pinaster* en el noroeste de la Península Ibérica.

Tareas implicadas: implementar modelos de producción de resina válidos para el noroeste peninsular; entrenar un modelo de clasificación capaz de asignar un grupo en función de diferentes variables relativas a las características dasométricas de la masa y al proceso extractivo que se desee emplear; desarrollar una aplicación web interactiva que integre los modelos desarrollados en este trabajo.

Abordado en: Capítulo 7 – *RESIM: Simulador de la producción de resina en proyectos de aprovechamiento resinero.*

3 METODOLOGÍA

Con el fin de alcanzar tanto el objetivo principal como los objetivos intermedios descritos en el Capítulo 2, en este capítulo se ofrece una breve visión general de las metodologías descritas en los Capítulos 4, 5, 6 y 7. Como se dijo anteriormente, cada uno de los capítulos 4, 5 y 6 corresponde a una publicación en una revista de ámbito internacional de alto impacto con revisión por pares. Además, estos cuatro capítulos están relacionados con cada uno de los objetivos intermedios necesarios para alcanzar el objetivo principal (*e. g.* el Capítulo 4 da respuesta al O1, el Capítulo 5 se corresponde con el O2, el Capítulo 6 con el O3 y el Capítulo 7 con el O4). Dado que esta sección únicamente va a tratar de forma breve cada una de las metodologías empleadas, si se desease una descripción más detallada de los procedimientos llevados a cabo se debe de dirigir a los Capítulos 4, 5, 6 y 7.

En el **Capítulo 4 - *Resin tapping: A review of the main factors modulating pine resin yield***, se realizó una revisión bibliográfica de la literatura existente hasta la fecha relacionada con la producción de resina. En ella se recogen las principales especies empleadas en la producción de resina de pino a nivel mundial, así como sus características físico-químicas, los factores ambientales y dasométricos que la regulan, los posibles métodos de extracción, así como los modelos existentes capaces de predecir la producción de resina. Para esto se realizó una revisión bibliográfica sistemática de la bibliografía relacionada con la producción de resina hasta el 2023 en las principales bases de datos de literatura científica (ScholarGoogle, ScienceDirect, Springuer, Web of Sacience, ReserarchGate y SemanticScholar). Los términos introducidos para la búsqueda en estas bases de datos se separaron en tres bloques diferentes en función de la temática de estos, (i) *resin production,* (ii) *factors* y (iii) *statistical análisis*. El proceso de selección de los documentos se realizó en dos fases, una primera de filtrado de los artículos en base a la lectura del resumen y las conclusiones, y una segunda en la que, tras el filtrado, se leyeron los documentos completos y se clasificaron en función a diferentes criterios. De todos estos documentos se extrajo su fecha de publicación (*Information sequence*), la localización donde se realizó el estudio (*Location*), las especies utilizadas (*Species*) y el tema principal (*Topic*), permitiendo hacer una caracterización de que países están apostando de una manera más intensa por la producción de resina, que especies son las más estudiadas y en que ámbitos de conocimiento son en los que están invirtiendo más recursos en la actualidad.

En el **Capítulo 5 - *Resin yield response to different tapping methods and stimulant pastes in Pinus pinaster Ait.***, se estudió cómo se comporta la producción de resina en árboles de la especie *Pinus pinaster* en el noroeste de la Península Ibérica, y de qué manera influyen un nuevo método de extracción y pastas frente al empleado tradicionalmente en España. Para ello se estableció una red de parcelas en masas adultas de pino resinero en diferentes localizaciones del norte de España (Culleredo, Godos, Pantón y Barcia) y, además, se instaló una quinta en la localidad de Coca (Segovia), epicentro de la actividad resinera en España, y la que permitió comparar el rendimiento de los árboles del noreste peninsular con aquellos seleccionados durante cientos de años para esta finalidad. En cada una de las parcelas se seleccionaron 90 árboles, y se separaron en tres bloques, en los que se probaron todas las combinaciones posibles entre los dos métodos empleados (pica de corteza y entalladura circular mecanizada) y los dos tratamientos químicos estimulantes (Ethephon y ASACIF). Además, para poder asegurar la comparación entre las producciones obtenidas por ambos métodos, se definió la producción de resina estandarizada, una unidad de medida que pondera la producción de resina obtenida en función de la longitud de la incisión realizada. Por último, las producciones obtenidas para las distintas localizaciones, métodos y pastas se compararon empleando pruebas estadísticas de comparación entre grupos y de medidas repetidas. Además, también se estudió si existían correlaciones estadísticamente significativas entre la producción de resina y las variables dasométricas.

En el **Capítulo 6 -** ***Base-age invariant models for predicting individual tree accumulated annual resin yield using two tapping methods in maritime pine (Pinus pinaster Ait.) forests in north-western Spain***, por primera vez se demostró que se puede modelizar la producción de resina acumulada a lo largo de la campaña empleando el enfoque de diferencias algebraicas (ADA), formalizado por Bailey & Clutter (1974), y el enfoque de diferencias algebraicas generalizadas (GADA), introducido por Cieszewski & Bailey (2000). Para ello, durante los meses de junio a octubre de 2021 se establecieron tres parcelas de experimentación en la provincia de Galicia, España. En total se emplearon 180 árboles, que fueron sometidos a dos procedimientos de extracción de resina (pica tradicional y entalladura circular mecanizada), y a dos tratamientos estimulantes diferentes (Ethephon y ASACIF). Lo primero que se hizo fue comprobar si todos los árboles pertenecían a la misma población, y por tanto los datos podían ser utilizados de manera conjunta, obteniendo como resultado que existían diferencias estadísticamente significativas entre las producciones de los métodos de extracción. Una vez separados los datos relativos a cada método de manera individual, las pastas estimulantes no obtuvieron diferencias estadísticamente significativas entre ellas, por lo tanto, se podían tratar los datos de forma conjunta. Tras verificar esto, se definieron los cuatro modelos base que se emplearon durante el proceso de modelización, Bertalanffy-Richards (Bertalanffy, 1949, 1957; Richards, 1959), Korf (citado en Lundqvist (1957)), Weibull (Weibull, 1951; Yang et al., 1978) y Hossfeld (Hossfeld, 1822), así como sus diferentes formulaciones. Por último, se calcularon diferentes métricas relacionadas con la bondad del ajuste de cada uno de los modelos probados con el fin de seleccionar aquel que mejor desempeño tuvo en cada caso.

Finalmente, en el **Capítulo 7 –** ***RESIM: Simulador de la producción de resina en proyectos de aprovechamiento resinero***, se crea por primera vez un simulador capaz de dar estimaciones de la producción total que potencialmente se podrá obtener en pinares de *Pinus pinaster* del noroeste peninsular. Para ello, se empleó una metodología en tres pasos: (i) implementación de los modelos de producción, (ii) desarrollo de un modelo de asignación e (iii) implementación informática. Para predecir las producciones de resina de las masas descritas por los usuarios se han empleado los modelos de producción de resina del capítulo 6, así como los desarrollados por López-Álvarez et al. (2024). En este artículo los modelos estiman la producción de resina de acuerdo con una metodología basada en técnicas de Machine Learning y Deep Learning. El desarrollo de los modelos de asignación es necesario, ya que una vez introducidos los datos en la aplicación, ésta debe de establecer que modelo emplear en base a la localización, las características dasométricas de la masa y los métodos de extracción que se vayan a emplear. Para ello, se entrenó un modelo XGBoost en base a los datos empleados en el Capítulo 5. Por último, en la fase de la implementación informática de ambos tipos de modelos se empleó R como lenguaje base de programación, aunque en partes del código aparece java embebido. El desarrollo se basó en módulos Shiny, los cuales permiten al usuario interactuar al usuario con la aplicación por medio de un navegador.

4 RESIN TAPPING: A REVIEW OF THE MAIN FACTORS MODULATING PINE RESIN YIELD

Este capítulo se corresponde con el siguiente artículo de investigación:

- **Título:** Resin tapping: A review of the main factors modulating pine resin yield
- **Revista:** Industrial Crops and Products
- **Editorial:** Elsevier
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- **Contribución de los autores:**
    - **Ó. López-Álvarez:** Conceptualización, Metodología, Análisis formal e investigación, Escritura de la versión original.
    - **R. Zas:** Revisión y edición.
    - **M. Marey-Perez:** Conceptualización, Metodología, Análisis formal e investigación, Revisión y edición, Adquisición de fondos, Recursos, Supervisión
- **Indicadores (2023):** Factor de Impacto, IF=5.6; Primer cuartil (Q1; 8/126) de la categoría *Agronomy*; Primer cuartil (Q1; 4/20) de la categoría *Agricultural Engineering*
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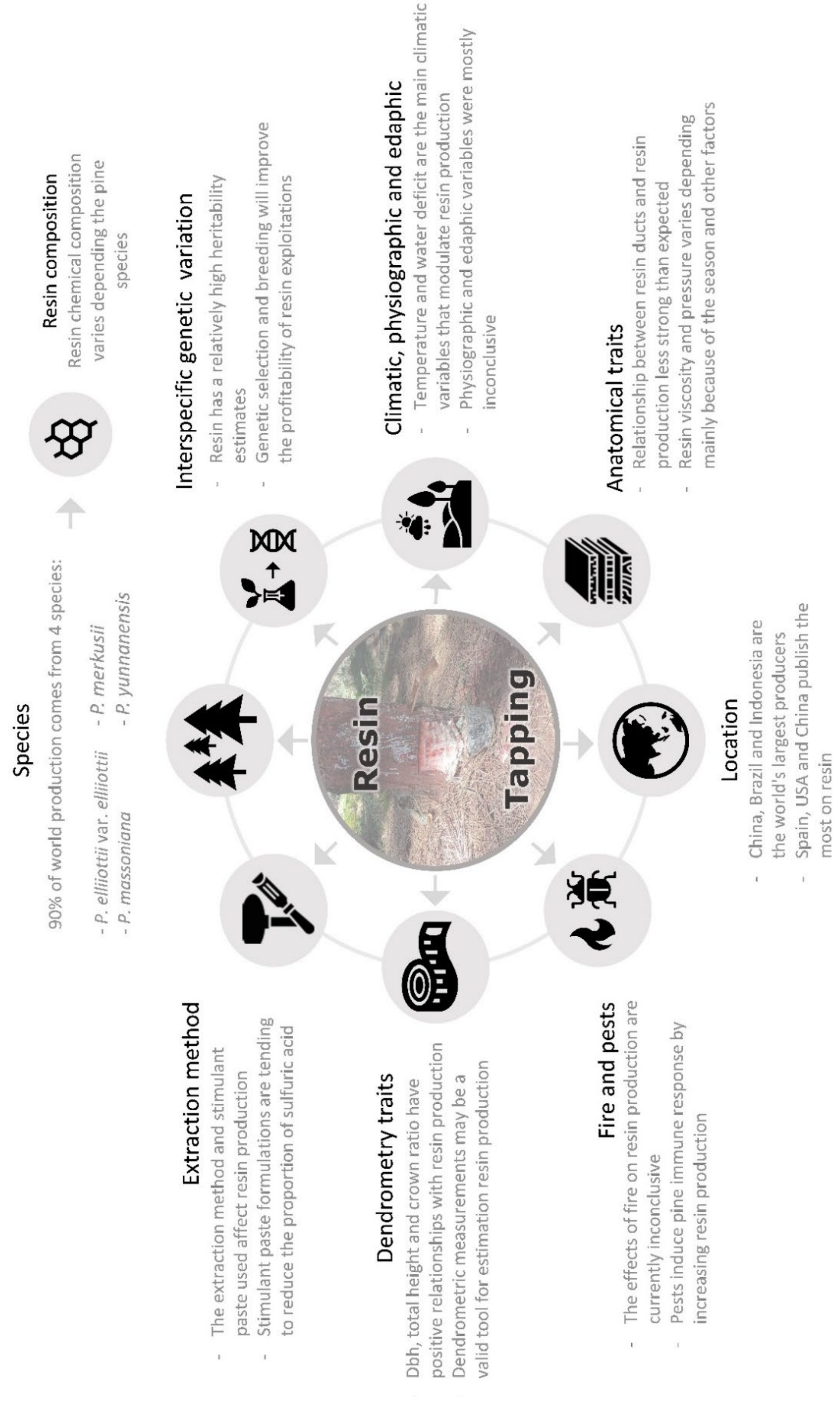
Resumen gráfico

A continuación, se muestra el resumen gráfico incluido junto con el artículo que expone los principales resultados.



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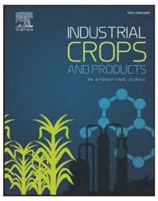

Resin tapping: A review of the main factors modulating pine resin yield

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ABSTRACT

Pine resin is a non-wood forest product that has been used for multiple purposes since ancient times throughout the world. In recent years, resin tapping activity has increased in countries that were historically producers, but in which it had practically disappeared since the late 1980 s, and is expected to grow in importance due to its bioproduct nature. The aim of this review is to provide an overview of the research work on the main factors modulating resin yield. A total of 205 papers were selected and classified according to their main topics. The species and its intraspecific genetic variation are two of the main factors influencing both the production and the quality of the resin obtained. The environmental factors most commonly studied and which in turn were the most successful when related to resin production, were temperature and water availability. Diameter at breast height was the most investigated dendrometric variable, although other variables such as total height or crown ratio were also studied, generally obtaining positive relationships between them and resin production. The resin ducts, which produce, secrete and transport resin through the tree, are the most influential anatomical variable and the focus of the anatomical research. Other factors that can modulate resin production are the presence of pests, which induce the tree's immune response, and fire, with contradictory results on their effects. Finally, the extraction method and the stimulant paste used influence resin production, research is focusing on new extraction methods and more efficient and cheaper stimulant pastes with lower proportions of sulfuric acid. Although interest in and knowledge about resin tapping has increased in recent years, research needs to further develop and deepen the relationships between resin production and the different factors involved.

1. Introduction

To defend themselves against antagonistic organisms, plants produce a wide variety of defensive substances that repel, impede or deter the progress of the invaders (Agrios, 2005). In addition, components of these substances can attract the natural predators of the invaders (Phillips and Croteau, 1999). One outstanding example of these defensive substances is resin, a viscous substance secreted by many different plant species, composed of volatile and non-volatile secondary metabolites (mainly mono and sesquiterpenes and resin acids) mixed heterogeneously in different proportions depending on the particular species. Resin is typically produced and stored in specialized cells that may form different types of structures in which resin is stored under pressure. When plant tissues are damaged, resin flows out expelling and/or capturing the aggressor. In addition, when exudation begins and the resin comes into contact with the atmosphere, the volatile compounds, evaporate, leaving a semi-crystalline mass which forms a protective barrier that seals the wound, thus preventing further access by insects and pathogens to internal tissues (Phillips and Croteau, 1999).

Many plant taxa, including species from phylogenetically distant orders such as Asparagales, Malvales, Apiales or Coniferales, to mention just a few, produce resins as a defensive mechanism (Langenheim, 2003).

In temperate regions, the main resin-producing plants are, however, the gymnosperms, and particularly the Pinaceae family which includes up to ten genera and 230 species distributed worldwide (Wu and Hu, 1997). Within the Pinaceae family, the *Pinus* genus stands out as the one with the highest investment in resin production. In pine trees, resin is produced and accumulated at high concentrations (up to 10–20% of dry mass) in all tissues (stems, roots, branches, needles, and even cones). Pine resin is stored in specialized structures that form an interconnected three-dimensional hub of resin ducts (Vázquez-González et al., 2020). When resin canals are injured, the resin accumulated in this network of tube-like structures flows out in amounts which, depending on the

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species, can be copious.

For thousands of years, different civilisations have harvested resin from pine trees, and benefited from the different uses it has (Meiggs, 1982). The activity of resin extraction from trees is called resin tapping, and consists of making wounds in the stems of living trees and collecting the resin that flows out from the exposed resin ducts (Sharma et al., 2018b). Formerly, the practiced wounds removed not only the bark and the cambium but also thin strips of wood, causing important lesions and large impacts on tree growth and timber quality (Chen et al., 2015; Rodrigues-Corrêa et al., 2013; Rodríguez-Soalleiro et al., 2008; Zeng et al., 2021). Nowadays, wounds do not penetrate into the wood reducing the impacts in tree growth while allowing the resin flowing from the exposed resin canals in the xylem and phloem to be collected (Van der Maaten et al., 2017; Martínez-Chamorro, 2016; Tomusiak and Magnuszewski, 2009). In the early stages of civilisation resin was used for motley purposes, such as, for example, mummification processes in ancient Egypt or in traditional medicine (Michavila et al., 2017), but the real boom in the use and trade of pine resin occurred in the 15th century, with the rise of the shipbuilding industry in Europe and the use of resin for waterproofing ships (Loewen, 2005).

With the emergence of the chemical industry in the 19th century, resin found an important industrial niche that has been maintained up to date (Michavila et al., 2017). The industrial uses of oleoresin and its derivatives cover a wide range of products, some of high added value such as pharmaceuticals, cosmetics, emulsifiers, adhesives, chewing gums or paints (Pinillos et al., 2009; Neis et al., 2019b; Rodrigues-Corrêa et al., 2013). With the professionalisation of the sector, an important effort was paid to improve the tapping techniques and the efficiency of exploitations, thus leading to a continuous increase in knowledge in the different fields involved in resin production, such as new extraction methods or the use of chemical stimulants to improve production (Hodges, 1995; Parham, 1976). In traditional producing countries (e.g. Spain, USA, France, Portugal), resin production continuously increased until, approximately the 1980′s, when the market was liberalised and practically monopolized by emerging producers in subtropical countries, dooming the production in traditional areas to practically disappear (Pinillos et al., 2009; Picardo, 2013; Soliño et al., 2018). The emergence of synthetic resins also contributed to the decline of resin tapping exploitations (Sebastián, J.A. (ed. lit.), Uriarte-Ayo, R. (ed. lit.), 2003). However, in the 2000 s, and as a consequence of the interest for substituting petroleum derivatives by renewable bioproducts in the industry (Aldas et al., 2020; Karademir et al., 2020) and the need to revitalize pine forests both from an economic and environmental perspective (Soliño et al., 2018), the resin tapping sector is regaining attention in different regions where it had almost disappeared, such as southwest Europe. This interest stems from the need to reduce the environmental impact of many industrial processes and their dependency on fossil nonrenewable raw materials (Demko and Machava, 2022). Pine resin is, indeed, postulated as a candidate to replace petroleum derivatives in the synthesis of many products, such as new printer inks or jet fuels based in hydrogenated turpentine, thus making them more ecofriendly and sustainable (Alonso-Esteban et al., 2022; Bolonio et al., 2022; Donoso et al., 2021; Hayta et al., 2022). This comeback of the sector is leading to a resurgence of the interest for understanding the main factors involved in pine resin production, and resin chemical properties, and practical issues related to the extraction methods to make resin tapping exploitations more profitable (Rodríguez-García et al., 2016; Rubini et al., 2021).

The general objective of the present work is to provide a systematical bibliographical review of the main factors that influence resin production and its physical and chemical properties. The specific objectives are: 1) To determine the main *Pinus* species, regions and temporal trends of the accumulated scientific knowledge on pine resin production and resin tapping; 2) To identify the most influential factors (genetic, environmental, dendrometric and phenotypic) that modulate resin production; and 3) To compile the different methodologies currently used for resin tapping and summarize their impact on resin yield and quality. The aim of this.

review is to provide an overview of the factors involved in the activity of resin extraction, serving both as a compilation of articles published to date, and as a starting point for future research.

2. Methods

We conducted a systematic review of scientific literature published up to the beginning of 2023 through a systematic search in the most common databases (ScholarGoogle, ScienceDirect, Springer, Web of Science, ResearchGate and SemanticScholar) using keywords and concepts related with the topic of resin tapping. The terms sought could be grouped into three blocks: *resin production*, *factors* and *statistical analysis*. The chosen terms related with the *resin production* block were: pine, *Pinus*, resin yield, oleoresin, resin production, resin flow, defenses, resin canals, resin ducts and gum. In relation to the *factor's* block, the expression and words used were: climate, genetic variation, heritability, temperature, precipitation, irradiation, water deficit, evapotranspiration, dendrometry, site index, diameter, total height, basal area, density, age, crown diameter, competition index, slenderness, bark thickness, soil properties, slope, orientation, altitude, tapping methods, wounding and stimulant paste. Finally, the terms related with the *statistical analysis* research were: regression model, statistical approach, modelling, factors, geostatistic, correlation values, Pearson, Spearman, stepwise, linear, regression, non parametric and distribution functions. A total of 49 different terms and their combinations were introduced in the distinct databases. The results were filtered in two steps, firstly by reading the abstract and conclusions, and then by reading the full paper, choosing those that had the strongest relationships with the main topics of this paper. Additional papers were identified throughout the reviewing process by referring to pertinent studies that were cited in the reviewed literature.

The selected papers were classified depending on the year of publication, the location of the study, the species used and the main topic (Fig. 1). The first group was the *Information sequence*, in which the articles were classified according to their publication year, analyzing the number of publications per year and the trend in recent years. In the second group, *Location*, the articles were classified according to the country where the study took place. This two first classification groups put into context the situation and interest in the study of resin tapping around the world. The third group, *Species*, allowed to list the world's leading pine species used for resin tapping and research and the main chemical components of the resin they produce. The fourth group, *Topics*, includes the articles exploring the behavior and influence of different factors both at the stand level (climatic, physiographic, edaphic and silvicultural) and the tree level (genetic, dendrometric, anatomic, fire and pests and extraction method) that can intervene in resin production.

3. Information sequence

The number of papers directly related to the topic of resin tapping as the main focus was scarce, so the search had to take cross-cutting paths to understand the processes and factors involved in resin production. A total of 205 papers were finally selected and classified according to the six groups defined in the Methods section (Table S1). The number of scientific publications related to the extraction of resin from pine trees showed a marked positive trend over time (Fig. 2), which was more pronounced than the general increase in publications that occurred in all scientific disciplines, such as those related to pine trees from a broad global perspective, represented by the number of publications when using the Web of Science as a filter on the topics "pine OR pinus OR pines". For this comparison, the Web of Science was used as a large collection of bibliographic databases of citations and references of scientific publications. The peak of publications related with resin tapping

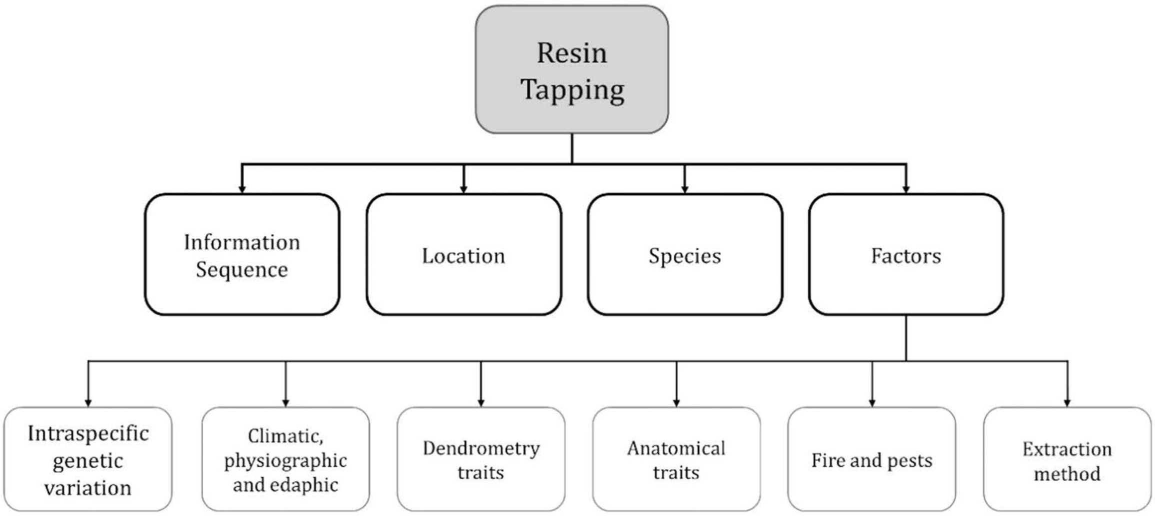

Fig. 1. Concept map of the four main groups into which the articles were grouped and the subgroups into which the articles were classified within the fourth group.

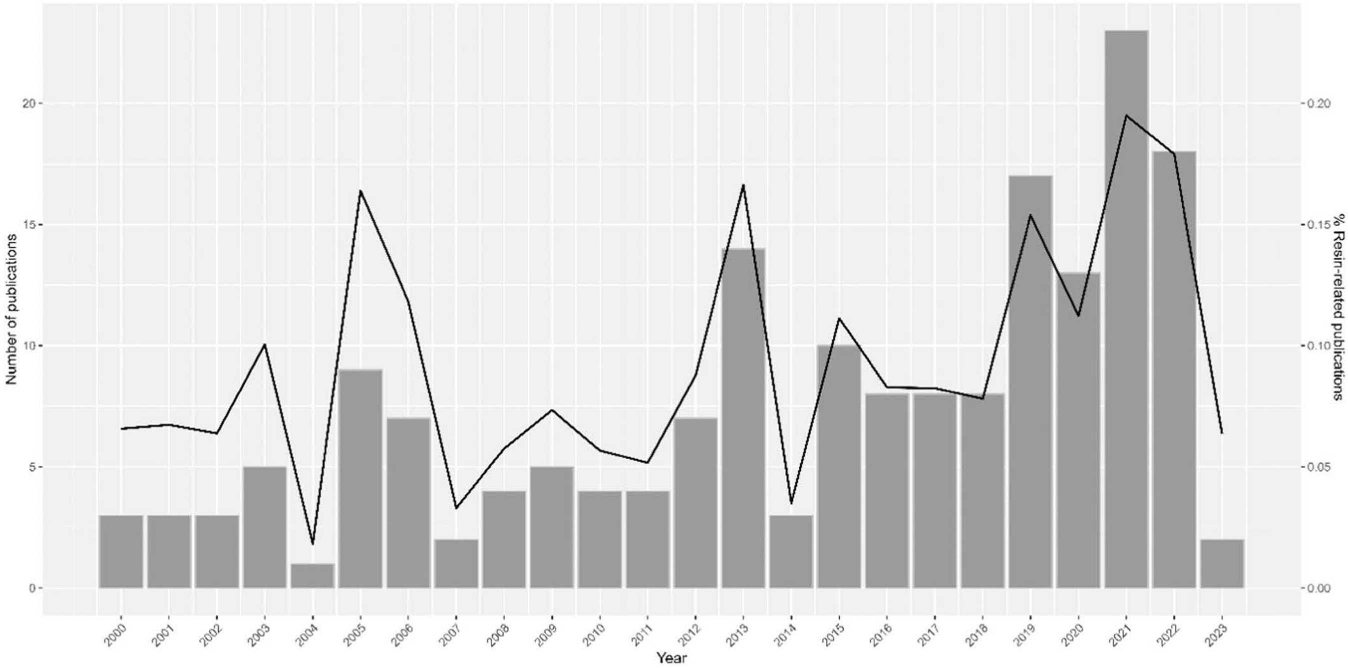

Fig. 2. Number of scientific publications related to resin tapping of pine trees from 2000 onward (barplot) and percentage of resin-related publications in the total number of publications with the words *pine*, *pinus* or *pines* as the topic in the Web of Science (continuous line). This global trend is referred to the right y-axis which was scaled to make the value 0.05% coincident with the value 5 of the publications. Note the stepper trend in the last 3 years of the publications related to resin tapping in relation to the general rise of publications related to pine trees.

occurred at the end of the studied period with 23 publications in 2021. The increase in the number of publications may be due to the emerging interest for renewable bioresources capable of substituting petroleum derivatives, such as resin, as mentioned above (Hayta et al., 2022). Particularly, the increasing interest for resin production has prompted many research activities aimed to determine the most productive territories and fine tune management alternatives to improve production, especially in countries where the activity had previously ceased (Moreno-Fernández et al., 2021).

4. Location

Additionally to the date of the publications, the country in which the studies were carried out is also important to see which geographical areas have the most interest in the field of study. Fig. 3 shows the.

number of publications related to pine resin production according to the country where the study was carried out. The variation in the size of the dots denote the total resin production in those countries (Clopeau and Orazio, 2019; Cunningham, 2022). An important mismatch can be seen between the number of publications and the total production of resin across countries. While scientific publications related to resin are abundant in Spain, USA, and other countries with little resin production. Some other resin producing countries such as Vietnam for which no publications were found are even missing in the figure. This decompensation between the number of publications and the total production of resin can also be seen in Fig. 4, which shows the proportion of publications according to the pine species studied in each paper. Clearly, *P. pinaster* is the most studied species despite contributing little to the

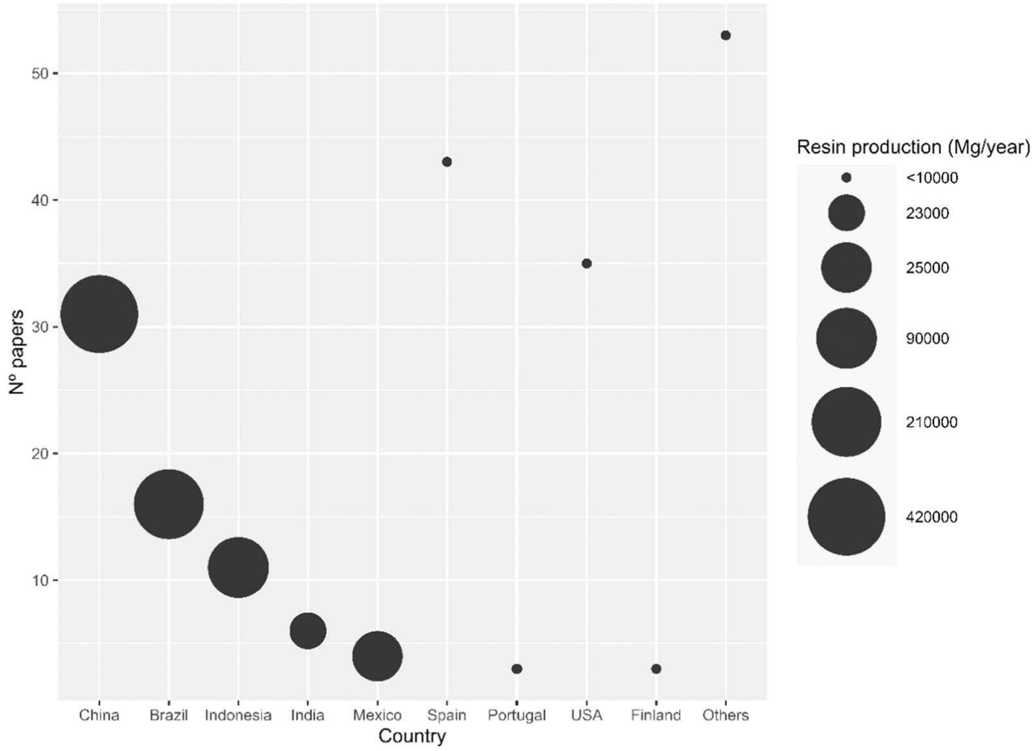

Fig. 3. Total number of publications related to resin tapping in relation to the country where the studies were carried out. The size of the symbols is proportional to the total resin production in each of these countries according to different references (Clopeau and Orazio, 2019; Cunningham, 2022).

Fig. 4. The outer part of the figure shows the number of publications related to resin tapping by species used, while the inner part of the graph shows the percentage of world production of each species.

world resin production. A high number of resin-related publications focused on *P. pinaster* come from the Iberian Peninsula (Spain and Portugal), where important research efforts related to resin production are currently in progress (Palma et al., 2012; Rodríguez-García et al., 2014; Zas et al., 2005; Martínez-Chamorro et al., 2019a). The next most studied species was *P. elliottii*, an important producing species widely present in China and Brazil (Li et al., 2012; Neis et al., 2019a; Yi et al., 2021) which are the world's largest producers. The rest of the species appear in similar percentages in the publications consulted.

Spain was the country that most contributed to the scientific literature related to resin production (Fig. 3), probably due to the research initiatives that are being carried out during the last decade to try to reactivate this practically extinct activity in the Iberian Peninsula (Clopeau and Orazio, 2019; Lainez et al., 2018). This research focuses, mainly, on fine tuning new extraction methods and estimating their yields, the development of new stimulants and the identification of the main environmental and dendrometric variables that determine resin production (Rodríguez-García et al., 2016, 2014; Vázquez-González et al., 2021; Zas et al., 2020).

Publications carried out in USA were also notably high, thanks to studies conducted in the 20th century and early 2000 s on resin yield and resin production in response to bark beetle injury (Hodges, 1995; Lombardero et al., 2000; McReynolds, 1971; Tisdale and Nebeker, 1992). China is the third in number of publications, with most of its publications in the fields of genetic variation and the factors modulators of resin production (Lai et al., 2020; Liu et al., 2022; Luan et al., 2022; Shi et al., 2021). Brazil and Indonesia are fourth and fifth respectively, with the Brazilian publications focusing mainly in elucidate the molecular basis of the pine oleoresin production (de Lima et al., 2016; Junkes et al., 2019a) and the study of new active compounds to increase resin production (Candaten et al., 2021; Rodrigues et al., 2008; Santos et al., 2016). Indonesian publications mainly focus on the relationships between dendrometric characteristics and resin production (Hadiyane et al., 2015; Lukmandaru et al., 2020; Sukarno et al., 2015). It is important to note that the countries in which the studies were carried out coincide with the country where the authors are based, suggesting that there is very little exchange of researchers between countries.

5. Species

The pine species used for resin tapping depends on the geographic area and the availability of high yielding native species, or exotic species capable of being grown in the region (Lauture, 2017). Almost 90% of the resin produced in the world comes from just four pine species (Cunningham, 2022), although many other pine species are also potentially high resin yielders (Table 1). These four species are *P. elliottii* var. *elliottii* (China and Brazil), *P. massoniana*, *P. merkusii* (Indonesia) and *P. yunnanensis* (China) (Cunningham, 2012). In addition to these four species, *P. pinaster* is widely used in the Iberian Peninsula and France (Picardo, 2013; Palma et al., 2016), *P. oocarpa* in Mexico (Reyes-Ramos et al., 2019), *P. roxburghii* in India (Sharma et al., 2018a), *P. kesiya* also in China (Wang et al., 2015), *P. nigra* ssp. *laricio* in Corsica (Rezzi et al., 2005), *P.caribaea* in Brazil and Malaysia (Jantan and Ahmad, 1999), *P. sylvestris* in north Europe and Slovenia (Rissanen et al., 2021; Zaluma et al., 2022) and *P. halepensis* in Greece and Tunisia (Aloui et al., 2022; Papadopoulos, 2013). Some hybrids between some of these species are also used for resin-tapping in different countries (Liu et al., 2022).

Resin production per individual tree is highly variable both across species but also within species (Table 1). According to the published data, some species (*P. kesiya* and *P. caribaea*) produce more resin than others (*P. sylvestris* and *P. roxburghii*). Usually, in the producer countries the tree's yield ranges between 3 and 6 kg, although there is a huge variation between productions. This variation is a consequence of different factors modulating resin production that will be discussed below. The extremely high values for some of the species (*P. yunnanensis* and *P. halepensis*) are due to a combination of these factors, mainly due to the extraction methods used.

The pine species and the geographic location not only influences resin yield but also determines the resin composition (Silvestre and Gandini, 2008). Resin is a complex mixture of turpentine (volatile fraction, mainly composed by mono and sesquiterpenes), and rosin (non-volatile fraction, mainly composed by diterpenes or resin acids) (Neis et al., 2019a; Rubini et al., 2022). Sometimes, resin is confused with oleoresin, which differs from oleoresin in that it is comparatively fluid with a higher proportion of volatile and non-volatile terpenes (Demko and Machava, 2022). From now on, both the term resin and oleoresin will be used to refer to resin, as they are used interchangeably to refer to resin. The proportion of both fractions is highly variable depending on the species, the genotype and the environmental conditions (Yi et al., 2021). As an example of this variations, Table 2 shows the proportions of mono- and diterpenes in the resin of the four most productive species and in *P. pinaster*, which is the most studied in the reviewed papers.

Table 1
Most commonly pine species used for resin production, the region where resin is produced, the contribution to world resin production and the range of individual tree production according to the literature. * : Note that individual tree production depends, among other factors, on the extraction method.

		Species		
Species	Region	% production	Tree production* (kg/tree)	Reference (s)
P. elliottii var. *elliottii*	China, Brazil, Argentina	48.8	3–8	Neis et al. (2019a)
P. massoniana	China, Vietnam	19.6		
P. merkusii	Indonesia	14.3	2–5	Hadiyane et al. (2015)
P. yunnanensis	China, Vietnam	4.2	2–12 <	Wang et al. (2015)
P. caribaea	Brazil, Malaysia	< 13.1	4–4.5	Santos et al. (2016)
P. pinaster	Iberian Peninsula, France	idem	1–4	Palma et al. (2012)
P. oocarpa	Mexico	idem	2–3	Heinze et al. (2021)
P. roxburghii	India	idem	< 1–1.3	Dutt and Kumar (2020); Sharma et al. (2013a)
P. kesiya	China	idem	3	Yi et al. (2018)
P. nigra ssp. *Laricio*	Corsica, Slovenia	idem	1–2	Cannac et al. (2009);Gajšek et al. (2018)
P. sylvestris	North Europe, Slovenia	idem	< 1	Gajšek et al. (2018)
P. halepensis	Greece, Tunisia	idem	< 1–13.5	Spanos et al. (2010)

The differences in the total proportion of monoterpenes and diterpenes vary according to the different species, making species valid for different purposes (Rodrigues-Corrêa et al., 2013). Table 2 shows how the contents of *α-pinene*, the most abundant monoterpene in all cases, vary according to the species from 27.43% in *P. elliottii* to 74.3% in *P. merkusii*. The case of the *β-pinene* is even more variable, since in *P. elliottii* and *P. pinaster* it appears in quite high levels, while in the other three species is much less abundant. In terms of diterpenes, the values are similar among all the species, although they vary in each one, especially the levels of Levopimaric+Palustric acid and neoabietic acid.

As mentioned above, the amounts of the different fractions that make up the resin vary between species. However, there is also intraspecific variation, which can be seen in the ranges between the different fractions for the species *P. elliottii* (three areas in Jiangxi Province, China), *P. merkusii* (East and West Java and North Sumatra) and *P. pinaster* (three areas in Segovia Province, Spain + 2 seasons) in Table 2. These ranges correspond to the variation in resin composition according to location and, in the case of *P. pinaster*, according to the season in which the samples were collected. These variations are accentuated by distance and differences in the environmental characteristics in which the trees were found. For example, *P. elliottii* samples collected by Lai et al. (2020) during the months of July to September had lower proportions of alpha and beta pinene than those recorded by Rodrigues et al. (2011) during the spring in Rio Grande do Sul, Brazil. The latter work also shows how the composition of resins can vary depending on the concentration of metals used to prepare the chemical stimulants.

6. Factors

Based on published data, resin production of pine trees shows wide variability both across and within pine stands. To understand this variability, the starting point is to explore the distribution functions that best fits to this variation, and then to explore the factors behind this variation. There are few works that have explored the frequency distributions of within-site variability in resin production and the distribution of resin production variability across the territory. Gómez-García et al. (2022) modeled the distribution functions of resin production for 45 *P. pinaster* stands with different treatments in Northwest Spain using the two-parameter Weibull function and the moments-based parameter recovery method. Similarly, Nanos et al. (2000) used the two-parameter Weibull but also the Chaudhry and Ahmad's probability function to model the resin production distribution function of *P. pinaster* in the Central Plateau of the Iberian Peninsula. Both works obtained the same results, with large differences in production between and within the plots and attributing this variation to climatic, edaphic, dendrometric and silvicultural factors, as will be discussed in the following sections.

Another type of data-driven modelling that remains poorly studied, as a tool for modelling resin production is geostatistics. Nanos et al. (2001) used this technique to model resin production in the Spanish Central Plateau, studying the spatial structure of resin production of maritime pine populations at two different scales. Results showed that within-stand variation was not spatially structured, however, variation in mean plot production was spatially structured. This reinforces the fact that the variation in resin production is due to several factors such as those mentioned above.

Table 2
Variation in chemical compositions between the four species with the highest production worldwide and *P. pinaster*. * :the percentages of these species are not relative to the total but according to the fraction to which they belong (monoterpenes or diterpenes).

Chemical compositions	*P. elliottii* var. *elliottii*	*P. massoniana*	*P. yunnanensis*	*P. merkusii* *	*P. pinaster* *
Reference(s)	Lai et al. (2020)	Song et al. (1995) Song	et al. (1995)	Wiyono et al. (2006)	Arrabal et al. (2002)
Monoterpenes (%)					
α-Pinene	27.43–28.31	31.7	38.5	57.7–74.3	67.95–70.6
Myrcene	1.59–1.98	0.4	0.5	0.7–1	0.65–1.04
Dipentene	0.43–0.52	0.5	1.7	0.9–2.8	1.44–185
Camphene	0.28–0.31	0.5	0.5	0.7–1	0.58–0.67
β-Pinene	13.41–15.08	1.2	2	0.8–4.8	17.53–18.91
Diterpene (%)					
Isopimaric acid	3.93–4.01		1.4	0.88–0.97	7.86–11.18
Abietic acid	10.51–11.31	10.9	5.5	1.05–1.15	12.78–13.67
Dehydroabietic acid	3.26–3.49	1.7	2.6	1	2.53–3.60
Neoabietic acid	10.62–11.65			1.10–1.34	16.84–18.84
Pimaric acid	0.22–0.24	0.1	0.7		6.53–7.19
Pimarene	0.27–0.31				
Pimarinal	0.25–0.28				0.48–0.61
Communic acid	0.20–027	4.1	2.9		
Sandaracopimaric acid	0.24–0.27	1.3	1.4	0.77–0.93	1.53–1.74
Palustric + Levopimaric acid	18.08–19.24	27.5	31	0.91–0.98	38.30–42.51
15-Hydroxydehydroabietic acid	0.33–0.41				
7,13,15-Abietatrienic acid	0.26–0.41	0.7	0.6		0.53–0.72
Dehydroabietal	0.29–0.33	1.7	2.6		
7-Hydroxydehydroabietic acid	0.35–0.45	0.2	0.1		
6,8,11,13-Abietatetraenoic acid	0.27–0.29	0.2	0.3		
8,14-Dihydropimaric acid	0.27–0.3	1.7	2.6		
Monoterpenes (%)	43.42–45.32	34.3	43.7		23.01–25.68
Diterpene (%)	50.41–53.00	51.9	56.1		61.36–66.85

6.1. *Intraspecific genetic variation*

As is generally the case for most phenotypic traits of pine trees (Ramírez-Valiente et al., 2022), resin yield not only varied among pine species, but also shows large genetic variation within species (Lai et al., 2020). Indeed, resin yield is a trait under high genetic and heritable control (Strom et al., 2002; Vázquez-González et al., 2021). This intraspecific genetic variation occurs both across (López-Goldar et al., 2019) and within (Vázquez-González et al., 2021) pine populations. Among population variation may be the result of divergent selection processes across heterogeneous environmental conditions within the natural range of a given species (Torre et al., 2019), to correlated responses to natural selection on other functional traits (Vázquez-González et al., 2020) or to neutral processes related to the demographic history of the species (López-Goldar et al., 2019). Little information is available on the relative contribution of these evolutionary forces on the differentiation processes of resin production across populations, but, as resin flow is directly related to the phenotypic expression of plant resistance, natural selection to biotic stresses are assumed to be important (Zas et al., 2005). Within population variation in resin flow is also high, with moderately to high heritability estimates (Lai et al., 2020). Narrow-sense heritability estimates of resin yield or resin flow vary from 0.11 to 0.77 depending on the species and assessment age (Table 3). Taking advantage of this high heritability, mass selection of high-yielder individuals and their establishment in clonal banks for tree selection or seed orchards as mother trees for seed production has been or is currently in progress in USA (Mergen et al., 1955), China (Mei et al., 2021a), Brazil (Assis and Resende, 2011) and Spain (Tadesse et al., 2001). Genetic gains of these genetic improvement initiatives have been not reported yet. However, large genetic gains in terms of improved resin production can be expected from the relatively high heritability estimates.

One important point that needs especial attention in tree breeding initiatives is to discard that the genetic improvement of a given trait does not come at the expense of a deterioration in other important functional or economical traits due to genetic correlations among traits (Santos–del-Blanco et al., 2015; Suárez-Vidal et al., 2021). From a physiological level, resin is a high-carbon resource (Rissanen et al., 2021) that is produced in huge amounts in all pine tissues, including needles, and phloem and xylem in roots and stems (Wu and Hu, 1997). This massive investment in resin implies a huge sink of photoassimilates that may no longer be available for other vital functions such as growth or

Table 3
Heritability estimates of resin flow or resin yield depending on the species and the study. h_i: individual narrow sense heritability. * : range for different estimates in the same genetic test but for different origins. * *: Repeatability value indicating the upper limit of the Hi.

Species	Age	hi	Reference (s)
P. elliottii var. *elliottii*	27	0.11	Lai et al. (2017)
		0.68	Li et al. (2012)
	26	0.19–0.32	Lai et al. (2020) *
	14	0.58–0.66	Salto et al. (2014) *
	15	0.54–0.66	
	4	0.04–0.12	Romanelli and Sebbenn (2004) *
	12	0.0.02–0.33	
	25	0.55	Roberds and Strom (2006) * *
P. merkusii	7	0.15–0.65	Nugrahanto et al. (2022) *
	29–30	0.58	Susilowati et al. (2013)
	13	0.52	Sukarno et al. (2015)
	12	0.52	Leksono and Hardiyanto (1996)
P. massoniana	7	0.17	Zeng et al. (2013)
	9	0.2	
	11	0.13	
	13	0.18	
	15	0.18	
	20	0.17	
	24	0.31	
	26	0.22	
	8	0.47	Liu et al. (2013)
P. pinaster		0.5	Tadesse et al. (2001) * *
	15	0.49	Vázquez-González et al. (2021)
P. taeda	10	0.44–0.59	Roberds et al. (2003) *
	6–7	0.12–0.30	Westbrook et al. (2013) *
	10–20	0.64–0.71	Roberds and Strom (2006) * * *
P. caribaea	27	0.25	Santos et al. (2016)
P. oocarpa	5	0.2	Fabián-Plesníková et al. (2022)

reproduction. Thus, negative relationships between resin production and growth and reproduction should be expected (Vázquez-González et al., 2021). However, resin is produced in resin ducts and the number and size of resin ducts increase with tree growth, so the more the tree grows, the more resin will produces (Hood and Sala, 2015). These explanations point to opposite directions of growth-resin relationships and may explain the lack of consensus of published data. Specifically, genetic correlations between growth and resin production range from no significant (Tadesse et al., 2001; Vázquez-González et al., 2021) to positive correlations (Lai et al., 2017; Liu et al., 2013; Zeng et al., 2013). Altogether, improving resin yield without affecting growth rate and timber quality traits seems feasible. However, the relation between growth and resin production is far from being clear. In *P. pinaster*, for example, despite the lack of additive genetic correlations, growth and resin production appear to be positively related at the phenotypic level (see also *Dendrometry and phenotypic traits* section), while they are negatively correlated at the population level (i.e. fast growing populations tend to produce less resin and vice versa) (Vázquez-González et al., 2021; Zas et al., 2020). This negative correlation at the population level has been explained in terms of evolutionary constraints associated to the large costs of resin production (Vázquez-González et al., 2021). As trait to trait correlations are known to be species-, population- and environmentally-dependent, further research is still needed to depict the complete picture of the relationships between growth and resin production in pine trees.

Intraspecific genetic variation is not restricted to resin yield but also affects other relevant traits involved in resin production, such as some physical properties or its chemical composition. For example, according to McReynolds (1971) heritability estimate for viscosity for the resin of slash pine is high. The chemical composition of *P. pinaster* resin is also known to vary across populations (Arrabal et al., 2005) and within populations (Arrabal et al., 2002) with large differences in some specific terpenes between high-yielders and control trees (Arrabal et al., 2002), a result that was also observed in other pine species (Chen et al., 2006; Lai et al., 2020; Neis et al., 2019a; Zhang et al., 2016). Genetic variation in resin duct metrics is also important and has been reported in several pine species such *P. pinaster* (Vázquez-González et al., 2019), *P. radiata* (Govina et al., 2021) or *P. taeda* (Westbrook et al., 2015).

More recently, an important research effort is in course to depict the molecular basis of resin production (both quantitatively and qualitatively), with notable progress in the identification of the genes involved in resinosis (Y. Li et al., 2022; Z. Li et al., 2022; Yi et al., 2022) as well as in the physical and chemical properties of the resin (Bai, 2022; de Lima et al., 2016; Junkes et al., 2019a; Liu et al., 2020). This progress has allowed to describe molecular markers and fine tune genomics tools to identify and select high resin yielders. Selection through molecular studies at the transcriptomic level is possible and may facilitate and accelerate the otherwise complex and slow breeding cycles. The selection of genes involved in resin quality is aimed at obtaining a resin whose chemical composition is better suited to the needs of the industry rather than to improve the final quantity obtained (Ding et al., 2023). In addition to molecular studies, Shi et al. (2021) also used proteomic analysis to reveal the regulatory pathways and protein targets associated with resin biosynthesis.

Taking all these results together, genetic selection and breeding for improved resin yield emerges as one of the key tools to improve the profitability of resin tapping exploitations. In forestry, these techniques have been successfully practised for decades to improve productivity and timber quality achieving significant genetic gains (Jansson et al., 2017). Given that intraspecific genetic variation in resin-related traits is generally very large and that heritability of resin yield is higher than that of growth traits, even larger genetic gains should be expected for resin yield genetic improvement. However, up to date there are only partial studies on the genetics of resin yield and very few and inconclusive breeding initiatives that have deployed improved material to be use in reforestation. Nonetheless, advances in molecular biology tools and progress on the identification of the genes involved in resin production and their expression (Liu et al., 2015; Mei et al., 2021b; Shi et al., 2021; Westbrook et al., 2015, 2013) will facilitate the implementation of effective breeding programs for rapid improving resin production of future plantations (Liu et al., 2019, 2020).

6.2. Climatic, physiographic and edaphic

Other factors that may affect the resin production of the pine trees are those related with the environment and, particularly with the climate, physiography and edaphic conditions of the site where the trees are established (Blanche et al., 1992). In other words, resin yield and resin components are known to be highly plastic traits to environmental variations (Sampedro et al., 2010). According to the literature, many different climatic parameters have been shown to modulate resin production (Table 4). Among them, the climatic variables that most affect resin flow and have the highest correlation values with resin production, are temperature and those related to soil water storage (Blanche et al., 1992; Lombardero et al., 2000; Lorio and Hodges, 1968; Zas et al., 2020). In most of the studies showed in Table 4, temperature affects positively resin yield while the effect of soil water storage departs from being linear, with resin yield increasing under moderate water deficit but decaying when water stress becomes more severe (Rodríguez-García et al., 2015).

In addition to these two main variables, the effects of other factors such as precipitation, potential evapotranspiration, relative humidity, accumulated water deficit and daily solar radiation were also shown to modulate resin yield in some extent (Table 4). The effect of precipitation varied across studies from negative (Neis et al., 2018) to positive correlations (Gajšek et al., 2018). Similarly in the case of relative humidity, the results of the relationship with resin yield were contradictory, with positive (Rodríguez-García et al., 2016) and negative (Sharma et al., 2018a) results, while PET tend to affect positively resin production (Rodríguez-García et al., 2015; Sharma et al., 2018a). Relationships between resin flow and the cumulative water deficit and the daily solar radiation were either negative (Gajšek et al., 2018; Rodríguez-García et al., 2015) or positive (Rodríguez-García et al., 2015; Sharma et al., 2018a; Zas et al., 2020b) results, although only the positive ones were statistically significant. Besides the variables showed in Table 4, Rodríguez-García et al. (2015) had positive relations with the mean water deficit (0.47) and the actual evapotranspiration (0.11). Due to the modulation of precipitation and temperature, resin production has a very strong seasonal component, especially in temperate and mediterranean climates. In these areas, resin tapping is typically carried out in the warmer months of the year, when temperatures are higher and water deficit is moderate (Hood and Sala, 2015; Kim et al., 2005; Kolb et al., 2019; Rodrigues-Corrêa and Fett-Neto, 2009; Tisdale and Nebeker, 1992; Touza et al., 2021; Yi et al., 2021). In non-Mediterranean and non-temperate areas, according to Rodrigues-Honda et al. (2023), water availability seems to be one of the most important factor affecting pine resin yield, as the lower the rainfall, the lower the resin yield.

Although comparatively much less studied, another group of factors that can intervene in resin yield are the physiographic factors such as altitude and slope. For altitude the results are contradictory, with positive (Lukmandaru et al., 2021) and negative (Sukarno et al., 2015) correlations between resin yield and this factor. Steeper slopes have been also shown to favored higher resin yields (Egloff et al., 2019; Luan et al., 2022).

Soil quality and nutrient availability are also expected to affect resin production as resin is highly costly to produce (Hood and Sala, 2015) and requires large amounts of resources that may ultimately depend on the availability of soil water and nutrient. The presence of clay together with intermittent flooding seems to influence the availability of water in the ground to the tree, thus stimulating resin production (Rodrigues-Honda et al., 2023). However, there seems to be no consensus within the literature about the relationship between soil resources and resin

Table 4

Correlations and simple linear regression r^2 between resin production and climatic variables. Statistically significant correlations ($p < 0.05$) are highlighted in bold. n: sample size; T: mean temperature; MaxT: maximum average temperature; MinT: minimun average temperature; P: average precipitation; PET: potential evapotranspiration; RH: relative humidity; AWD: acummulative water deficit; DSR: daily solar radiation.

Species (n)	Country	T	MaxT	MinT	P	PET	RH	AWD	DSR	Reference (s)
Correlations (r)										
P. nigra (58)	Slovenia	**-0.59**	**-0.51**	**-0.66**	**0.42**				-0.36	Gajšek et al. (2018)
P. sylvestris (39)	Slovenia	-0.2	-0.21	-0.28	-0.13				-0.09	Gajšek et al. (2018)
P. ponderosa (60)	USA	**0.83**								Gaylord et al. (2007)
P. merkusii	Indonesia									Lukmandaru et al. (2021)
P. elliottii var. *elliottii* (398)	Brazil	**0.95/0.78**			-041/-0.90					Neis et al. (2018)
P. pinaster (561)	Spain	**0.49**			0.09	**0.68**		-0.32	**0.64**	Rodríguez-García et al. (2015)
P. pinaster (577)	Spain	**0.93**					**0.67**			Rodríguez-García et al. (2016)
P. pinaster(21)	Spain	**0.62**						**0.57**		Zas et al. (2020b)
P. roxburghii	India		**0.63**	0.07	-0.05	**0.46**	**-0.52**		0.19	Sharma et al. (2018a)
Simple Linear Regression (r^2)										
P. taeda (30)	USA	0.66								Ruel et al. (1998)
P. elliottii (1620)	Brazil	**0.76**								Neis et al. (2018)
P. ponderosa (60)	USA	**0.88**								Gaylord et al. (2007)

production. Some authors claim that better soils increase resin production (Garcia-Forner et al., 2021; Knebel et al., 2008; Novick et al., 2012; Wei et al., 2014) but others found the opposite (Kytö et al., 1998; Lombardero et al., 2000; Rodrigues-Honda et al., 2023; Ruel et al., 1998; Warren et al., 1999). Most authors reporting that impoverished soils increase pine resin explain their findings in terms of growth defence balance (Loomis, 1932; Lorio, 1986) and carbon-nutrient balance (Bryant et al., 1983) hypotheses, which state that resources tend to be shifted from growth to secondary metabolite production when resource availability decreases. However, trees located in rich soils with abundant nutrients or high water availability may have, in absolute terms, more resources to invest in defence (Knebel et al., 2008; Lombardero et al., 2000; Lorio and Sommers, 1986).

In summary, the number of studies and the results obtained clearly indicate that certain climatic variables are responsible for, and therefore explain, at least part of the environmental variation in resin production. Edaphic or physiographic variables were, however, studied to a lesser extent and the obtained results are mostly inconclusive.

6.3. *Dendrometry traits*

As seen before, resin yield is a plastic trait highly influenced by climatic, physiographic and edaphic factors. Besides this plasticity to macroenvironmental differences, large variation in resin production is commonly reported within single pine stands, under relatively homogeneous environmental conditions (Vázquez-González et al., 2021). This variation is likely due to plasticity to microenvironmental variation, developmental plasticity and to genotypic variation within sites, and it can be modeled in terms of the variation in phenotypic traits of individual trees within stands. Several phenotypic tree characteristics (related to growth, size or morphology of the whole tree or of particular organs such stems or leaves), have been shown to be correlated with the resin yield of individual trees (Li et al., 2022). In particular, different dendrometric measurements typically used in forest management to control tree growth have been shown to be strong determinants of resin production (Hadiyane et al., 2015; Rodrigues et al., 2008; Rodrigues-Honda et al., 2023; Rodríguez-García et al., 2014). The main dendrometric traits related to resin yield are diameter at breast height (dbh) and total height (ht), but some works also reported significant relationships between resin production and other traits such as crown

Table 5

Correlations between resin production and dasometric variables at the individual tree level. Statistically significant correlations ($p < 0.05$) are highlighted in bold. n: sample size; dbh: diameter at breast height; ht: total height; CR: crown ratio; CI: competition index; BA: basal area; V: volume; Bark: bark thickness.

					Correlations (r)					
Species (n)	Country	Case study	dbh	ht	CR	CI	BA	V	Bark	Reference (s)
P. taeda (45)	USA	Early summer	0.07	0.14	-0.03		-0.15			Lombardero et al. (2000)
P. taeda (45)	USA	Late summer	**0.65**	0.11	**0.48**		**-0.61**			Lombardero et al. (2000)
P. pinaster (26)	Spain			**0.46**						Rodríguez-García et al. (2014)
P. pinaster (44)	Portugal		**0.57**							Garcia-Forner et al. (2021)
P. pinaster (504)	Spain	June	**0.14**	**0.18***						Zas et al. (2020b)
		July	**0.13**	**0.10**						
		September	**0.18**	**0.17**						
P. pinaster (1584–1636)	Spain	Carbonero	**0.16**	**0.12**						Vázquez-González et al. (2021)
(893–896)	Spain	Saviñao	-0.06	**-0.10**						Vázquez-González et al. (2021)
P. caribaea (96)	Brazil		**0.41**	**0.23**				**0.36**		Santos et al. (2016)
P. oocarpa (251)	Mexico		**0.14**		**0.16**	**-0.78** (n = 15)				Egloff (2019)
P. nigra (58)	Slovenia		**0.46**							Gajšek et al. (2018)
P. sylvestris (39)	Slovenia		0.09							Gajšek et al. (2018)
P. roxburghii	India		**0.48**	**0.48**					**0.41**	Sood et al. (2019)
P. merkusii (10)	Indonesia		0.16	-0.03						Abdillah et al. (2020)

ratio (CR), competition index (CI) or basal area increment (BAI)(Table 5 and Table 6).

The most studied relationship is between resin yield and the diameter at breast height, for which most of the results are significantly positive (Table 5). Other factors such as total height, crown ratio, competition index, basal area, basal area increment, volume, bark and phloem thickness, radial growth, needle length and thickness, mean leaf angle and LAI have been also studied but the number of available studies is much lower. The effect of total height and crown ratio was mostly positive and significant (Rodríguez-García et al., 2014; Sood et al., 2019). The positive relationships between diameter, height and crown ratio with resin production denotes a size effect where bigger trees tend to produce more resin. This may be explained in terms of an increasing capacity to produce and accumulate more resin in larger trees due to a greater net of resin canals. Competition index and basal area were always negatively related with resin flow (Table 5). This is not surprising given the large amounts of resources needed for resin production (Egloff et al., 2019; Lombardero et al., 2000; McDowell et al., 2007).

Besides to the information presented in the Table 5 and Table 6, Lombardero et al. (2000) also explored the correlations between the inducible resin flow after mechanical wounding and different dendrometric variables in *P. taeda*. While inducible resin flow in early summer was not related to any tree trait, inducible resin flow in late summer (when conditions for tree growth were less favourable) was positively related to radial growth ($r = 0.62–0.63$) and phloem thickness ($r = 0.40$). The relationships between resin production and several other morphologic traits not included in Table 5 have been explored in a few studies. For example, Sood et al. (2019) estimated in Indian *P. roxburghii* trees the correlations between resin yield and number of branches ($r = 0.14$), needle length ($r = 0.33$), needle thickness ($r = 0.27$), leaf area index (LAI) ($r = 0.31$) and mean leaf angle ($r = 0.35$). The positive relationships with needle size and LAI have been explained in terms of increased resin flow with greater tree vigor, rather than a direct effect of the canopy characteristics on resin production. However, McDowell et al. (2007) exploring the relation between the resin yield and LAI in *P. ponderosa* found no significant relationships. Some authors have also explored whether the relationships between dasometric traits and resin flow may depart from being linear, but the results gave no support for this idea (Sood et al., 2019).

In addition to univariate approaches described up to here, other studies have tried to predict resin upon multiple linear regression models that use climatic and dasometric variables together in different combinations. These studies are summarized in Table 7. The climatic variables used in these models are temperature, precipitation (Wang et al., 2006) while those related to dendrometry were, mainly, tree diameter. Wang et al. (2006), modelling resin production in *P. kesiya* species, obtained a high predictive value ($r^2 = 0.91$) with temperature, precipitation and dbh appearing the equation with positive coefficients, meaning that they positively affect resin production. In another study with *P. oocarpa*, Reyes-Ramos et al. (2019) modeled.

Table 7
Values of r^2 of other regression models between resin production and dasometric variables.

Multiple Regressions (r^2)				
Species	Country	Variable	,2	Reference (s)
P. kesiya	China	Temperature, precipitation, dbh	0.91	Wang et al. (2006)
P. oocarpa	Mexico	Climatic unit, number of tapping faces open in the tree, unbranched stem height	0.68	Reyes-Ramos et al. (2019)
P. pinaster	Spain	Age, Slenderness	0.45	Zas et al. (2020)
P. caribaea	Brazil	dbh, total height, C	0.75	Brito et al. (1982)

resin production using climate unit, the number of tapping faces open in the tree, and the unbranched stem height. The coefficient of determination was, in this case, $r^2 = 0.68$. Zas et al. (2020) predicted resin flow in.

P. pinaster using tree age and tree slenderness as the independent variables, and explained the obtained.

model in terms of the positive relationship between tree age and abundance of resin canals and the effect of tree competition on tree slenderness. Finally, Brito et al. (1982) utilised the diameter, the total height and the average of the lengths of the exudation lines of the north and south faces for predict resin yield in *P. caribaea*.

Given the general positive relationships between the dendrometric measuremnts and resin production summarized here, simple and classical dendrometric traits may be valid tools or at least help for estimating resin production of individual trees of forest stands.

6.4. *Anatomical traits*

From an anatomical perspective, the phenotypic elements that intervene most in resin yield were the resin ducts (Lin et al., 2002; Neis et al., 2019a; Rigling et al., 2003). These tube-like structures that are distributed in axial and radial directions, in different tissues (cortex and xylem) and organs (stems, roots, needles, cones) (Krekling et al., 2000; Wu and Hu, 1997), accumulate under pressure the resin synthesized in the epithelial cells that conform the canals (Krokene and Nagy, 2012). Higher inner volume of the resin canal network is thus assumed to be directly related with the potential to produce resin. In addition, the differentiation of resin canals may be induced in response to damage of the cambium by frosty, mechanical, chemical, or pathogenic origin (Cabrita, 2021). The so called traumatic resin ducts (Eyles et al., 2010; Krokene and Nagy, 2012) enhance the defensive status of pine trees preventing the progression of the damage. As resin tapping implies large traumatisms in the trunks, new traumatic resin ducts are assumed to be differentiated in response to tapping with these new canals likely contributing to increase resin yield, at least in the following tapping campaigns (Touza et al., 2021). Different characteristics of the resin duct network have been associated with resin flow or resin yield (Esteban et al., 2012; Lai et al., 2017). The results of this association are shown in Table 8.

The results shown in Table 8 show mostly positive significant

Table 6
Values of r^2 of the simple linear regression models between resin production and dasometric variables. Values of statistically significant correlations ($p < 0.05$) are in bold. n: sample size; dbh: diameter at breast height; ht: total height; BA: basal area; BAI: basal area increment; Bark: bark thickness.

Simple Linear Regressions (r^2)							
Species (n)	Country	dbh	ht	BA	BAI	Bark	Reference (s)
P. pinaster (26)	Spain	**0.38**					Rodríguez-García et al. (2014)
P. pinaster (100)	Spain	0.24/0.23					García-Meijome et al. (2019)
P. pinaster (150)	Spain	**0.46**		**0.36**	**0.84**		Martínez-Chamorro et al. (2016)
P. ponderosa	USA						McDowell et al. (2007)
P. halepensis (195)	Greece	**0.31**					Spanos et al. (2010)
P. nigra (58)	Slovenia	0.21					Gajšek et al. (2018)
P. sylvestris (39)	Slovenia	0.01					Gajšek et al. (2018)
P. roxburghii	India	0.22	**0.48**			0.16	Sood et al. (2019)

Table 8
Correlations and simple linear regressions between resin production and resin ducts (RD) and traumatic ducts (TD) characteristics. Significant correlations are highlighted in bold. r: value of correlations.

			Correlations (r)		
Species	Country	Case study	Variable	r	Reference (s)
P. taeda	USA	Early summer	RD density (*RD/cm*^{2})	0.03	Lombardero et al. (2000)
		Early summer	Number RD (*RD/year*)	0.25	
		Late summer	RD density (*RD/cm*^{2})	**-0.41**	
		Late summer	Number RD (*RD/year*)	0.31	
P. pinaster	Portugal	PCO	Average RD size (*mm*^{2})	**0.51**	Garcia-Forner et al. (2021)
		PCO	RD production (RD)	**0.58**	
		PCO	RD area (*mm*^{2})	**0.70**	
		PCO	RD density (*RD/mm*^{2})	-0.21	
		PCO	Relative RD area (%)	0.19	
		VPA	Average RD size (*mm*^{2})	0.03	
		VPA	RD production (RD)	**0.62**	
		VPA	RD area (*mm*^{2})	**0.56**	
		VPA	RD density (*RD/mm*^{2})	0.31	
		VPA	Relative RD area (%)	0.31	
	Spain		RD volume (*mum*^{3}/*mm*^{3})	**0.51**	Rodríguez-García et al. (2014)
P. elliottii var. *elliottii*	Brazil		RD diameter (*mum*)	**0.64**	Neis et al. (2019a)
Axial RD frequency (*RD/mm* RD volume (*mm*^{3})				^{2}) **0.53**	
				0.49	
RD area (*mm*^{2})				**0.39**	
Simple Linear Regression (r^2)					
P. pinaster	Spain		RD frequency (*RD/mm*^{2})	**0.23**	Rodríguez-García et al. (2014)
P. oocarpa	Mexico	Progenies	TD area (*mm*^{2})	**0.53**	Fabián-Plesníková et al. (2022)
		Mother trees	TD diameter (*mm*)	**0.50**	
		Progenies	TD area (*mm*^{2})	**0.69**	
		Mother trees	TD diameter (*mm*)	**0.63**	

correlations, although in some few study cases the relations are not significant or even significantly negative. The highest positive correlation values have been obtained for the size measurements (ducts area or mean duct diameter), but resin duct density was also positively related with resin production in some cases (Neis et al., 2019a; Rodríguez-García et al., 2014). Taking all together, although there is evidences supporting the general idea that the greater the number and size of resin ducts, the more resin, the relationships were, in general, less strong than expected. Other physical factors related to the resin ducts that can also affect the resin flow are the viscosity (Hodges et al., 1981) and the pressure (Rissanen et al., 2016) at which the resin is subjected when it circulates through the resin duct network. Resin viscosity has been shown to be variable depending on the season (McReynolds, 1971) and the resin chemical components (Cabrita, 2021). Resin pressure is a factor that varies daily and seasonality because it is directly related to temperature and water turgor in tissues surrounding the resin ducts (Rissanen et al., 2021, 2019, 2016).

6.5. *Fires and pests*

Resin ducts, which support the production of resin and, thus, together with the bark, tree first defences against external factors (Franceschi et al., 2005; Valor et al., 2021), are highly responsive to externalities, including fire (Hood et al., 2015; Lombardero et al., 2006; Vázquez-González et al., 2020), pests (Kolb et al., 2019; Lombardero et al., 2006; Santoro et al., 2001) and pathogens (Luchi et al., 2005; Nagy et al., 2006). These topics have been widely studied within the plant defence field, but not that much in relation to resin production and resin tapping. For example, important research efforts have been paid to understand the role of resin canals and their inducibility upon damage or fire in the resistance to bark beetle attacks in the USA (Lombardero et al., 2006; Santoro et al., 2001; Wallin et al., 2003). According to some authors, low-intensity fires have been shown to increase resin flow by inducing the differentiation of resin ducts (Cannac et al., 2009; Hood et al., 2015; Prasetya et al., 2017; Roberds and Strom, 2006; Vázquez-González et al., 2020) and reducing resin viscosity (Davis et al., 2011), but others have shown that the effects of fire are not reflected in resin yield (Perrakis and Agee, 2006; Rodríguez-García et al., 2018). Resin production also increases after mechanical wounding (Hood and Sala, 2015; Knebel et al., 2008; Li et al., 2022; Ruel et al., 1998), pathogen infection (Knebel et al., 2008; Luchi et al., 2005; Phillips and Croteau, 1999), or pest attack (Franceschi et al., 2005; Kane and Kolb, 2010; Phillips and Croteau, 1999), with this increase being part of the immunological induced response to these attacks.

6.6. *Extraction method*

A number of factors related to the tapping procedure itself can largely vary the amount of raw material a resin harvester can collect. These factors include the extraction method, the frequency of the grooves and the use of stimulant pastes. Generally, extraction methods consist of making incisions by removing strips of bark and phloem from living pine trees, cutting and causing the formation of new resin canals, thus triggering resin production. According to Cunningham (2009), there are currently four methods of extraction that are widespread in the world, two with the application of chemical stimulants and two without. The methods using chemical stimulation are the "bark streak" or "American" method, widely used in Brazil and Argentina (Candaten et al., 2021; Füller et al., 2016; Rodrigues et al., 2008) and variants used mainly in the Mediterranean area (Spain, Portugal and France) (Serrano et al., 2013; Torrijos et al., 2013), and the "Mazek" or "Rill" method (Sharma et al., 2018b), extended in India and Indonesia. In the "American" method, a horizontal groove of 2–3 cm wide and a length of about one third of the tree perimeter is made every 14 days (Rodríguez-García et al., 2014). In the "Mazek" method, a V-shaped upward groove of 2–3 mm wide is made every 3–7 days (Cunningham, 2012). The methods that do not use chemical stimulation are the "Chinese" method (Wei et al., 2014), used in China, and the "Hughes" or "French" method, developed in the 19th century in France and currently only used in Indonesia and Mexico (Hartiningtias et al., 2020; Reyes-Ramos et al., 2019). The "Chinese" method consists of making a V-shaped downward groove every day by cutting approximately half the circumference of the tree, in the "Hughes" method an 8–10 cm groove is cut every 10–15 days (Cunningham, 2009; Williams et al., 2017).

Other methods less commonly used than the above are the "Bore-hole" (Hodges, 1995; Sharma et al., 2013a; Sukarno et al., 2015) and

"EuroGem" (Picardo, 2013; Rubini et al., 2022) methods, extraction systems that collect the resin in a closed container. In the first method, a hole 15 cm deep and 2.5 cm in diameter is drilled into the trees (Sharma et al., 2018b), in the second method a circular disc of bark and phloem 8 cm in diameter is extracted from the trunk of the trees (Picardo, 2013). In order to improve the ergonomy of the tapping work, innovation attempts to mechanize the debarking and drilling processes and to collect and transport the resin production through the forest are also in progress (Gurau et al., 2021; Rodríguez-García et al., 2016; Serrano et al., 2013; Yovi et al., 2021).

Within each of these methods, resin production can largely vary depending on the size (length and width) and the direction of the incisions (Gómez-García et al., 2017; Jimeno and Crespo, 2013; Rodríguez-Soalleiro et al., 2008; Rodríguez-García et al., 2016; Sharma et al., 2013b). The timing of the interventions is other important variable with major impacts on resin yield. Groove frequency largely varies according to the stimulant paste used and the labour costs in the region (Touza et al., 2021). According to the literature the time between successive grooves in open-container methods, can range from two to fourteen days (Heinze et al., 2021; Pinillos et al., 2009; Martínez-Chamorro et al., 2019b; Yi et al., 2021). It is also important to note the disadvantage of the "Rill" and Chinese methods, as the wound needs to be renewed every few days. In addition, some of available methods are more damaging to the tree than others. This is the case of the "Hugues" and borehole methods, in which strips of wood are removed, making resin extraction incompatible with subsequent timber harvesting.

In remote times, no stimulants were used during the resin tapping process. However, the incorporation of stimulant pastes produced a drastic increase in the production of resin and the profitability of the exploitations. These chemical stimulants applied after the mechanical wounding induce a slow necrosis of living cells, which favours the resin production of the remaining living cells (Wolter et al., 1980), increasing the amount of resin generated and preventing wound healing, thus prolonging the exudation process. Stimulant sprays were first used in Germany, USSR and USA to increase resin production in the 1930′s, but it wasn't until 1964 when R.W. Clements developed a stimulant in the form of a viscous and sticky paste, that the use of stimulant pastes was generalized thus reducing the hazards derived from the use of sprays (Parham, 1976).

The main pastes used today are based on different proportions of sulfuric acid, potassium, salicylic acid, Ethephon, Ethrel, benzoic acid, neftalene acetic acid, paraquat, copper and 2-Chloroethyl phosphonic Acid (CEPA) (Füller et al., 2016; Neis et al., 2018; Rodrigues-Corrêa et al., 2013; Rodrigues-Corrêa and Fett-Neto, 2013, 2012; Silverman et al., 2005; García-Meijome et al., 2019; García-Méijome et al., 2020; Martínez et al., 2013). Among the above compounds, salicylic acid, is a phytohormone involved in signaling the induced response to biotic damage, and Ethephon, Ethrel and CEPA are synthetic precursors of ethylene, which is also a phytohormone involved in the signaling of defensive responses to mechanical and biotic stimuli (Rodrigues-Corrêa and Fett-Neto, 2012). Several studies have compared the different yields of the above-mentioned stimulant compounds (Junkes et al., 2019b; Neis et al., 2018; Liu et al., 2022; Rodrigues et al., 2011, 2008; Rodrigues-Corrêa and Fett-Neto, 2013, 2009). Current trends in the formulation of stimulant pastes are more in line with ecofriendly trends, trying to reduce the proportion of sulfuric acid. This is why it is increasingly common to use pastes with a higher proportion of other components, such as citric acid or methyl jasmonate, the last being another phytohormone involved in the signaling of induced response to biotic damage (López-Villamor et al., 2021; Michavila et al., 2021; Vázquez-González et al., 2022).

7. Conclusion

After this bibliographical review, it can be stated that the subject of resin extraction has experienced a growing trend in publications in the last years, with the three main producing countries (China, Brazil and Indonesia), plus USA and Spain, contributing the most to the scientific production. This increasing interest for resin production is likely linked to the current need to find natural resources capable of substituting petroleum derivatives, and how to optimise their production. Up to date, the different studies carried out have produced results that are not very homogeneous in terms of the variables that intervene in resin production and how they do so. What is clearly deduced from the revised literature is that resin production is extremely variable both genetically and plastically. At the genetic level, variation in resin production and resin composition occurs both across and within species, and across and within populations with resin yield showing moderate to high heritability estimates. The significance of attaining enhanced management over tree productivity and resin composition is growing, driven by the diverse applications it offers. Consequently, initiatives such as transcriptomic-level molecular studies are gaining prominence, as they enable the identification of genes associated with these traits. At the environmental level, resin production varies in response to multiple abiotic and biotic factors.

The environmental variables modulating resin production on which most of the research effort has focused is temperature with positive correlations in the majority of the studies consulted, and water availability, as key factors involved in resin production. The influence of temperature and water availability on resin production explains the seasonal nature of resin tapping activities.

Variation in resin production also occurred within environmentally homogeneous stands. Several phenotypic traits at the individual tree level have been shown to explain this variation. Diameter at breast height is the trait that most frequently correlated (positive) with resin production, although other dasometric traits related to tree size such as tree height and crown radius are also typically positively related. From a mechanistic point of view resin ducts characteristics are the main factors determining resin productivity. Research related to extraction methods and different stimulants has increased in recent years, looking for new extraction methods and pastes with lower sulfuric acid content.

Despite the increasing interest for pine resin production and the relatively abundant scientific literature that has been produced up to date, conclusions on the sources of variation of resin production are far from being definitive. More research effort is still needed at least on 1) exploring in greater depth the correlations between the different variables involved in resin production, 2) new resin tapping methods and pastes should be further investigated, in order to automatize resin extraction and obtain a higher resin quality, 3) new statistical modelling approaches, as machine learning or deep learning, should be tested to see if it is possible to obtain more robust and statistically significant models to predict resin production potential of individual trees and pine stands and 4) implementing all this knowledge in accessible tools for forest managers who are interested in this type of use.

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Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.indcrop.2023.117105.

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5 RESIN YIELD RESPONSE TO DIFFERENT TAPPING METHODS AND STIMULANT PASTES IN PINUS PINASTER AIT.

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ORIGINAL PAPER

Resin yield response to different tapping methods and stimulant pastes in *Pinus pinaster* Ait

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Abstract

Selecting the best resin tapping method and stimulant paste in the resin tapping process is crucial. In timber-oriented rainy Atlantic pine forests of north-west Spain, the interest in resin tapping is raising but information on the best tapping methods and pastes is still lacking. In this study, an appropriate experimental design used on five representative plots of *Pinus pinaster*, allowed us to explore the resin productive differences between two tapping methods (traditional Spanish method and circular groove) and three stimulant treatments (control, Ethephon and ASACIF). The use of a standardized measure of resin yield allowed to adequately compare methods differing in groove length. Results indicated that the standard resin yield was 1.43 times greater with the traditional method than with the circular groove method. The two stimulant pastes drastically increased resin yield (up to sixfold) in all sites and for all tapping methods. The effectiveness of the paste was also influenced by the tapping method, obtaining greater increases in resin yield after the application of stimulant paste in trees with the circular groove method. Resin yield was only slightly related to the dasometric variables and varied among test sites when no pastes were used, but differences among sites disappeared when stimulant pastes were used. Our results contribute to the understanding of the factors involved in resin performance and the technological development of the sector.

Keywords *Pinus pinaster* · Tapping methods · Stimulant paste · Constitutive defences · Inducibility of defences · Standard resin yield

Introduction

In the Pinaceae family, resin is the tree's main defence against biotic challenges (Phillips and Croteau 1999). Resin is constitutively produced in all tree tissues providing a physical and chemical barrier to invaders (Luan et al. 2022). In addition, resin production is highly inducible in response to biotic stimuli, with large increases in production after mechanical injury or attacks by pathogens and insects (Lombardero et al. 2000, 2006; Kim et al. 2010). Pine resin is a viscous and sticky substance formed by a complex mixture of volatile and non-volatile terpenes with a wide variety of potential uses in different industrial sectors (Neis et al. 2019b; Demko and Machava 2022). For centuries, humans have taken advantage of resin properties by harvesting this non-wood forest product from living pine trees (Soliño et al. 2018; Cunningham 2009, 2012). Nowadays, resin is tapped from trees by applying repeated mechanical wounds enhanced by acid-based stimulant pastes and collecting the resin flowing from the wounds in open or closed recipients (Sharma et al. 2018).

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Maritime pine (*Pinus pinaster*) is the resinous species with the greatest presence in southern Europe and northern Africa. It ranges from southern France, through the whole Iberian Peninsula, northern Italy, Corsica and northern Tunisia, Algeria and Morocco (Caudullo et al. 2017). Spain is one of the countries where maritime pine is one of the most representative forest tree species in terms of both timber volume ($153 \cdot 10^6\ m^3$, 14% of total timber volume) and surface area (1.1 Mha, 5.35%) (MITECO 2019).

Maritime pine has been resin-tapped for long in Spain, mainly in Segovia (Sebastián and Uriarte 2003; Pinillos et al. 2009; Rodríguez-García et al. 2014), a province located in the Spanish Meseta Central, which consists of a sandy plateau surrounded by several mountain chains. After a pronounced crisis in the Spanish resin sector in late past century (Pinillos et al. 2009), the increasing demand from the industry for alternative renewable bioproducts has prompted the reactivation of the sector since 2000 (Soliño et al. 2018).

In addition to the resin-tapping activities already existing in the Spanish Meseta Central, new initiatives are currently being taken to promote this activity throughout the country, even in areas where resin production had not been previously tested (Martínez 2016). Specifically, resin yield is seen as an attractive complementary activity in the timber-oriented maritime pine forest of northwest Spain (Gómez-García et al. 2017; Zas et al. 2020a, b; Touza et al. 2021), not only because of the potential contribution to profitability (Martínez et al. 2019) but also because of the multiple and valuable ecosystem services that resin tapping provides (Demko and Machava 2022; Soliño et al. 2018). With vast extensions of maritime pine (> 400,000 ha) (MAGRAMA 2012) and high net primary production (Martins et al. 2009), Atlantic pine forests may have large potential for resin yield. However, maritime pine forests in these areas are markedly different (e.g. higher growth potential, lower temperature oscillation, higher precipitation, lower summer drought) from those of the Meseta Central where knowledge on resin yield has been produced (Benito-Garzón et al. 2011). Whether the technological advances made in traditional areas are transferable to Atlantic areas remains to be adequately tested.

In the Iberian Peninsula, resin has been traditionally extracted following the method presented in Rodríguez-García et al. (2016), which consist in the periodical execution of horizontal striped wounds ("grooves") on the main trunk moving upwards, and the application of a strip of stimulant paste (typically including sulfuric acid) on the upper-inside border of each groove. Although information is still limited, this method implies large traumatisms on the trees and may likely impact wood production and wood quality (Génova et al. 2014; Rodríguez-García et al. 2016). In timber-oriented forests, such as those of the Atlantic regions, there is a need to find out alternative methods to make resin tapping compatible with obtaining quality timber. This is a rare topic in the literature, as normally in the most productive countries, the aim is not to make these two activities compatible, but rather to maximise one or the other. In addition, in traditional tapping, resin is collected in open pots which may be easily filled with water in rainy weathers. Besides the operational complications for separating resin and water, the rain water diminishes the volume capacity of the pots and favors resin leakage. Alternative methodologies that prevent water contamination are thus required in Atlantic regions where annual precipitation may more than triplicate that on Central Spain (Serrano-Notivoli et al. 2018).

One of the alternative and most promising closed-bottling methodologies is the mechanised circular notching extraction method (Pinillos et al. 2009). This method consists of making circular holes by means of a battery-powered screwdriver in the trunk, thus avoiding the debarking process and reducing the operator's workload. A cylindrical plastic device, introduced in the hole, connects to a plastic bag where the resin is stored (Martínez et al. 2021). Another advantage of this method is that it does not allow water to get into the resin containers. Finally, storage in bags makes the harvested resin easier to transport through the pine forest, an advantage that is particularly relevant in pine forests such as the Atlantic ones, which usually have steep slopes. These methods are still under development, and its efficiency has been not formally compared with other methods yet.

Since early times, different chemicals stimulants are used to increases the resin yield (Parham 1976). These stimulants allow to (i) enhance and extend the wounding effects (Neis et al. 2018), (ii) induce the defensive machinery of the tree to stimulate resin yield (Neis et al. 2018, 2019a) and (iii) avoid resin crystallization lengthening the period during which resin flow remains active (de Oliveira Junkes et al. 2019; Michavila et al. 2021). Many of the most widely used stimulants includes corrosive acids such sulfuric acid as the main principle active (da Silva Rodrigues et al. 2011; Michavila et al. 2021). Over time, the form of application of stimulants has changed (formerly sprayed as an aerosol and currently in paste form) (Zamorano and Solís 1974) and the proportions of acids is trying to be reduced, as they are highly corrosive and impose hazards to the field workers. Other types of stimulants with alternative active components (e.g. ethylene, paraquat, auxin, fungal treatments, metal cofactors of terpene synthases) are continuously appearing (Rodrigues-Corrêa and Fett-Neto 2012, 2013). Several studies have explored the effectiveness of different pastes applied in resin tapping (de Oliveira Junkes et al. 2019; Neis et al. 2018; da Silva Rodrigues et al. 2011; Rodrigues and Fett-Neto 2009) but little effort has been paid to explore the suitability of a specific paste depending on the geographical area where it is applied. Whether the effectiveness of the different stimulants is context dependent remains to be tested before generalising their use to a specific biogeographical region.

Currently, in *P. pinaster*, the most commonly used stimulants are based on sulfuric acid (Vázquez-González et al. 2021). Other stimulants based on different phytohormones (e.g. Ethephon, salicylic acid, methyl jasmonate) have been also shown to enhance resin yield in this species (Michavila et al. 2021; Vázquez-González et al. 2022) but formal comparisons of the effectiveness increasing resin yield of different stimulants under different environmental conditions are still lacking. In addition, the effectiveness of the chemical stimulants may largely differ depending on whether the extraction procedure uses closed or open recipients to collect the resin, something that has remain elusive in previous investigations.

After the resurgence of the interest for resin tapping in the Spanish *P. pinaster* forests in recent years, it is highly desirable to move towards the technicalisation and professionalisation of the sector. In particular, optimizing the tapping methodology (extraction procedure and stimulant pastes) emerges as one the main topics that remain to be fine-tuned according to the environmental and silvicultural particularities of the tapped stands. The objectives of this work carried out in maritime pine forests across an environmental gradient from Atlantic areas to the Mediterranean Meseta Central of the Iberian Peninsula were (1) to compare the effectiveness in terms of resin yield of the Spanish traditional method for resin tapping and the emergent circular groove methodology, (2) to compare the effectiveness of the two most promising stimulate pastes (Ethephon and ASACIF), (3) test how dendrometry affects resin yield as a function of tapping method and stimulant paste and (4) to study the efficiency during the tapping season of the two methods and the two stimulant pastes.

Material and methods

Study area and data acquisition

Therefore, the present study was carried out in five stands of maritime pine (*P. pinaster*) located in Galicia, Asturias and Castilla y León: Culleredo, Pantón, Godos, Barcia and Coca (Fig. 1). The test sites were representative stands of two of the most potential resin-producing areas of Spain: the Northwest and the Meseta Central. The area of study followed a marked climatic gradient from the humid and thermal Atlantic climates of the northwest coastal areas to the drier and more continental areas of Central Spain (Table S1). The five sites (n_{total} = 433 trees) were pure adult regular pine forests between 35 and 40 years, in which resin tapping had not been carried out before. Average normal diameter at breast height in the five stands was greater than 25 cm, the threshold upon which resin extraction is allowed in the area.

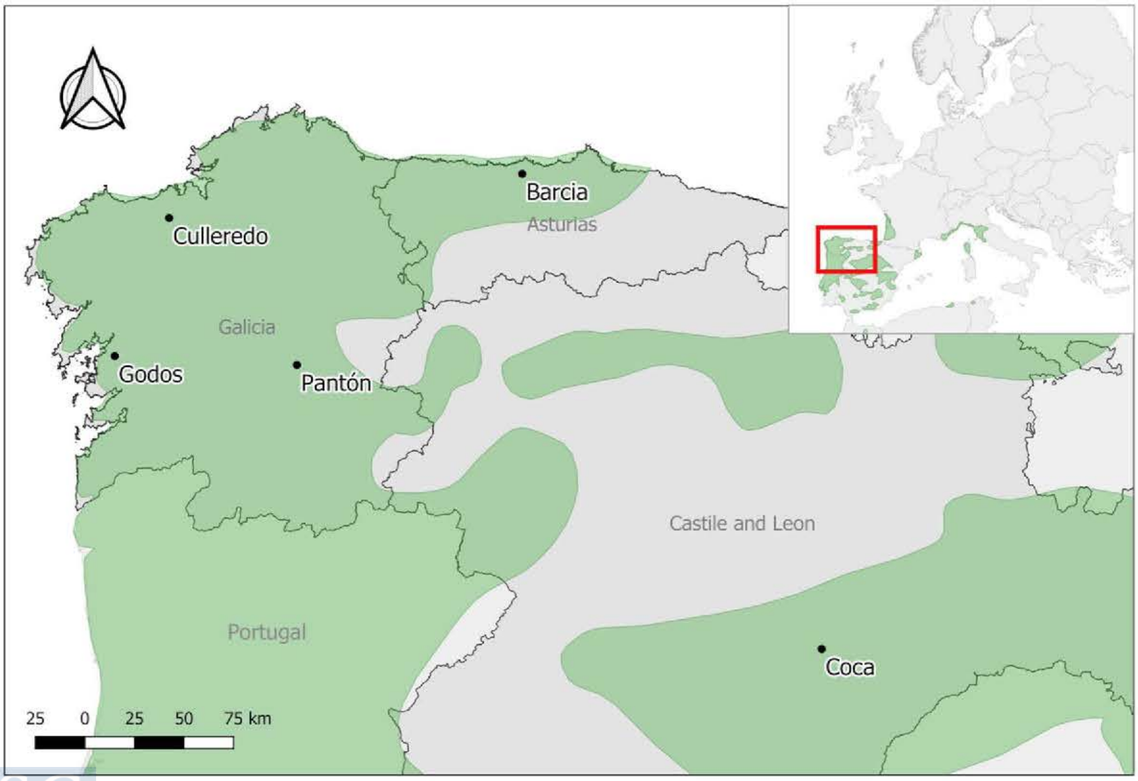

Fig. 1 Study area and spatial distribution sampling plots. Green area is the distribution range zone delimited by Caudullo et al. (2017)

In each of the stands, 90 trees with similar dendrometric characteristics between them were selected and separated into three blocks of 30 trees according to topography and environmental particularities. Within each block, 6 groups of five contiguous trees were made, and treatments allotted randomly to each group. A total of six treatment, corresponding to the combination of three stimulant pastes (Control, Ethephon and ASACIF), and two different extraction methods (traditional and circular) were tested between June and November 2021. Some of the trees sampled were written off because they died during the tapping period.

The first tapping method was the traditional method used in the Iberian Peninsula (Rodríguez-García et al. 2016). In this method, after removing most of the bark from the area to be resin-tapped during the whole campaign, a strip of phloem 2–3 cm wide and, 16 cm long was removed manually every two weeks moving upward. Resin flowing from the practiced wounds was collected in 2L plastic open pots (Fig. 2a). Starting at a height of approximately 20 cm from the ground, a total of 8 groves were made in each tree. The second method was the circular groove (Pinillos et al. 2009), which is a mechanised method in which circular wounds of 5 cm in diameter (15.7 cm in perimeter) were made every 2 weeks with the aid of a battery-powered screwdriver. Successive wounds were spaced 2–3 cm upward or lateral from previous wounds. Specifically-designed plastic devices were introduced within the practiced holes and the resin collected in closed plastic bags (Fig. 2b). The total number of grooves was the same than in the other method. Grooves of the two methods were done simultaneously within each site.

For each of the two extraction methods, different stimulant pastes were applied either in the inner-upper border of the horizontal grooves or in the inner contour of the circular holes. Three different treatments were considered, a control without stimulant paste and two commercial pastes that have shown promising results in previous experiments (Michavila et al. 2021; Gómez-García et al. 2022), the Ethephon (8% Ethephon(60% v/v), 14% sulfuric acid (50% v/v), 55% distilled water, 1.7% polysorbate, 1% cetyl alcohol, 4% vaseline, 5.5% silica, 10.8 sawdust) (Gómez-García et al. 2022) and the salicylic paste ASACIF (1% salicylic acid, 25% sulfuric acid (96% v/v), 5% propylene glycol, 19% wheat straw, 50% distilled water) (Michavila et al. 2021). The production per tree was weighed each time a new groove was made with a scientific scale calibrated in decigrams. Due to inconveniences during the weighing of the intermediate grooves, especially in the Coca site, there were values of these weighings that were not registered at the moment of making the new groove and were added to subsequent weighings. Periodical yields were summed up to obtain the resin yield per tree across the experimental campaign.

Fig. 2 Resin tapping methods used in the study, **a** traditional extraction method and **b** circular groove extraction method. Source: FORESIN and Inés

Before resin tapping, diameter at 1.30 m from the ground (diameter at breast height, dbh), the height to the tree's apex (total height, h_t) and the height to the insertion of the first live branch into the stem (h_{flb}) of all experimental trees were measured. The slenderness and volume of each tree were also calculated. The slenderness was calculated as the relation between the total height and the diameter at breast height. The regional formulas of the IV National Forest Inventory of Spain were used to estimate volumes (MAGRAMA 2012).

Standard resin yield

To ensure reproducibility and homogeneity in comparisons between resin extraction methods (which differ slightly in the length of the practiced strips), resin yield was adjusted according to the length of the strips of each method. The standard resin yield (SRY, i.e. the resin yield per unit of strip length) was estimated as:

$$\mathrm{SRY} = P_t / \sum_{i=1}^{n} L_i \ \left(g\ \mathrm{cm}^{-1}\right)$$

$$L_{\mathrm{traditional}} = 2 \cdot \mathrm{dbh}/2 \cdot \mathrm{arcsen}\left(\frac{p/2}{\mathrm{dbh}/2}\right) = \mathrm{dbh} \cdot \mathrm{arcsen}(p/\mathrm{dbh})$$

$$L_{\mathrm{circular}} = 2 \cdot \pi \cdot \sqrt{\frac{L^2_{\mathrm{taditional}} \cdot p^2}{2}}$$

where P_t is the total resin yield of the tree (g), L_i is the length of each strip as a function of tree diameter (cm), n the number of strips within the season, dbh is the diameter at breast height and p is the theoretical groove length (in the case of circular groove was the diameter).

Statistical analysis

Before choosing the tests to be used to analyse the differences between methods, pastes and sites and the correlations between the SRY and the dasometric and estimated variables, we verified that the assumptions of normality and homogeneity of variance of the parametric versions of the tests were fulfilled in any case. The Shapiro–Wilk test was used for checking normality and the Levene test (normal data) or Fligner Killeen test (non-normal data) for homogeneity of variance.

In order to test for statistical differences in central tendency between the SRY of the two extraction methods a Mann–Whitney U test was performed, this test is a non-parametric version of the 2-sample t-test to compare two independent groups. Comparisons of the SRY accumulated up to the eighth groove between methods and stimulant pastes were made using the Welch one-way ANOVA, which evaluates the differences among three or more independently sampled groups, with a slight deviation from normality and unequal variances. To test for statistically significant differences between the SRY of the different plots, two tests were used, Fisher's one-way ANOVA, when the data had a normal distribution, and Kruskal–Wallis one-way ANOVA, when the data did not have a normal distribution, in all cases the assumption of homoscedasticity was met. The Spearman's correlation test was used to calculate the correlations between the SRY and the dasometric variables and those estimated on the basis of them; this test is a non-parametric statistical measure of the strength of the association between two variables. The non-parametric Friedman rank sum test, which is the alternative to repeated-measures ANOVA when the assumptions are not fulfilled, was employed to determine whether there were statistically significant differences within the periodic SRY of each of the methods and pastes (the Coca plot was not included in this analysis because the first two periodic yields were accumulated in the third).

The post-hoc tests employed were the Games-Howell test for the Welch one-way ANOVA, Student's t-test for the Fisher's one-way ANOVA, Dunn test for the Kruskal–Wallis test and the Durbin-Conover test for the Friedman rank sum test.

The significance level used in all cases was 95%. All statistical analyses were performed with version 4.2.2 of the statistical software R (R Core Team 2022) and the "ggstatsplot" package (Patil 2021) was used to perform the comparisons between and within groups.

Results

Comparation between resin tapping methods

The Mann-Whithney test showed that there were statistically significant differences between the SRY obtained by the traditional and the circular groove methods (Fig. 3). The median of the SRY was 1.43 times higher in the traditional method than in the circular groove method. Furthermore, the observed effect size (Glass rank biserial coefficient) of -0.35 was medium according to Vargha and Delaney (2000).

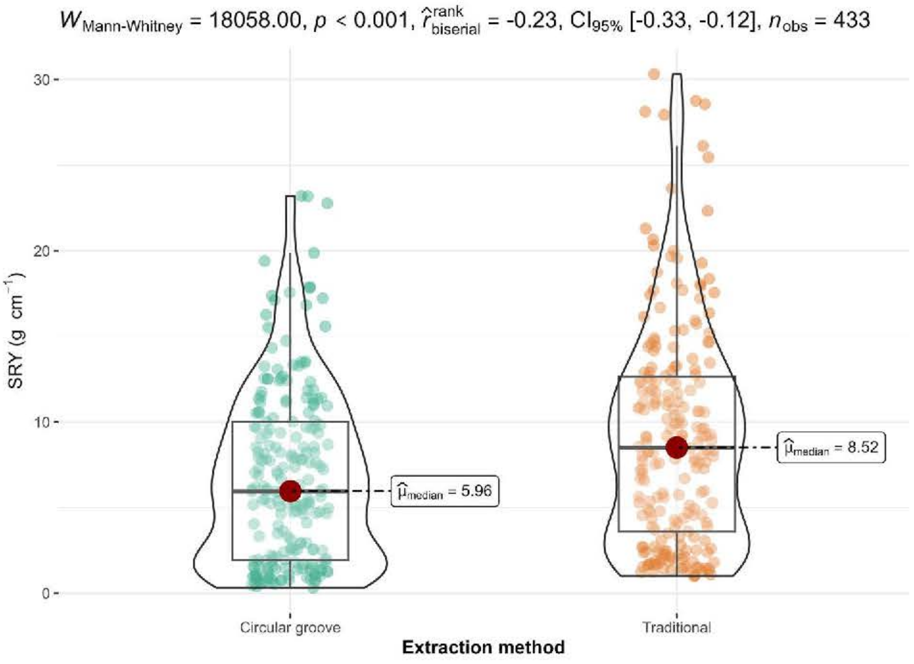

Fig. 3 Results of the non-parametric Mann–Whitney test, carried out on the SRY data to check if there were statistically significant differences between the productions obtained by the two different methods. $W_{\text{Mann–Whitney}}$: Mann–whitney test result; p: p-value; $\hat{r}^{\text{rank}}_{\text{biserial}}$: Glass rank biserial coefficient; $\text{CI}_{95\%}$: confidence intervals of Glass rank biserial coefficient; n_{obs}: number of observations

As there were differences between the median yields of the two methods, the performance of the pastes was analysed for each of the extraction method separately.

Comparation between stimulant pastes

For both tapping methods, the Welch test revealed significant differences between the SRY of the control trees and those with stimulant paste applied (Fig. 4). There was no significant difference between the pastes in both cases. The size effect of the test (rank epsilon squared) was similar in both cases (0.63 and 0.60) and can be qualified as large according to Field (2013).

Comparing the medians showed in Fig. 4b, in the circular groove the Ethephon paste yields 5.98 times more SRY than the control, while SRY with the ASACIF paste was 6.26 times higher. In the traditional method, the efficiency of the Ethephon and ASACIF pastes was relative lower

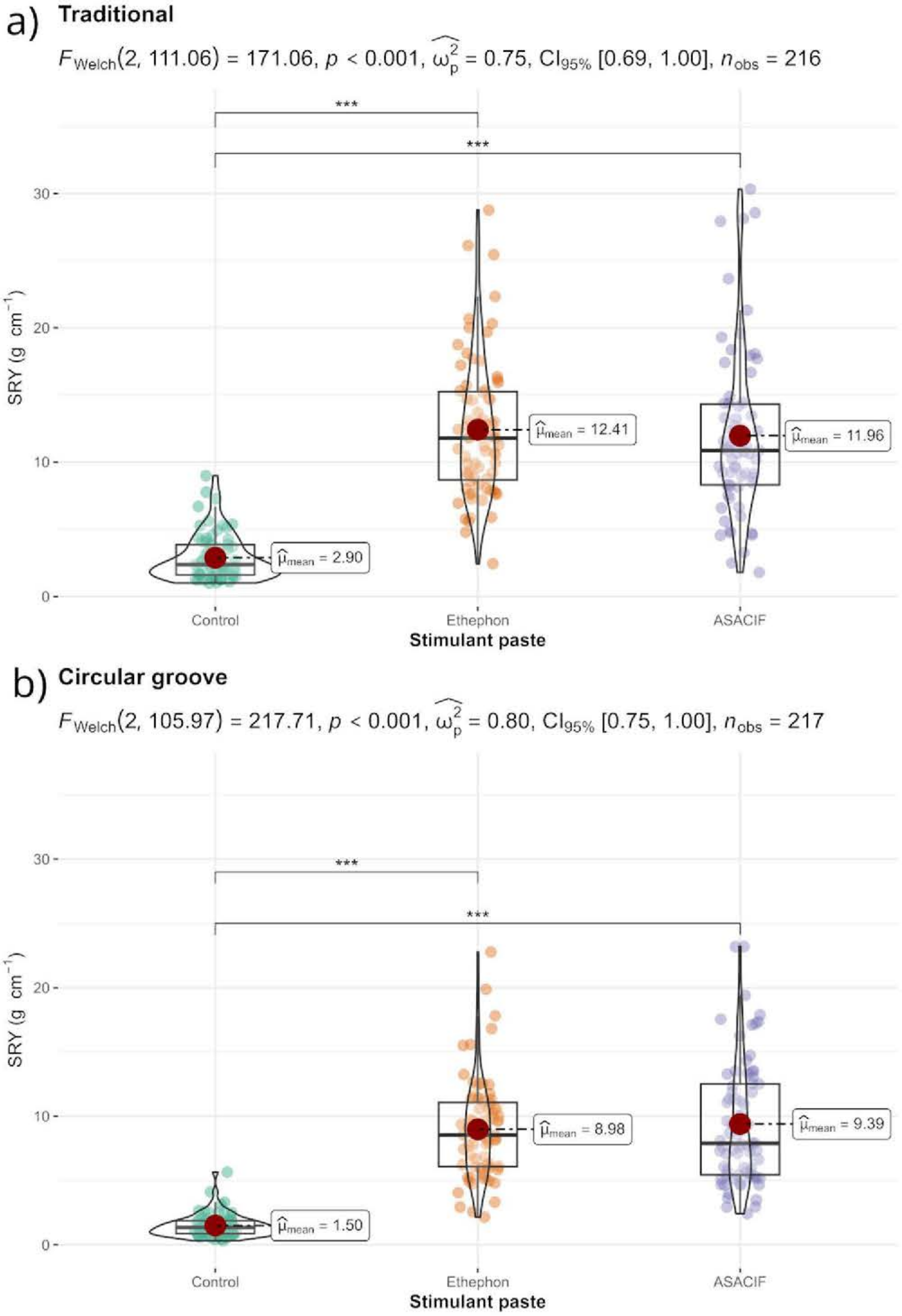

Fig. 4 Results of the Welch non-parametric tests performed on the SRY data of the cumulative production values with the pastes and the control up to the eighth strip for each extraction method, **a** traditional and **b** circular groove. F_{Welch}: Welch test result; p: *p*-value; $\widehat{\omega_p^2}$: rank epsilon squared coefficient; $\text{CI}_{95\%}$: confidence intervals of rank epsilon squared coefficient; n_{obs}: number of observations

(4.27 and 4.12 times higher than the control, respectively) (Fig. 4a).

Effects of tapping methods and pastes on inter-site variation in SRY

Statistically significant differences and large effect sizes in SRY among plots were observed when the traditional method was used (Fig. 5). Resin tended to be higher in the plot located in Coca, especially in control trees tapped without stimulant paste (Fig. 5a). In the case of the circular groove tapping method, no significant differences in SRY was observed between any of the plots irrespective of the stimulant paste (Fig. 5d, f).

Dendrometry effects in SRY depending the tapping methods and pastes

Correlations between the SRY and dendrometric variables were mostly not statistically significant, only between the traditional tapping method and control trees the total height and slenderness had low negative significant correlation values (Table 1).

Trend in SRY during the season

Standardized resin yield after each groove showed significant temporal variation across the tapping season irrespective of the tapping method and the stimulant paste used (Fig. 6). In general, SRY after each groove tended to increase along the tapping campaign, with this relative

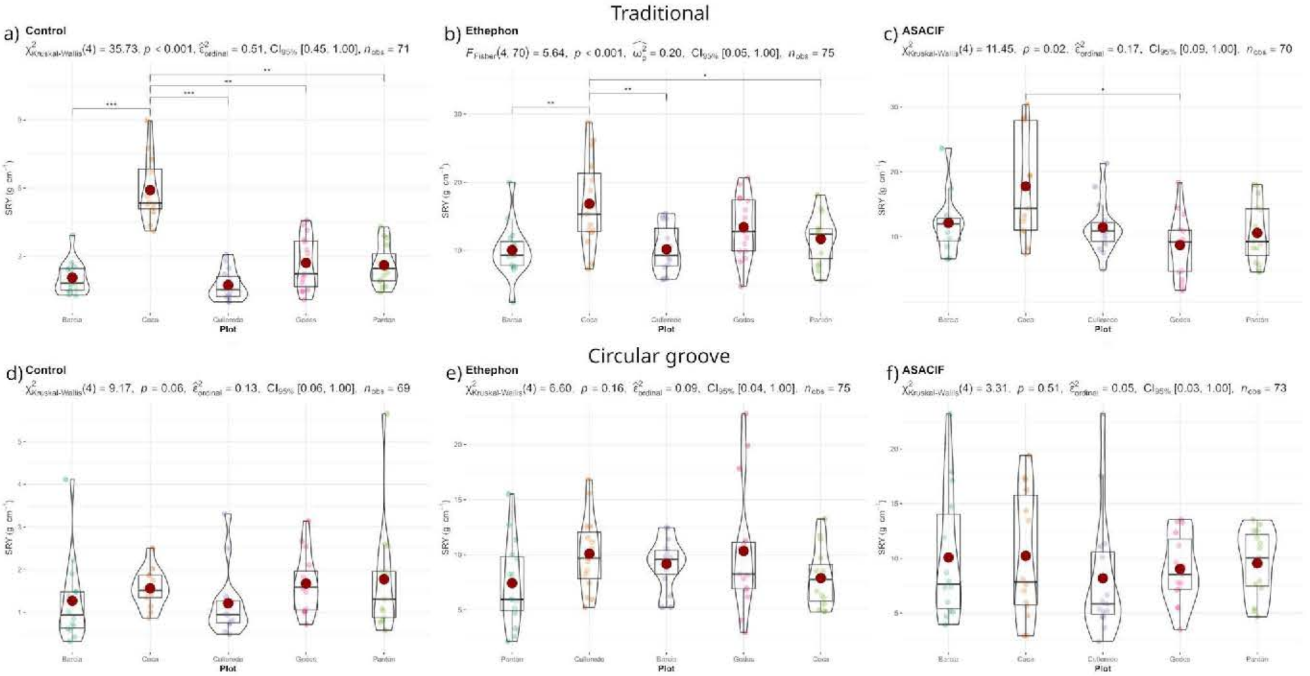

Fig. 5 Results of the Kruskal–Wallis non-parametric tests performed on the standard yield data of the cumulative production values in the study plots. The scale on which the graphs are represented is not the same for control and stimulant pastes. $\chi^2_{Kruskal\text{-}Wallis}$: Kruskal–Wallis test result; F_{Fisher}: Fisher test result; *p*: *p*-value;$\widehat{\omega_p^2}$: rank epsilon squared coefficient;$\hat{\varepsilon}^2_{ordinal}$: epsilon squared coefficient; $CI_{95\%}$: confidence intervals size effect coefficient; n_{obs}: number of observations

Table 1 Spearman correlations values between resin yield and dendrometry variables. dbh: diameter at breast height; ht: total height; h_{flb}: height to the insertion of the first live branch into the stem; V: tree volume; Values in bold have *p*-value < 0.05

Resin tapping method	Paste	*dbh*	h_t	h_{flb}	Slenderness	V
Traditional	Control	0.11	**−0.3**	−0.27	**−0.34**	0.14
	Ethephon	0.07	−0.18	−0.18	−0.2	0.07
	ASACIF	0.19	0.04	0.03	−0.19	0.23
Circular groove	Control	−0.03	−0.08	−0.17	−0.11	−0.04
	Ethephon	0.07	−0.18	−0.08	−0.2	0.07
	ASACIF	0.13	0.14	−0.01	−0.05	0.16

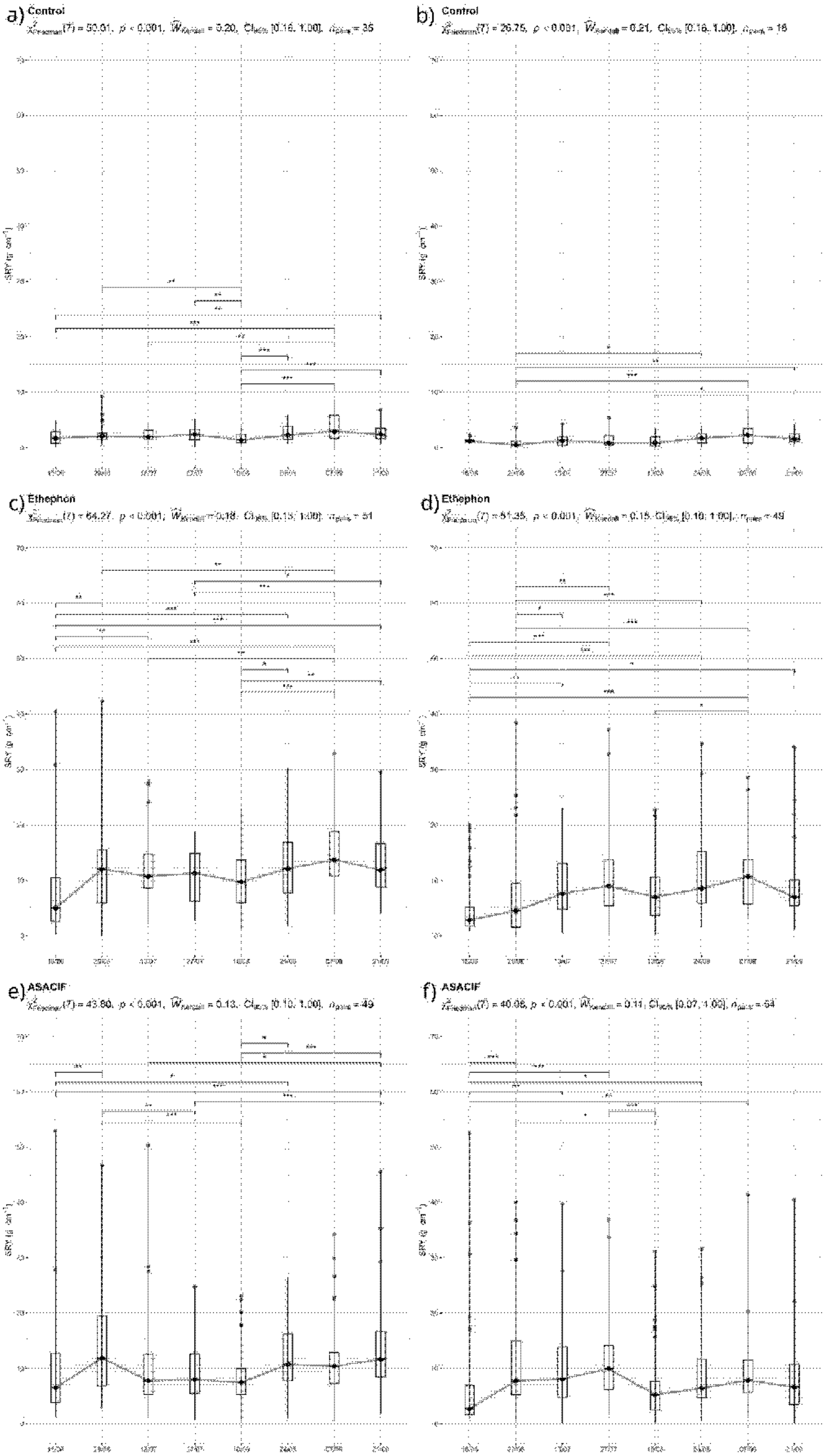

Fig. 6 Results of the non-parametric Friedman test, carried out on the complete trends in standard yields for each of the methods and stimulant paste to check if there were statistically significant differences. **a, c** and **e** traditional tapping method; **b, d** and **f** circular groove tapping method. $\chi^2_{Friedman}$: Friedman test result; p : *p* – value; $\widehat{W}_{Kendall}$: Kendall coefficient, reports the effect size; $CI_{95\%}$: effect size confident interval; n_{pairs} : number of pairs used in th test.

increase varying depending on the tapping method and the stimulant paste used, with the last groove decreasing in most cases. Judging from the effect sizes (Kendall's W coefficient), temporal trends were slightly more pronounced in the control treatment than in trees tapped with stimulant pastes (Fig. 6).

Discussion

Our study obtains clear and sharp results on the influence of tapping methods and stimulant pastes on resin yield of maritime pine trees across an environmental gradient in Spain. An appropriate experimental design and the use of a standardized measurement of resin yield per unit of strip length make the results obtained from different tapping methods, pastes and sites comparable. Understanding how the tree reacts to different stimulants and tapping methodologies is fundamental for optimizing tapping extraction protocols during the tapping season.

Tapping methods

The traditional tapping method produced higher SRY than the circular groove method, regardless of the chemical stimulant applied and the environmental characteristics of the test site (Fig. 3). These results were in line with those obtained by Pinillos et al. (2009), who found, in average, 1 kg per tree more resin using the traditional method than the circular groove method. Higher SRY in the traditional method could be because the number of axial resin ducts cut per unit of strip length was likely higher in the horizontal strips of the traditional method than in the circular strips of the circular groove method, in which axial ducts are exposed to a greater extent in the upper and lower parts of the notch than on the sides. In addition, the bottom part of the circular notch could produce less resin than the upper part of the notch, just as the downward methods produce less than the upward methods (Rodríguez-García et al. 2016).

Differences in the mean SRY between the two tapping methods was greater in control trees (1.93 fold change) than in trees tapped with stimulant (1.38 with Ethephon and 1.27 with ASACIF). This may be because the application of the stimulant paste in a closed environment, such as that of the circular groove method, could favour or sustain during a longer time the effect that the paste has on the tree. Another effect of the circular groove tapping method is that equalizes the standard yields between the different locations and masks the differences in SRY that appears in the traditional method between the Coca plot and some of the other locations, especially when no stimulants were used (Fig. 5).

Pastes performance

Results also clearly demonstrate a huge effect of the two stimulant pastes increasing resin yield, with the effectiveness of the different treatments varying depending on the tapping method used and the plot. These results were in line with other works reporting a positive effect of the application of chemical stimulants on resin yield (Rodrigues et al. 2008; Liu et al. 2022; Neis et al. 2018) and with the expected influenced of the environmental conditions in the resources allocated to defence (Zas et al. 2020b; Vázquez-González et al. 2019).

The extraction method affected the performance of the stimulant pastes, but it can further accentuate the effect of a specific paste. This can be seen by comparing the average yields per paste and method (Fig. 4). The ASACIF paste gives a slightly higher SRY with the circular method than the Ethephon stimulant paste, whereas the opposite is true with the traditional method. This may be due to the fact that the ASACIF paste reacts slightly better to the closed circular device used in the circular notching method.

The improvement in resin yield obtained in our work (ranging from 4.12 to 6.26 times the yield obtained by the control trees depending on the method and the paste) (Fig. 4) was greater than the reported by Neis et al. (2018) and Liu et al. (2022) in *P. elliottii* and *P. elliottii* × *P. caribaea* (2.15 and 2.14 fold change relative to control trees, respectively). This difference may be due to the fact that most of the pines used in this study were timber-oriented and therefore fast-growing. Following the Resource Availability Hypothesis (RAH), fast-growing trees tend to produce less constitutive resin than those with slower growth rates but may produce greater amount of induced defences (Endara and Coley 2011). According to this idea, in the present study, constitutive resin production (i.e. that produced by control trees with no stimulant paste) was 2.2 and 3.4 times higher in the less favourable site of Coca than in the other timber-oriented and fast growing stands. This trend is consistent, for example, with the negative relationship between growth potential and constitutive resin production observed across populations of *P. pinaster* (Zas et al. 2020b). Resources available in the Coca plot are much more limiting for tree growth (poorer soil and greater water deficit) than in the rest of the plots, thus increasing the availability of carbohydrates for defence (Hood and Sala 2015).

When stimulant paste was applied to the timber-oriented trees in the favourable sites, resin yield was much more similar to that of the resin-oriented and resource-limited site of the Meseta Central (Coca). This result can again be explained by the RAH, which predicts that induced defences are favoured under abundance of resources due to lower tissue replacement costs (Endara and Coley 2011). Therefore, as higher resource availability and higher growth rates of the Atlantic timber-oriented plots may have favoured greater responses to the application of stimulant paste, thus reducing the difference between the yields of the plots.

Dendrometry effects in SRY as a function of tapping methods and pastes

The correlations show that the dendrometric variables h_t and tree slenderness have a slight negative correlation with SRY when the traditional method is used on control trees. When one of the stimulating pastes or the circular groove method is used, the values of the correlations become non significant, indicating that the resin production in a tree stimulated or tapping by the circular groove method does not depend to a great extent on the dendrometric variables or the volume.

The significant correlations obtained could indicate that trees with a smaller height and higher *dbh* in relation to their total height produce a higher amount of resin when no chemical stimulant is used in the traditional method. These results are in agreement with those obtained by Zas et al. (2020a), they reported that tree size does not contribute significantly to explain resin yield and slenderness has a negative effect on resin production. The negative effect of slenderness can be explained as a function of stand density, according to previous studies, at lower densities, resources for growth and defence are greater, increasing resin production (McDowell et al. 2007; Rodríguez-García et al. 2014, 2015; Hood and Sala 2015; Miina et al. 2020).

Seasonal trend in SRY

The temporal trends of the SRY after each groove through the season varied depending on the tapping methods and the stimulant paste used. For the control and Ethephon pastes, regardless of the method utilised, the trends peaked in late summer, around 100 days after the start of wounding. These results were similar to the results obtained in other studies (Zas et al. 2020a; Touza et al. 2021), but deviations from this general pattern have also been reported (Rodríguez-García et al. 2016). The decrease of the SRY observed in the fifth groove coincides with the maximum average temperature (Fig. S1) and the minimum values in the accumulated precipitation during the period between grooves (Fig. S2). These two phenomena have likely increased the water deficit, which could be the reason for the decrease of resin production as previous studies have shown that extreme water deficits can reduce resin yield (Lombardero et al. 2000; Turtola et al. 2003; Rodríguez-García et al. 2015; Neis et al. 2018; Hood and Sala 2015). The ASACIF positive trend at the end of the season was uncommon when compared to other papers (Rodríguez-García et al. 2016; Touza et al. 2021; Zas et al. 2020a), as resin production normally decreases in autumn when temperatures start to decrease, due to the seasonal component of the resin (Hood and Sala 2015; Neis et al. 2018; Rodrigues-Corrêa and Fett-Neto 2013).

Conclusions

Pine resin is one of the main non-wood forest products that can be carried out alongside timber production and that is gaining relevance in Spain today's social context. In order to fine-tune resin taping exploitations, it is crucial to know the responses of pine trees to different extraction methods and stimulant pastes. In this study, we found that the extraction method was one important factor influencing the quantity of resin yield, with the traditional method being more productive than the circular groove. It is important to note that the use of a standardized measure of resin yield adjusted to the length of the inflicted groove allowed to adequately compare the different tapping methods. The application of stimulant pastes was another factor that drastically increased to resin production in all sites and tapping methods. However, no significant differences were observed in the efficacy increasing resin yield of the two tested pastes (ASACIF and Ethephon). Another main result of our study was the positive effect of the closed extraction device utilised in the circular groove method, increasing the effect of the pastes on the trees. Furthermore, there was no clear evidence that the dasometric variables alone were able to explain resin production. Finally, important differences in resin yield were observed between sites when no stimulants were used but these differences tend to disappear when trees were tapped with stimulant pastes. Consistent with theoretical predictions on plant defence investment, constitutive resin yield was maximized in the harder environment of Central Spain while response to stimulants seem to be greater in the milder Atlantic sites. This study represents a further step in the standardisation, understanding and comparison of factors influencing resin yield in pine forests in Northwest and Central Spain. Future research should focus on evaluating the effect generated by the combination of the pastes with the rest of the factors that intervene in the resin yield (climatic, edaphic, genetic factors or a combination of all of them) and continue developing final production models with new methodologies.

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contributed to Formal analysis and investigation; O.L.A contributed to Writing—original draft; M.M.P., R.Z., E.M., contributed to Writing—review and editing; M.M.P. contributed to Funding acquisition; M.M.P. contributed to Resources; M.M.P. contributed to Supervision.

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Data Availability The datasets generated during and/or analysed during the current study are available from the corresponding author on reasonable request.

Code availability Not applicable.

Declarations

Competing interests The authors declare no competing interests.

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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6 BASE-AGE INVARIANT MODELS FOR PREDICTING INDIVIDUAL TREE ACCUMULATED ANNUAL RESIN YIELD USING TWO TAPPING METHODS IN MARITIME PINE (PINUS PINASTER AIT.) FORESTS IN NORTH-WESTERN SPAIN

Este capítulo se corresponde con el siguiente artículo de investigación:

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Base-age invariant models for predicting individual tree accumulated annual resin yield using two tapping methods in maritime pine (*Pinus pinaster* Ait.) forests in north-western Spain

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A B S T R A C T

In southern Europe, especially in Spain and Portugal, maritime pine resin is one of the main non-timber forest products. After suffering a crisis at the end of the 20th century, it is currently a growing sector. In Spain, depending on the area, the management of pine forests is one of the pillars of the national bioeconomy. In addition to timber production, these forests may be oriented towards resin production only, or resin production as a complementary activity to timber production. In both cases, as in any sector, it is essential to have tools to manage and anticipate production, especially in the new context of the bioeconomy. For this reason, the aim of this study is to develop a dynamic model to estimate the accumulated resin yield during the resin production season. For this study, 180 trees from three plots located in the northwest of the Iberian Peninsula were resin tapped using two extraction methods (non-mechanized and mechanized circular notching) and stimulant pastes. Four base models were used from which eight equations were derived using ADA and GADA techniques. The most efficient equations, both for modelling with the train data and for prediction with the test data, were those derived from the Bertalanffy-Richards model. The RRMSE was 23% for the non-mechanised method and 29% for the mechanised circular method. The results of this study make it possible to add the cumulative annual resin yield of maritime pine to the processes that the Bertalanffy-Richards equation is capable of modelling. Furthermore, the great versatility of these models will be of great use to the forest manager in optimising the annual harvesting season as well as for the scientific community.

1. Introduction

Throughout history, the resources generated by forests have provided different types of goods relevant to society (Sheppard et al., 2020). The social and environmental benefits associated with multi-functional forest management practices have an important impact, especially in rural areas (Lovrić et al., 2022). Worldwide, the main forest resource in terms of volume and revenue is timber, but other commodities such as non-timber forest products (NTFPs) are also valuable (Sardeshpande and Shackleton, 2019). According to FAO (2015), the NTFPs are “goods derived from forests that are tangible and physical objects of biological origin other than wood” like food additives, fibres, resins or gums. The high added value of NTFPs makes them a perfect complement to timber production, providing an extra source of income between timber harvests (Hernández-Rodríguez et al., 2017). One such benefit, derived from their nature as a bioproduct, is their role in mitigating the carbon footprint and reducing the use of fossil-based materials (Solomon, 2016). This is due to the ability of some of them (fibres, gum, or resin) to fix CO_2 and to replace petroleum derivatives (Demko and Machava, 2022).

In Europe, according to Vacik et al. (2020), the economic importance of plants-derived NTFPs remains modest, with the reported value of NTFPs reaching 1.6 billion euros. Data for statistics are difficult to obtain, since a large proportion of NTFPs are intended for self-consumption (Lovrić et al., 2020; Winkel et al., 2022). Despite this, there are European countries that dedicate exclusive resources to this type of activities, such as France, Portugal, and Spain, which are committed to NTFPs with the highest added value (Wolfslehner et al., 2019). In Spain, the value of NTFPs in relation to timber varies between 10 % and 50 %, depending on the source (Díaz-Balteiro et al., 2020).

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According to MITECO (2022), the main Spanish NTFPs products are truffles and edible fungi (106.6 million euros), cork (83.6 million euros), chestnut (18 million euros), pine resin (10.3 million euros) and pine nuts (2.6 million euros). Pine resin is the main defensive barrier against external attacks caused by pests and diseases of pine trees (Rissanen et al., 2019). Spanish pine resin production has experienced ups and downs throughout history. Since the 1980 s, resin tapping activity has lost importance until it practically ceased at the beginning of this century (Soliño et al., 2018). But since 2000 s it has been growing in importance again within the national forestry sector and is expected to continue to grow in the coming years (Gómez-García et al., 2022). This is reflected in the increase in publications on the subject in some regions of Spain in recent years, as in the case of Galicia (García-Méijome et al., 2023; López-Álvarez et al., 2023; Touza et al., 2021; Vázquez-González et al., 2021; Zas et al., 2020a,b). This growth is due to its multiple industrial uses, the environmental benefits associated with extraction and the boost the sector is receiving from public and private initiatives (Soliño et al., 2018; Oono et al., 2020).

The progressive decline of the sector in the past century has led to a lack of technical expertise and knowledge generation, which does not correspond to other sectors such as the wood sector (Génova et al., 2014; López-Álvarez et al., 2023a). In addition, existing databases have problems in obtaining complete data series (Sainz et al, 2010; Calama et al., 2020). The complexity of collecting these data series is due to the large number of intermediate measurements that need to be made and the fact that it is a very laborious process. In order to make the sector more competitive, the work of producers must be facilitated by providing them with different types of resources. Regarding issues related to the mechanization of tapping process, various authors have compared the performance between different mechanized and non-mechanized extraction methods (Rodríguez-García et al., 2016; López-Alvarez et al., 2023b; García-Méijome et al. 2023) and between different stimulant pastes used (Neis et al., 2018; Michavila et al., 2021). In terms of planning tools, there is a lack of statistically robust models that can predict final production before or once the tapping season has started. This type of modelling is essential for multifunctional forest resource planning, as it allows the stock and expected value of resinous pine to be estimated.

This lack of robust models may be due to the complexity of identifying the explanatory variables of total production, as it depends on the interaction of multiple interrelated variables (Zas et al., 2020a). The paper by López-Alvarez et al. (2023b) shows the important biometric and production variability of pines within and between plots, and previous studies mainly relate resin yield in temperate zones to two environmental factors, temperature and water stress (Zas et al., 2020b). These results are in line with the markedly seasonal behaviour of annual resin production, with the highest productions obtained in the warmer and less rainy months (Rodríguez-García et al., 2015). This pattern causes the individual tree accumulated resin production curve in the season to follow a sigmoidal curve, a pattern widely studied in multiple fields (Caglar et al., 2018). For example, tree and stand growth behaves similarly when represented over time (Piovesan and Biondi, 2021).

Foresters use the construction of site index curves to model this trend over time. They use three main techniques: guide curve, parameter prediction and algebraic difference approach (Clutter et al., 1983). The last methodology has the advantage that it allows the development of dynamic equations derived from developing age-invariant models from repeated measurements taken over time (Jordan et al., 2006). The main methods for developing these equations are the algebraic difference approach (ADA), formalized by Bailey and Clutter (1974), and the generalized algebraic difference approach (GADA), introduced by Cieszewski and Bailey (2000). The ADA method has the limitation that the models derived from it only allow the creation of families of anamorphic curves or those with a single asymptote (Cieszewski, 2001). To solve the limitations of the ADA method, the GADA methodology was developed, which allows the creation of families of polymorphic curves with multiple asymptotes (Cieszewski, 2002). In GADA, to obtain these families of curves, the base equations are expanded according to several characteristics that are rooted on different growth theories (Diéguez-Aranda et al., 2005). According to these theories, the curves should start from the origin, be polymorphic, have multiple asymptotes, and have the same estimated value between prediction and reference age (Cieszewski and Bailey, 2000).

The aim of this paper is to evaluate the feasibility of modelling the individual tree annual accumulated resin production developing an invariant model for pine forests in northwestern Spain. To carry out the main objective, the paper has been structured into two parts: (1) evaluation of the validity of the ADA and GADA methods for modelling the individual tree accumulated annual resin yield and (2) the forecasting performance of models.

2. Material and methods

2.1. Study area and data

The data used to carry out the study were limited due to the difficulty of collection and the lack of previous studies. As a result, information for the dataset came from three newly established plots located in low-density pure stands of *Pinus pinaster* in the northwestern Spanish region of Galicia (Fig. 1). The study area is characterized by moderate annual average temperatures (11–14 °C) and accumulated annual rainfall between 800 and 1500 mm.

During the months of June to October 2021, a total of 180 trees were selected from the plots for resin tapping procedures. The minimum, mean, and maximum diameters at breast height (*dbh*), total heights (*h*), and resin yield (*Y*) values for the trees in each plot are presented in Table 1. The average *dbh* meets the legal requirements for resin procedures in the region. As a preliminary step, the dasometric variables were tested for their lack of influence on resin yield by calculating Spearman correlations between resin and *dbh* (corr = 0.18, p-value = 0.02) and *h* (corr = 0.07, p-value = 0.37), as neither variable followed a normal distribution according to the Shapiro-Wilk test (*dbh* = W = 0.96, p-value = 0.001; *h* = W = 0.98, p-value = 0.03).

It was also checked whether the yields of the plots belonged to the same population. For this purpose, the Shapiro-Wilk test (W = 0.969, p-

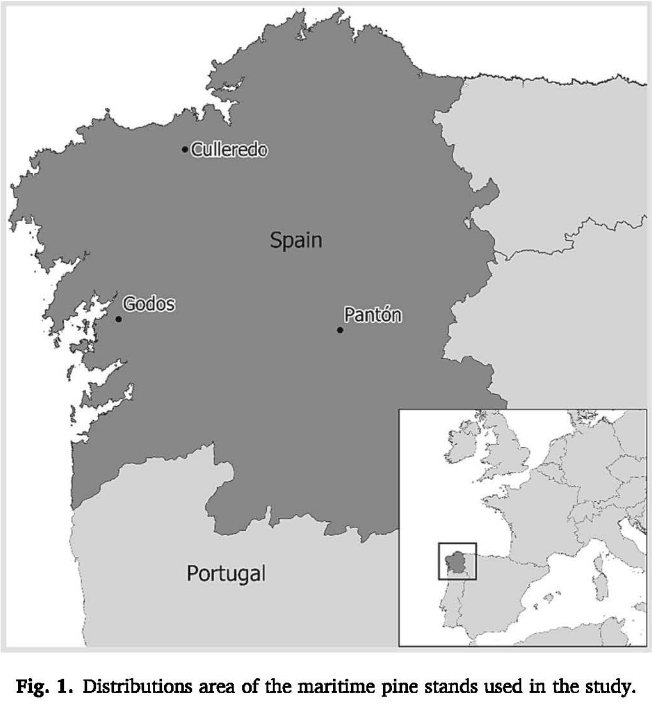

Fig. 1. Distributions area of the maritime pine stands used in the study.

Table 1
Dasometric and resin yield characterization of the plots utilized in the study. dbh: diameter at breast height (cm); h: total height (m); Y: tree resin yield (g).

Plot	dbh_{min}	$\overline{dbh}$	dbh_{max}	h_{min}	$\overline{h}$	h_{max}	Y_{min}	$\overline{Y}$	Y_{max}
Culleredo	21.4	31.6	45.9	12.0	16.1	21.0	407	1419.11	3359
Pantón	23.1	32.6	47.9	17.0	22.5	27.0	642	1564.47	2862
Godos	25.5	39.5	54.4	17.3	20.4	24.1	339	1492.27	2974

value = 0.001) was used to verify that the data of yields as a function of plot did not satisfy the assumption of normality, but the Levene test (F = 0.246, p-value = 0.781) did satisfy the assumption of homoscedasticity. Having verified this, the Kruskal-Wallis test (Fig. 2) was used to test whether there were statistically significant differences between the yields of each plot, which showed that there were no statistically significant differences between them.

Resin tapping was carried out using two different methods, applying each method to 90 trees (30 trees per plot using each method, a total of 180 trees). One was a non-mechanized variant of the "American" extraction method described in Rodríguez-García et al. (2014), used mainly in the Iberian Peninsula and France. The other extraction method was the mechanized circular groove method (López-Álvarez et al., 2023b), in which a circular notch is made in the stem of the tree and a circular device is placed to collect the resin in a closed plastic bag. The non-mechanized method cut a 16 cm long and 3 cm wide rectangular strip of bark and cambium, while the mechanized circular groove method used a 5 cm diameter tool and a battery-powered screwdriver (cutting circumference of 15.71 cm). A new strip was made every 14 days. By the end of the tapping season, which lasted five months, a total of 10 cuts had been made. Two different pastes were used as a resin production stimulant, ethephon (8 % ethephon (60 % v/v), 14 % sulphuric acid (50 % v/v), 55 % distilled water, 1.7 % polysorbate, 1 % cetyl alcohol, 4 % vaseline, 5.5 % silica, 10.8 sawdust) and ASACIF (1 % salicylic acid, 25 % sulphuric acid (96 % v/v), 5 % propylene glycol, 19 % wheat straw, 50 % distilled water). These pastes were applied each time a new strip was made. Due to inconveniences in the data collection process, there was a small group of trees for which some intermediate yield could not be measured at the precise moment when the new cutting was made and were therefore accumulated in the next weighing. To fit the models, periodic yields were accumulated monthly, giving a total of five measurements for each tree.

2.2. Model development

To model the behaviour of resin yield over the year, we chose to split the data sample by extraction method, but not by stimulant paste. This data splitting was done because there was a high variability between the

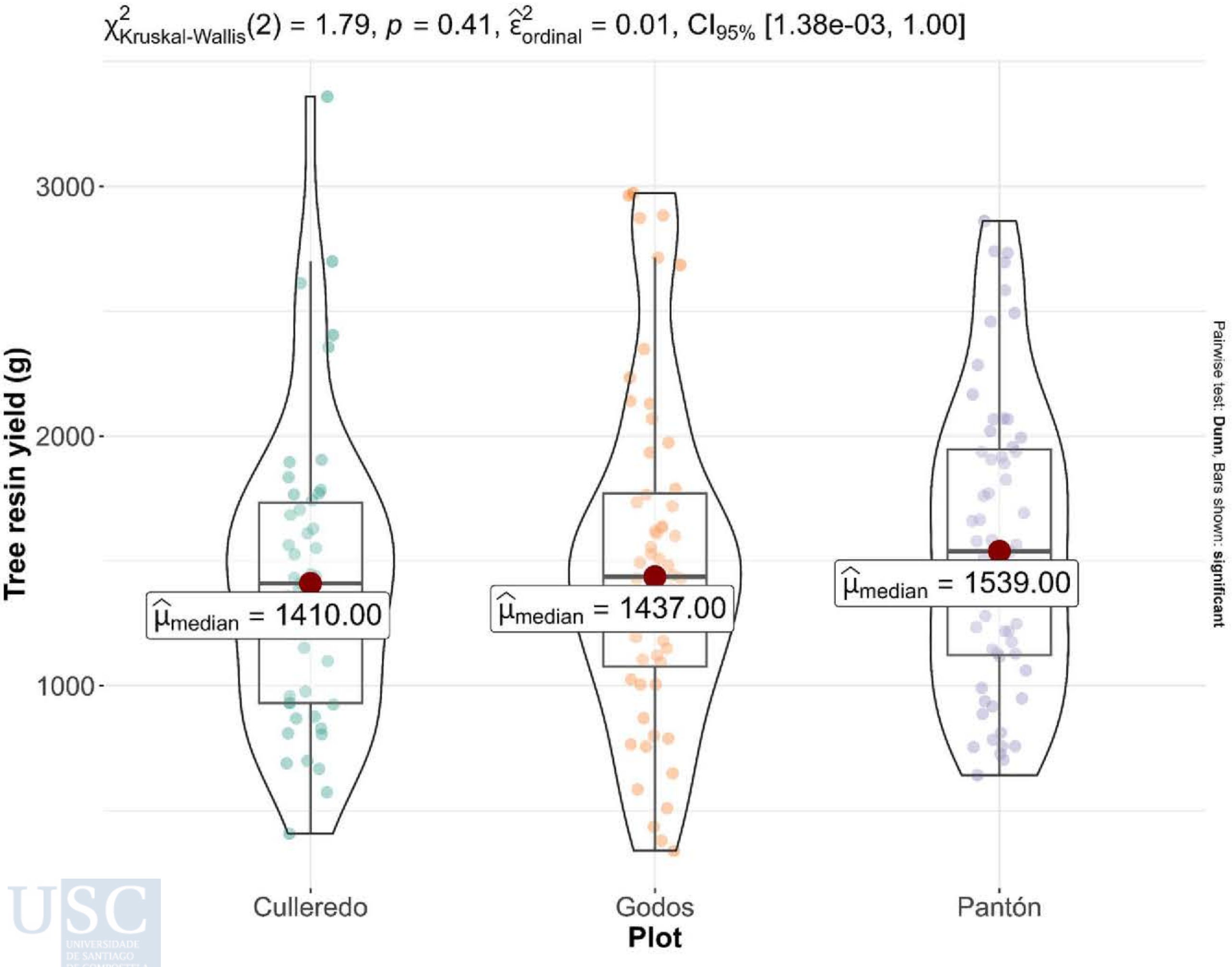

Fig. 2. Statistical differences test between the resin yields of each plot. The statistical tests between groups were perform with statistical software R (R Core Team, 2022) and the "ggstatsplot" package (Patil, 2021).

yields in the data set and statistically significant differences between the extraction methods, as can be seen in Fig. 3. There are no statistical differences between the stimulant pastes (Fig. 3).

2.2.1. Models tested

Several models have been tested, including both ADA and GADA models derived from different base equations. Therefore, there are equations with one or more variable parameters depending on the specific site. The general notation (Diéguez-Aranda et al., 2005; Sánchez-González et al., 2008; Panik, 2014) used to develop the models has been, $a_1, a_2, \ldots, a_n$ to denote the parameters in the base models, and $b_1, b_2, \ldots, b_n$ for the parameters that were fitted in the different formulations of the base equations. Hence, the general formulation of the derived models has the form $Y = f(t_0, t_1, Y_0, b_1, b_2, \ldots, b_n)$. These types of equations have multiple uses, such as describing the growth of trees and their phenotypic elements, or the growth of cork thickness, as mentioned before. Although there are other uses besides those purely forestry, like its use in fisheries (Flinn and Midway, 2021), mussels (Fuentes-Santos et al., 2017) or chicken (Mata-Estrada et al., 2020) growth models.

Different ADA and GADA formulations from base equations were tested, but finally the selected base equations that achieved convergence (Table 2) were the Bertalanffy-Richards (Bertalanffy, 1949, 1957; Richards, 1959), Korf (cited in Lundqvist (1957)), Hossfeld (Hossfeld, 1822) and Weibull (Weibull, 1951; Yang et al., 1978). A total of eight equations derived from the previous base equations were fitted. Four of them (Eqs. E1 to E4) have been based on the Bertalanffy-Richards model. Of which, three (Eqs. E1 to E3) were derived by the ADA methodology, thus possessing only one site-specific parameter. Equation E1 generates families of anamorphic curves with multiple asymptotes, whereas Equations E2 and E3 generate polymorphic curves with a single asymptote (Manso et al., 2021). The result of deriving the Bertalanffy-Richards equation with the GADA methodology is Eq. E4, it has more than one parameter that is site-specific and allows generating families of polymorphic curves with multiple asymptotes (Prada et al., 2019). In the case of Eqs E5 to E8, which are derived from the various equations mentioned above, these are models obtained using the ADA methodology, only having a site-specific parameter.

2.2.2. Parameter estimation, model selection and validation

To perform the fit and subsequent validation of the models, the data without outliers was randomly stratified into quartiles according to the time lag predictor variable in training (80 %) and test (20 %). The first set was used to adjust the model parameters simultaneously (local and global parameters) using the dummy variable method described in Cieszewski et al. (2000), and select the one with the best goodness-of-fit statistics. The second set was used to evaluate the performance of the selected model in an unbiased manner.

Model selection was performed by numerical and graphical analysis of the residuals of the fits. To evaluate the performance of the models on the training data, goodness-of-fit statistics such as.

pseudo-R^2 (R^2), calculated according to Schabenberger and Pierce (2001) using the residual sum of squares and the total corrected sum of squares, Root Mean Square Error (RMSE) and Akaike's information criterion (AIC) were used. The predictive performance of the models was evaluated using the Relative Root Mean Square Error (RRMSE). To provide additional model details, we have included the bias (the average of the prediction residuals) and MAE (the average of the absolute values of the prediction residuals).

The statistical software R (R Core Team, 2022) was used for the calculations. The "rsample" package (Frick et al., 2022) was used to randomly separate the sample into test and training sets. The "stats" package (R Core Team, 2022) was used to perform the non-linear models fitting. The following functions and packages were used to calculate the goodness-of-fit statistics and measure the accuracy of the models on the test data: the "aomisc" package (Onofri, 2020) for R^2, the "Metrics" package (Hamner and Frasco, 2018) for RMSE, the "stats" package (R Core Team, 2022) for AIC, and the "metrica" package (Correndo et al., 2022) for RRMSE.

3. Results

3.1. Accumulated resin yield pattern

The smoothed trend of the resin yield obtained at individual harvests during the collection of resin tapping data for each of the extraction methods, follows the patterns shown in Fig. 4. In the non-mechanized

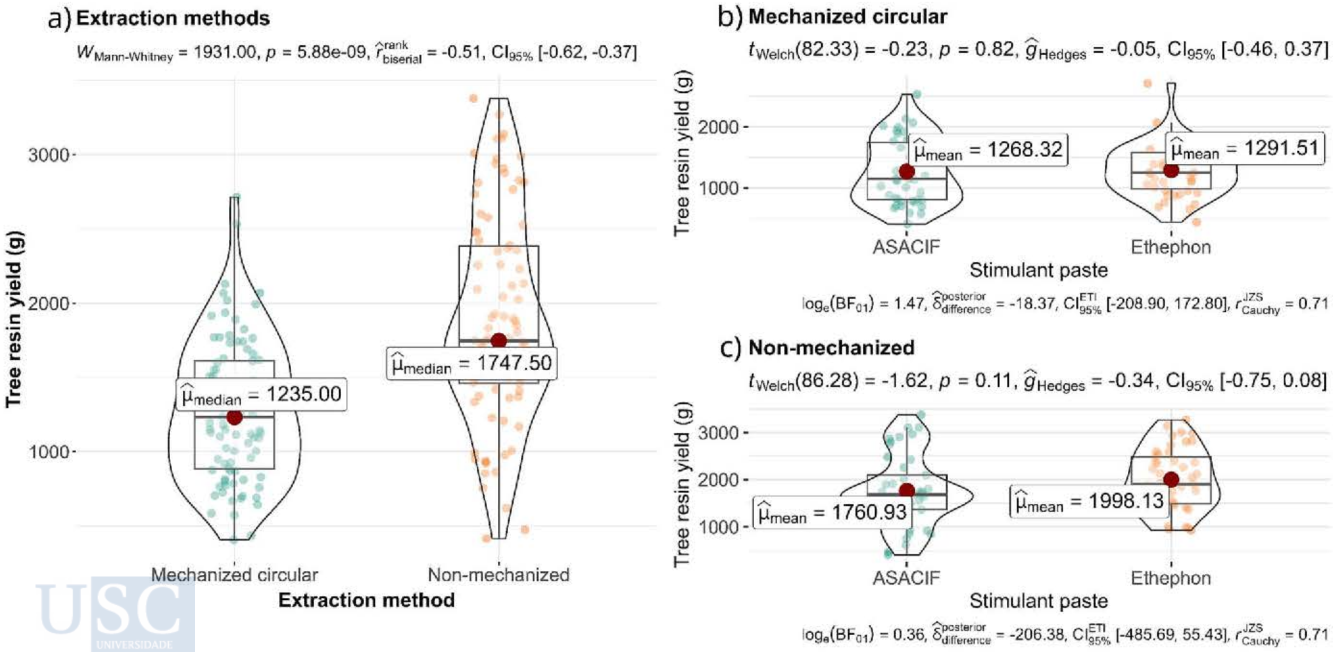

Fig. 3. Statistical differences between a) the extraction methods and b) and c) the stimulant pastes according to the extraction method. The statistical tests between groups were perform with statistical software R (R Core Team, 2022) and the "ggstatsplot" package (Patil, 2021).

Table 2
Base models and ADA and GADA formulations considered.

Base model	Parameter related to site	Solution for *X* with initial values (t_0, Y_0)	Dynamic equation	
Bertalanffy-Richards $Y = a_1 \cdot (1 - e^{-a_2 \cdot t})^{a_3}$	$a_1 = X$	$X_0 = \frac{Y_0}{(1 - e^{-b_2 \cdot t_0})^{b_3}}$	$Y = Y_0 \cdot \left(\frac{1 - e^{-b_2 \cdot t}}{1 - e^{-b_2 \cdot t_0}}\right)^{b_3}$	(E1)
	$a_2 = X$	$X_0 = \frac{-\ln\left(1 - (Y_0/b_1)^{1/b_3}\right)}{t_0}$	$Y = b_1 \cdot \left(1 - \left(1 - \left(\frac{Y_0}{b_1}\right)^{1/b_3}\right)^{t/t_0}\right)^{b_3}$	(E2)
	$a_3 = X$	$X_0 = \frac{\ln(Y_0/b_1)}{\ln(a - e^{-b_2 \cdot t_0})}$	$Y = b_1 \cdot \left(\frac{Y_0}{b_1}\right)^{\frac{\ln(1 - e^{-b_2 \cdot t})}{\ln(1 - e^{-b_2 \cdot t_0})}}$	(E3)
	$a_1 = e^X$ $a_3 = b_2 + b_3/X$	$X_0 = \frac{1}{2} \cdot \left(\ln Y_0 - b_2 \cdot L_0 + \sqrt{(\ln Y_0 - b_2 \cdot L_0)^2 - 4 \cdot b_3 \cdot L_0}\right)$ with $L_0 = \ln\left(a - e^{-b1 \cdot t_0}\right)$	$Y = Y_0 \cdot \left(\frac{1 - e^{-b_1 \cdot t}}{1 - e^{-b_1 \cdot t_0}}\right)^{b_2 + b_3/X_0}$	(E4)
Korf $Y = a_1 \cdot e^{-a_2 \cdot t^{-a_3}}$	$a_1 = X$	$X_0 = \frac{Y_0}{e^{-b_2 \cdot t_0^{-b_3}}}$	$Y = Y_0 \cdot \frac{e^{-b_2 \cdot t^{-b_3}}}{e^{-b_2 \cdot t_0^{-b_3}}}$	(E5)
	$a_2 = X$	$X_0 = -\ln(Y_0/b_1)/t_0^{-b_3}$	$Y = a_1 \cdot \left(\frac{Y_0}{b_1}\right)^{\left(\frac{t_0}{t}\right)^{b_3}}$	(E6)
Weibull $Y =$ $a_1 \cdot \left(1 - e^{(-a_2 \cdot t^{a_3})}\right)$	$a_2 = X$	$X_0 = -\ln(1 - (Y_0/b_1))/t_1^{b_3}$	$Y = b_1 \cdot (1 - (1 - Y_0/b_1))^{(t/t_0)^{b_3}}$	(E7)
Hossfeld $Y = \frac{a_1}{1 + a_2 \cdot t^{-a_3}}$	$A_2 = X$	$X_0 = t_0^{-b_3} \cdot (b_1/Y_0 - 1)$	$Y = \frac{b_1}{1 - \left(1 - \frac{b_1}{Y_0}\right) \cdot \left(\frac{t_0}{t}\right)^{b_3}}$	(E8)

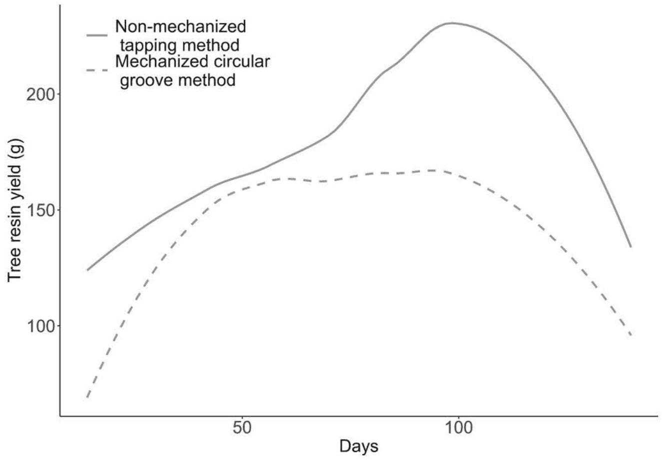

Fig. 4. Resin yields of individual grooves during the tapping season of the two methods, non-mechanized tapping method (continuous line) and mechanized circular groove method (dashed line).

tapping method, which was the most productive in terms of total resin yield, the immediate resin yield between strips was increased from the beginning of the season reaching the highest values in the late summer months and then decreased until the end of the tapping season. In contrast, the mechanised circular groove method showed a more consistent pattern. Its trend increased from the start of the resin extraction campaign until 30 days after the start, remained stable until 40 days before the end, and then decreased until the end of the season. Consequently, the circular method did not show as pronounced a peak as the non-mechanised method.

As a consequence of the phenomenon shown in Fig. 4, when the cumulative yields over the resin tapping season of individual trees are plotted as a function of resin extraction method, they follow a sigmoidal pattern (Fig. 5). It can also be seen that the slope of the curves of the non-mechanised method is greater than the slope of the mechanised circular method, which is a consequence of the same phenomenon.

3.2. *Final models*

The estimated parameters, standard errors of the estimates, goodness-of-fit statistics and performance on validation data are shown in Table 3 and Table 4. All the fitted parameters were statistically significant at a 1 % level.

3.3. *Non-mechanized tapping method*

All the fitted models exhibited satisfactory performance after adjusting for cumulative resin yield (Table 3). Upon evaluation using the training data, the R^2 values obtained ranged from 0.818 to 0.873, depending on the specific model. The RMSE values varied from 246.980 to 300.758, while the AIC values ranged from 17964.02 to 18474.63. As a measure of the good performance of the models, we looked for those with the lowest RMSE and AIC values. On the test data, the models demonstrated fair RRMSE values below 30 % (Li et al., 2013; Despotovic et al., 2016), with none exceeding 27.018 % and the lowest being 23.189 %. The bias range was between −24.34 and 19.74 g while the MAE was between 164.38 and 177.78 g.

During the training phase, the top performers in terms of R^2, RMSE and AIC were three models derived from the Bertalanffy-Richards model, followed by one model derived from the Korf, Hossfeld, and Weibull equations. Conversely, the least effective models were the anamorphic and multiple asymptotic models derived from the Bertalanffy-Richards equation, as well as the Korf model when solving for the "a_1" parameter. Similar results were obtained when assessing the predictive performance of the models on the test data.

Among the models, equation E3, which corresponds to the ADA model when solving for the "a_3" parameter in the Bertalanffy-Richards equation, exhibited the highest R^2 value, as well as the lowest RMSE and AIC values. When assessing the predictive performance of this model on the test data, an RRMSE of 23 %, a bias of −19.48 g and a MAE of 170.38 g were obtained. Furthermore, graphical analysis of the residuals for the E3 model revealed no evidence of heteroscedasticity or autocorrelation between the residuals (Fig. 6).

To represent the evolution of the cumulative productions generated by the model (Fig. 6), a time (*t*) of 56 days from the beginning of the tapping campaign was selected. This period was chosen as a reference since it is two months after the start of the campaign and one month before the halfway point of the campaign, allowing for an early estimation of the inputs for the season. To represent the production curves, the difference between the maximum and minimum cumulative production in the time *t* was divided by four, and this amount was added

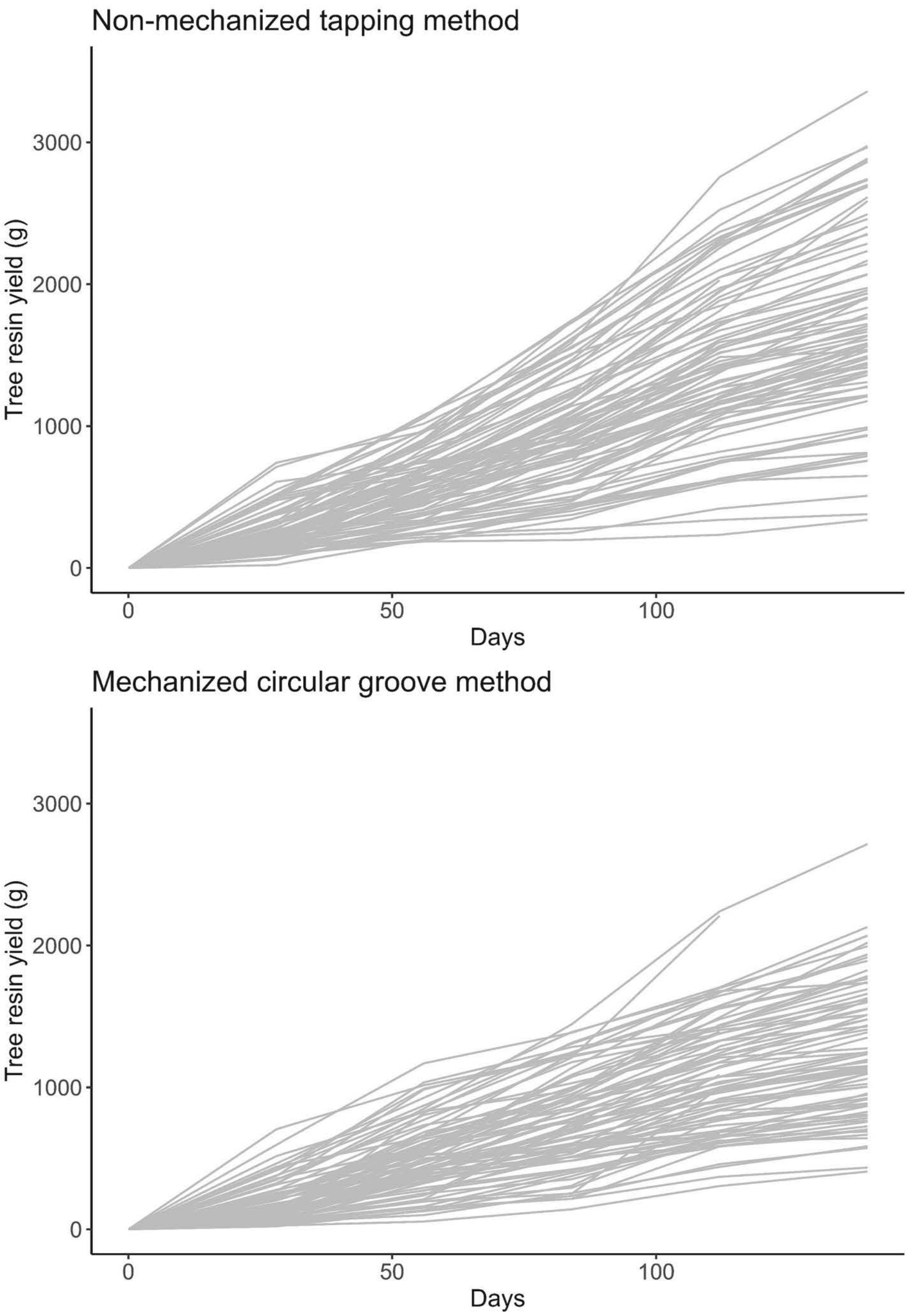

Fig. 5. Accumulated resin yield during resin tapping season for both resin tapping methods, non-mechanized tapping method (graphic at the top) and mechanized circular groove method (graphic at the bottom).

from the minimum to the maximum production in the period *t*. The represented curves are those of 187.00, 410.25, 633.50, 856.75, and 1080.00 accumulated grams at time *t*. Fig. 8 plots the RRMSE obtained by the model when making predictions on test data as a function of time. The model achieves an RRMSE of less than 30 % for forecasts up to 90 days (Fig. 8), which is very good for forecasts of less than one month, good for forecasts of two months and fair for forecasts of three months according to Li et al. (2013). This statistic rises above 30 % for forecasts longer than 90 days.

3.4. *Mechanized circular groove method*

The fits to the data obtained with the mechanized circular groove method (Table 4), show favourable results but more modest compared to the non-mechanized tapping method. The R^2 values achieved with the training data range from 0.695 to 0.82. The RMSE values and AIC values range from 212.512 to 276.569 and from 16844.4 to 17496.84, respectively. When assessing the models on test data, the RRMSE was again obtained values below 30 %. The bias varied from 0.98 to 41.45 g, and the MAE ranged from 150.95 and 199.56 g.

Consistently, equations derived from the Bertalanffy-Richards model demonstrate superior goodness-of-fit statistics, yielding the most optimal fit to the data. Conversely, the poorest fits are observed with the same equations as in the non-mechanized tapping method case, specifically the anamorphic and multiple asymptotic form of the Bertalanffy-Richards equation, as well as the Korf model by solving the "a_1" parameter.

The E4 or GADA form of the Bertalanffy-Richards model is found to

Table 3
Parameter estimates and goodness-of-fit statistics for non-mechanized tapping method.

Model	Train						Test		
	Parameter	Estimate	Standard error	R^2	RMSE	AIC	RRMSE (%)	Bias	MAE
E1	b_2	−0.003	0.001	0.818	295.901	18432.44	26.370	16.09	177.78
	b_3	0.984	0.037						
E2	b_1	4180.555	16.090	0.856	263.305	18129.92	24.806	−14.66	167.41
	b_3	1.535	0.028						
E3	b_1	15767.82	$2.216x10^{3}$	0.873	246.980	17964.02	23.189	−19.48	170.38
	b_2	$1.497x10^{-3}$	$2.148x10^{-4}$						
E4	b_1	$1.608x10^{-3}$	$1.425x10^{-4}$	0.873	247.330	17969.69	23.415	−24.34	170.85
	b_2	$-1.029x10^{4}$	$1.284x10^{3}$						
	b_3	$9.908x10^{4}$	$1.228x10^{4}$						
E5	b_2	17	3.582	0.812	300.758	18474.63	27.018	19.74	175.57
	b_3	0.096	0.034						
E6	b_1	$3.447x10^{4}$	$7.237x10^{3}$	0.857	261.883	18115.89	24.198	−11.32	164.38
	b_3	0.318	0.019						
E7	b_1	$3.768x10^{3}$	$1.286x10^{2}$	0.854	264.460	18141.26	25.047	−14.12	167.66
	b_3	1.398	$1.631x10^{-2}$						
E8	b_1	$5.233x10^{3}$	$2.449x10^{2}$	0.855	263.686	18133.66	24.827	−14.19	167.72
	b_3	1.465	$2.202x10^{-2}$						

Table 4
Parameter estimates and goodness-of-fit statistics for mechanized circular groove method.

Model	Train						Test		
	Parameter	Estimate	Standard error	R^2	RMSE	AIC	RRMSE (%)	Bias	MAE
E1	b_2	0.005	0.001	0.696	276.414	17495.44	41.971	41.45	199.43
	b_3	1.247	0.059						
E2	b_1	$2.845x10^{3}$	64.180	0.770	236.704	17110.2	33.698	12.67	170.69
	b_3	1.589	0.029						
E3	b_1	$4.935x10^{3}$	$3.447x10^{2}$	0.811	217.614	16901.33	29.844	4.29	156.77
	b_2	$3.603x10^{-3}$	$3.076x10^{-4}$						
E4	b_1	$1.077x10^{-2}$	$9.118x10^{-4}$	0.820	212.512	16844.4	29.244	0.98	150.95
	b_2	−13.780	1.543						
	b_3	$1.197x10^{2}$	12.040						
E5	b_2	11.931	0.629	0.695	276.569	17496.84	41.916	44.63	199.56
	b_3	0.189	0.046						
E6	b_1	$5.885x10^{3}$	$4.574x10^{2}$	0.817	214.433	16864.75	29.437	0.83	152.23
	b_3	0.541	$2.092x10^{-2}$						
E7	b_1	2820.459	67.679	0.763	244.104	17186.67	35.540	21.69	178.76
	b_3	1.357	0.017						
E8	b_1	$3.120x10^{3}$	92.570	0.781	234.208	17083.87	33.020	12.54	167.14
	b_3	1.563	0.024						

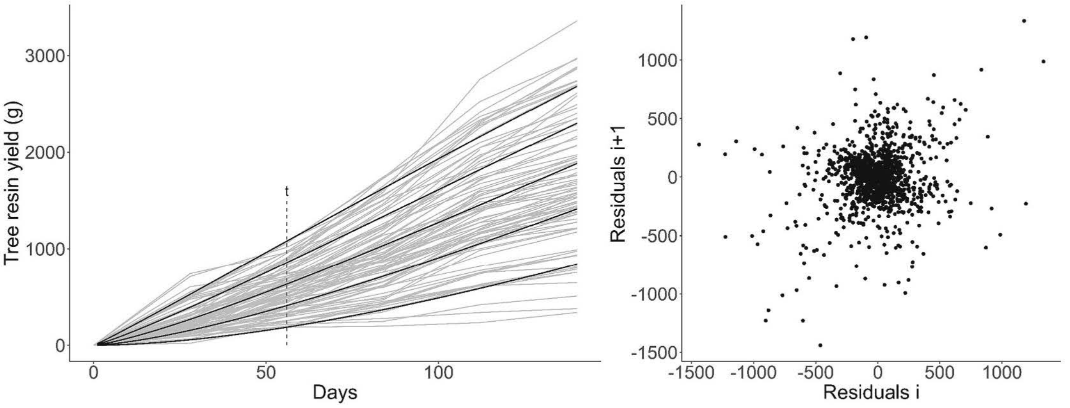

Fig. 6. The left figure was the age-dependent dynamic model E3 for non-mechanized notching and the accumulated resin yield curves of187.00, 410.25, 633.50, 856.75, and 1080.00 g at the time t of 56 days. The right figure is the Residuals vs Residuals i + 1 for non-mechanized notching model E3.

be the equation that achieves the highest level of statistical goodness of fit with the training data (Table 4). Graphical analysis of the residuals for the E4 model indicates the absence of any observable heteroscedasticity or autocorrelation among the residuals (Fig. 7). When tested against the validation data, the equation displayed the lowest RRMSE value of 29 %, a bias of 0.98 and a MAE of 150.95 g.

To represent the curves of the adjustments made with the equation on the original data, it has been done in the same way as in the previous

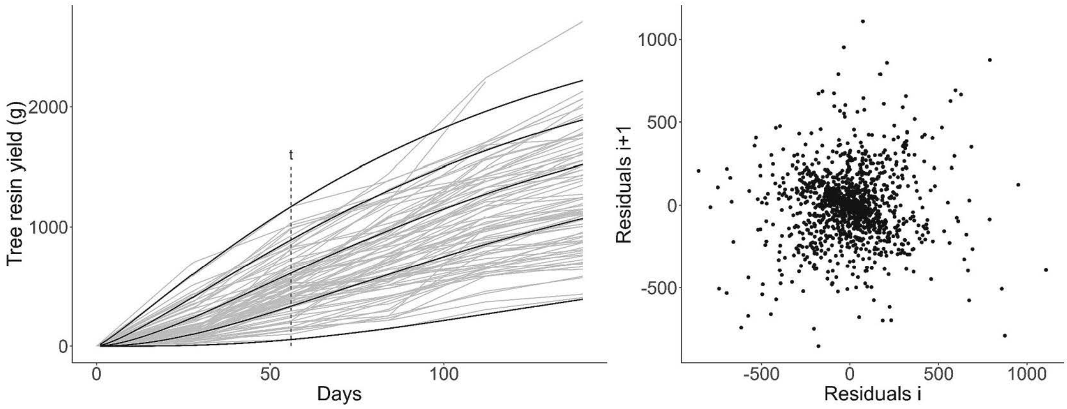

Fig. 7. The left figure was the age-dependent dynamic model E4 for mechanized circular groove and the accumulated resin yield curves of 55.00, 333.75, 612.50, 891.25, and 1170.00 g at the time t of 56 days. The right figure is the Residuals vs Residuals i + 1 for mechanized circular groove model E4.

case. In this case, the curves represented at time *t* are those of 55.00, 333.75, 612.50, 891.25, and 1170.00 g (Fig. 7). The model obtained an RRMSE lower than 35 % when the prediction lag was 85 days (Fig. 8), also reducing the mean prediction error at the end of the tapping season below that obtained by the model fitted to the other extraction method. In this case, forecasts of less than one month could be described as good and those of less than two and a half months as fair (Li et al., 2013; Despotovic et al., 2016).

4. Discussion

This study represents the first case of modelling individual tree accumulative resin yield throughout the resin production season. It demonstrates that methods similar to those used to model different natural growth processes can be successfully applied. The unprecedented nature of this production modelling poses a challenge to the discussion, given the lack of previous studies on resin to establish a comparative framework. Fitting models describing the trend of cumulative production during the NTFP harvest season is challenging due to the high variability in individual tree production (Gómez-García et al., 2022; López-Alvarez et al., 2023b) and the influence that environment changes have on the yield of this renewable product (Vázquez-González et al., 2021b).

Regardless of the extraction method, the equations derived from the Bertalanffy-Richards model with ADA and GADA methodologies were the ones that presented the best performance. Likewise, when comparing the statistics of the models based on the extraction methods, the model for the non-mechanized method obtained better goodness-of-fit than the mechanized method.

The obtained results suggest that non-mechanized tapping may lead to a more pronounced yield increase in individual grooves towards the middle and end of the season when compared to the mechanized circular groove method (Fig. 4). This behavior, derived mainly from the tapping method (López-Álvarez et al., 2023b), accentuates the presence of an inflection point in the cumulative production curve, making it more similar to growth processes. In the non-mechanized tapping method, the equations that obtained the highest R^2 in the training phase were those derived from the Bertalanffy-Richards equation by ADA and GADA methodology (E3 and E4, respectively). The similarity in describing the trend of the data between the ADA and GADA forms of the Bertalanffy-Richards model is common in other forest species growth modelling works (Trim et al., 2020; Wang et al., 2020). The GADA form generally obtains better goodness-of-fit statistics, as it can generate polymorphic curves with multiple asymptotes. This statement is verified in the case of the non-mechanized extraction method, as the GADA formulation obtained the best statistics, similar to the reported by Sánchez-González

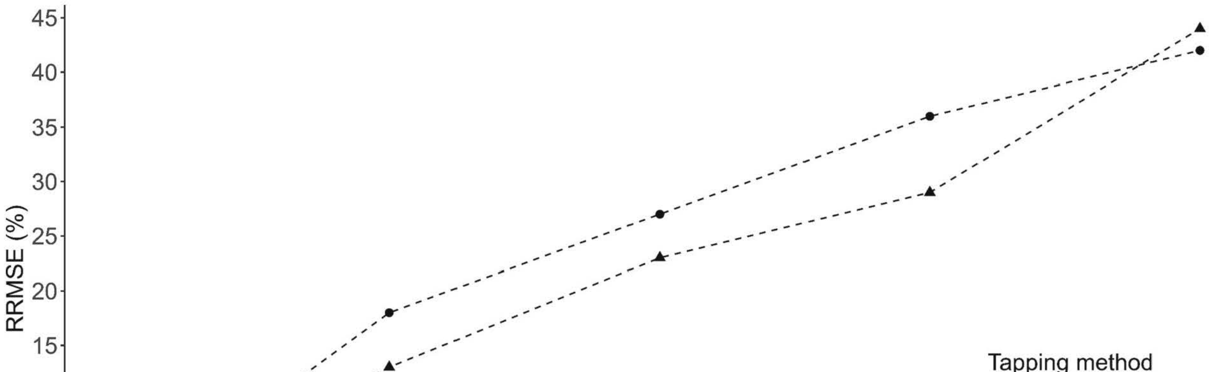

Fig. 8. Relative root mean square error (RRMSE) by lag of prediction for mechanized circular groove (circles) and non-mechanized notching (triangles).

et al. (2008) when modeling cork growth. The goodness-of-fit statistics obtained in both fits are similar to those obtained when using the GADA form of the Bertalanffy-Richards equation to model production over time of long rotation species such as the pedunculate oak (Gómez-García et al., 2015), and slightly lower than those obtained when modeling short rotation species (Diéguez-Aranda et al., 2005; Seki and Sakici, 2017) or cork production (Sánchez-González et al., 2008).

The good performance of the models in terms of goodness-of-fit, as obtained in this ground-breaking study, verifies that these techniques can be used to model resin production during the season. To make these models a valid tool for modelling cumulative resin production, both in the field of activity of forest workers, in the resin tapping industry and in the resin processing industry, it would be necessary to develop this preliminary study further and to carry out a larger sample, representative of the whole environmental gradient and including all the possible casuistry under which resin pine forests can be found. Therefore, based on the above, describing the individual tree accumulated resin production of *P. pinaster* can be included among the uses of the von Bertalanffy model (Bertalanffy, 1949, 1957).

The predictions made with the test data yielded average RRMSE values below 30 %, regardless of the extraction method. These average values can be classified as fair according to Despotovic et al. (2016) and Li et al. (2013). Simplifying and not considering the particular lag of each prediction, the models have an average accuracy of 76.81 % and 70.76 %, for the non-mechanized and mechanized methods, respectively. These accuracy percentages are slightly lower than those achieved by the growth models used in dendrometry (Prada et al., 2019) and are more similar to those obtained by Sánchez-González et al. (2008) modeling cork growth. When evaluating the accuracy percentage as a function of the lag of the predictions, it was found that a prediction made with an 80-day lag, which is usually half of the resin-tapping campaign, had an error rate of approximately 35 %. These accuracy percentages as a function of the lag are slightly lower than those achieved by dendrometric models (Gea-Izquierdo et al., 2008). The lower precision values may be due to the small sample size or the high variability of resin production over time due to dasometric and environmental variables, as data from dendrometric variables tend to show less variability in production between measurement periods.

To facilitate scientific research, one potential functionality of the results obtained is their usefulness to recover missing data from the temporal weight series. Collecting intermediate weight data is a difficult task (Calama et al., 2011), and usually there are data that were not measured at the precise moment when each new strip was done but were accumulated and weighed after two or more tapping periods. In this way, the accumulated production is accounted for, but it is not known which production belongs to each period. By using this type of models, the production curves can be recreated, and the missing intermediate data can be recovered. They are particularly relevant for researchers who wish to generate and monitor production curves and have missing data in the production series. The good predictive capacity of the models makes them a valid tool for the multifunctional management of pine forests, which is feasible as long as the owners are provided with the appropriate tools to carry it out (Sabastian et al., 2019). By using these models, forest managers will be able to predict inputs before the resin harvesting season ends, allowing them to optimize the duration of the campaign to maximise the annual income from resin sales. This makes resin extraction more attractive to forest producers, creating green jobs and promoting the bioeconomy by encouraging the production of a bioproduct such as pine resin.

5. Conclusion

With the increasing importance of resin production in the NTFPs and forestry sector, there is a need to further develop and expand our knowledge. This work demonstrates for the first time that age-invariant models are a valid tool for the management of pine forests under resin tapping procedures.

According to R^2, RMSE, AIC, RRMSE, Bias and MAE, the ADA and GADA formulations of the Bertalanffy-Richards model performed best in modelling cumulative resin production. This implies the inclusion of accumulative resin yield of individual trees as one of the many phenomena that can be modelled with these equations. Furthermore, the ability to accurately predict final production once the campaign has started using these models represents a significant advance in multifunctional forest management. In addition, this type of model applied to cumulative annual resin production can provide a basis for reconstructing missing data series with a high degree of accuracy. To further advance this sector, public or private initiatives should provide support and follow the example of forest growth models by establishing a network of permanent plots for parametrising national-scale resin production variables and developing more robust models. Enabling advancement in the effective joint management of wood resources and resin production, facilitating the creation of technical–economic models and the implementation of innovative, cutting-edge methodologies in constructing said models.

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CRediT authorship contribution statement

Óscar López-Álvarez: Conceptualization, Methodology, Formal analysis, Writing – original draft, Visualization. **Luis Franco-Vázquez:** Methodology, Writing – review & editing. **Manuel Marey-Perez:** Conceptualization, Methodology, Formal analysis, Resources, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Permission to share the data must be obtained from the institutions that funded the research

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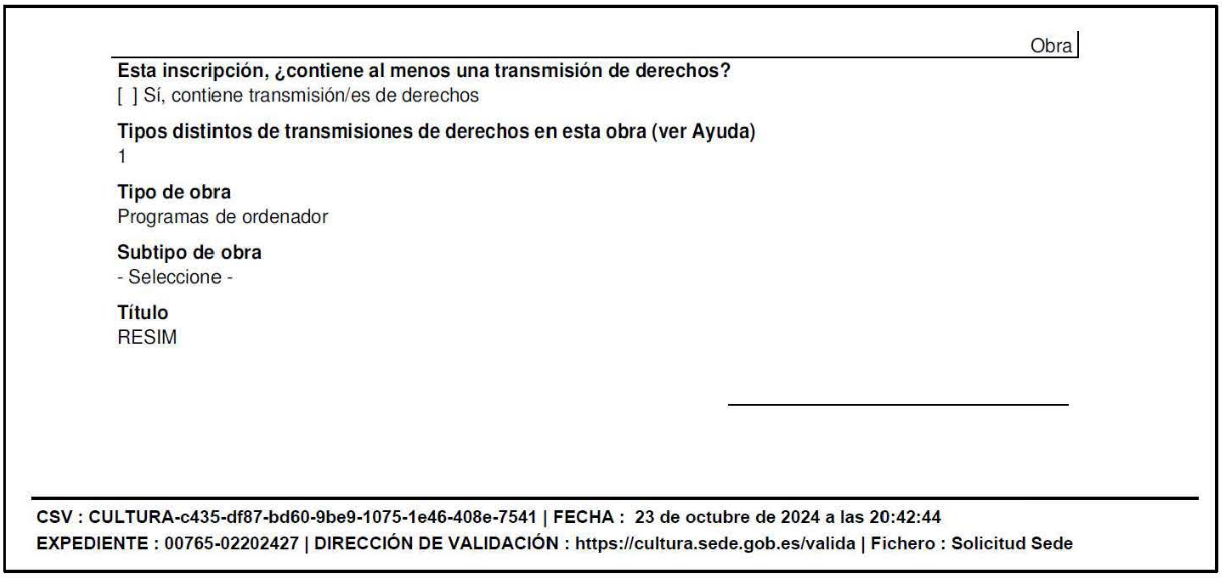
7 RESIM: SIMULADOR DE LA PRODUCCIÓN DE RESINA EN PROYECTOS DE APROVECHAMIENTO RESINERO

Este capítulo contiene una explicación detallada de la aplicación web interactiva RESIM, la cual tiene una solicitud de primera inscripción en el Registro Central de la Propiedad Intelectual – EA0042017/Ministerio de Cultura con número de expediente 00765-02202427 como programa de ordenador:



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Título
RESIM

CSV : CULTURA-c435-df87-bd60-9be9-1075-1e46-408e-7541 | FECHA : 23 de octubre de 2024 a las 20:42:44
EXPEDIENTE : 00765-02202427 | DIRECCIÓN DE VALIDACIÓN : https://cultura.sede.gob.es/valida | Fichero : Solicitud Sede

- **Título:** RESIM
- **Información del asiento**
    - **Tipo Asiento:** Entrada
    - **Asunto:** Registro de Solicitud
    - **Unidad de tramitación:** Registro Central de la propiedad Intelectual – EA0042017 / Ministerio de Cultura
    - **Nº Expediente:** 00765-02202427
- **Autores:** Óscar López Álvarez, Luis Franco Vázquez, Manuel Francisco Marey Pérez
- **Porcentaje de autoría:**
    - Óscar López Álvarez: 33.33%
    - Luis Franco Vázquez: 33.33 %
    - Manuel Francisco Marey Pérez: 33.33%

- **Documentación acreditativa:** La documentación acreditativa de la presentación de la solicitud de primera inscripción en el Registro Central de la Propiedad Intelectual se puede consultar el código CSV.

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7.1 INTRODUCCIÓN

Como ya se ha explicado en los capítulos anteriores, la producción de resina en los últimos años ha experimentado un incremento en el interés que suscita tanto a la comunidad científica como a los gestores forestales. Esto es debido a que se trata de un producto que se está posicionando en ciertos procesos productivos industriales como un posible sustituto de compuestos derivados del petróleo. Junto con este renovado interés, que había disminuido en los años 90 del siglo pasado, comienza a existir un fenómeno de expansión territorial de esta actividad, comenzando a aprovecharse en territorios como el noroeste de la Península Ibérica, que se caracteriza por contener vastas áreas cubiertas por árboles del género *Pinus*, principal género empleado a nivel mundial para la extracción de resina.

Dada la índole expansiva de la actividad resinera con su implantación en nuevos territorios, es necesario proveer a los productores forestales de herramientas con las que sean capaces de seleccionar aquellas masas cuyas condiciones sean las más adecuadas para esta actividad, proporcionándole una estimación de la cantidad de resina que podrá obtener antes del comienzo de la campaña, así como de estimar la producción que potencialmente podrán obtener una vez iniciada a partir de sus propios datos de producción. Esto permitirá a los propietarios o gestores forestales realizar un manejo eficiente de los recursos de los que dispone, permitiendo, en muchos de los casos, compatibilizar el aprovechamiento maderero con el resinero u otros aprovechamientos complementarios, generando de esta manera una fuente de beneficios extra a la venta de la madera.

Es por ello que uno de los objetivos de esta tesis doctoral consiste en proporcionar a los interesados potenciales herramientas accesibles de manera gratuita, que sean capaces de respaldar el proceso de toma de decisiones relacionado con la gestión y la implementación de iniciativas productoras de resina en bosques de *Pinus pinaster* ubicados en el noroeste de la Península Ibérica.

7.2 DESARROLLO

Para el desarrollo de RESIM se ha seguido una metodología que consta de tres fases: (i) desarrollo de los modelos de potencial productivo, (ii) desarrollo de los modelos de clasificación de potencial productivo y (iii) implementación informática.

7.2.1 Desarrollo de los modelos de potencial productivo

Para obtener una estimación de la producción de resina al final de la campaña en la masa seleccionada por el usuario, se han empleado los modelos desarrollados por López-Álvarez et al. (2024), artículo que forma parte de esta línea de investigación, desarrollado por el autor de esta tesis y actualmente en revisión en la revista *Industrial Crops and Products*. Es debido a esta circunstancia que se hará una breve descripción de la metodología empleada en el citado artículo para obtener dichos modelos de producción. En él se propuso un proceso de modelización en dos fases, basado en técnicas de aprendizaje no supervisado, machine learning y Deep Learning, capaz de estimar la producción de resina de árboles individuales de *Pinus pinaster* en el noroeste de la Península Ibérica.

La primera fase del proceso de modelización se podría denominar "*divide and conquer*", o en español, "divide y vencerás". En esta fase se lleva a cabo un proceso de aprendizaje no supervisado, con el que se pretende identificar la estructura interna de los datos y obtener la manera óptima de agruparlos en función de las variables disponibles. Estas variables pueden ser numéricas o categóricas, ya que en el proceso de resinado existen procesos medibles (producción, diámetro a la altura del pecho, altura total…), y otros que son inherentes al proceso de resinado y que se podrían categorizar como factores (método de extracción, pastas estimulantes, localización…). Es por ello que se empleó un algoritmo de clusterización capaz de trabajar con datos mixtos, como el algoritmo k-prototype (Huang, 1998).

En la segunda fase, una vez establecida la pertenencia de cada uno de los datos a un clúster determinado, se ajustó un modelo por cada una de estas agrupaciones capaz de estimar la producción de resina. Para ello se emplearon las variables numéricas y categóricas anteriormente citadas junto con técnicas de machine learning tales como bagging, boosting, redes neuronales o ensamblado de modelos. Los resultados obtenidos indican que estos modelos obtuvieron un buen desempeño modelizando la producción de resina. El RRMSE combinado de los modelos para todos los clústeres fue de 26.5%. Si se compara el resultado del modelo sin agrupar los datos con el de los modelos para los datos agrupados, el primero obtuvo un RRMSE un 50% mayor, y de la misma manera el modelo base obtuvo un RRMSE un 67% superior.

7.2.2 Desarrollo de los modelos de clasificación de potencial productivo

El siguiente paso consistió en ajustar un modelo capaz de clasificar los datos introducidos por los usuarios asignándoles su pertenencia a un clúster, para de ese modo saber que modelo emplear en la estimación de la producción de resina. En su construcción se empleó el algoritmo XGBoost (Chen y Guestrin, 2016) y las variables que el usuario deberá introducir en la aplicación informática relativas a su masa (localización, método de extracción, método de estimulación, diámetro a la altura de pecho y altura total). El algoritmo XGBoost proporciona una serie de características destacadas, como la incorporación de técnicas de regularización para prevenir el sobreajuste; el ensamblado iterativo de árboles de decisión basados en errores previos o la optimización de la función objetivo mediante el empleo del método de descenso de gradientes. El modelo desarrollado que empleó este algoritmo obtuvo un porcentaje de acierto del 90%.

Posteriormente, se calcularon los valores de SHAP (SHapley Additive exPlanations), método basado en la teoría de juegos cooperativa empleado para aumentar la transparencia e interpretabilidad de los modelos de machine learning. De este modo se facilita la interpretación y la contribución de cada variable al modelo final. En la Figura 1 se puede observar la contribución de cada variable al modelo de clasificación para cada uno de los clústeres.

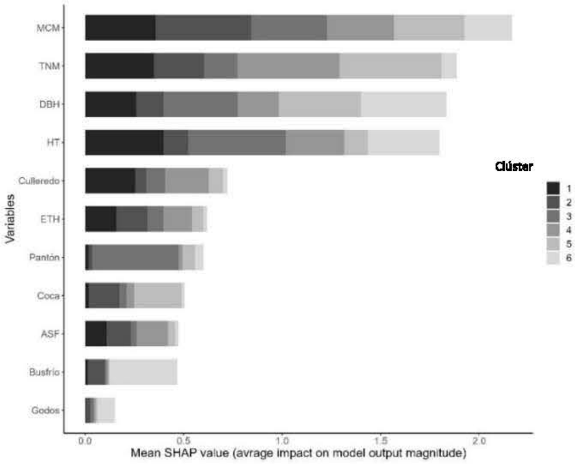


Figura 1. Contribución de cada variable al modelo de clasificación para cada uno de los clústeres. MCM; método circular mecanizado; TNM: método tradicional no mecanizado o pica de corteza; DBH: diámetro a la altura del pecho; HT: altura total; Localizaciones: Culleredo, Pantón, Coca, Busfrio, Godos; ETH: pasta estimulante Ethephon; ASF: pasta estimulante ASACIF.

En la Figura 1 se observa que de entre todas las variables empleadas para ajustar el modelo de clasificación aquellas que más influyeron fueron las relacionadas con el método de extracción el MCM, o método circular mecanizado, y el TNM, o método tradicional no mecanizado o pica de corteza. Seguidas de las variables relativas al método de extracción, las variables que tuvieron un mayor impacto en el modelo de asignación fueron las dasométricas: el diámetro a la altura del pecho, o DBH, y la altura total, o HT. Las siguientes variables en importancia, aunque poseen un menor impacto en el modelo de clasificación, son las variables relativas a las pastas estimulantes (ETH o Ethephon, y ASF o ASACIF) y cada una de las localizaciones en donde se obtuvieron los datos (Culleredo, Pantón, Godos, Busfrio y Coca).

7.2.3 Implementación informática

Para la construcción de la aplicación web interactiva se empleó como lenguaje base el lenguaje de programación R, aunque en partes del código se tuvo que recurrir a javascript embebido. El método más empleado para realizar aplicaciones interactivas empleando R es utilizar el paquete de código abierto Shiny. Como se muestra en la Figura 2, las aplicaciones creadas con Shiny se dividen en dos partes, la interfaz de usuario, o UI (del inglés User Interface), y el servidor. La interfaz de usuario es la responsable de crear el aspecto final de la aplicación, es decir, la maquetación y el diseño. Además, gestiona las entradas del usuario a través de diferentes widgets, como botones, controles deslizantes o cuadros de texto. Por su parte, el servidor es el encargado de realizar los cálculos e implementa la lógica de la aplicación, reaccionando al tráfico de datos de entrada para actualizar los resultados mostrados en la interfaz de usuario. El flujo de información entre el usuario y la aplicación se realiza mediante un servidor Shiny, el cual a su vez emplea un servidor web NGINX que sirve de puente entre aplicación y usuario.

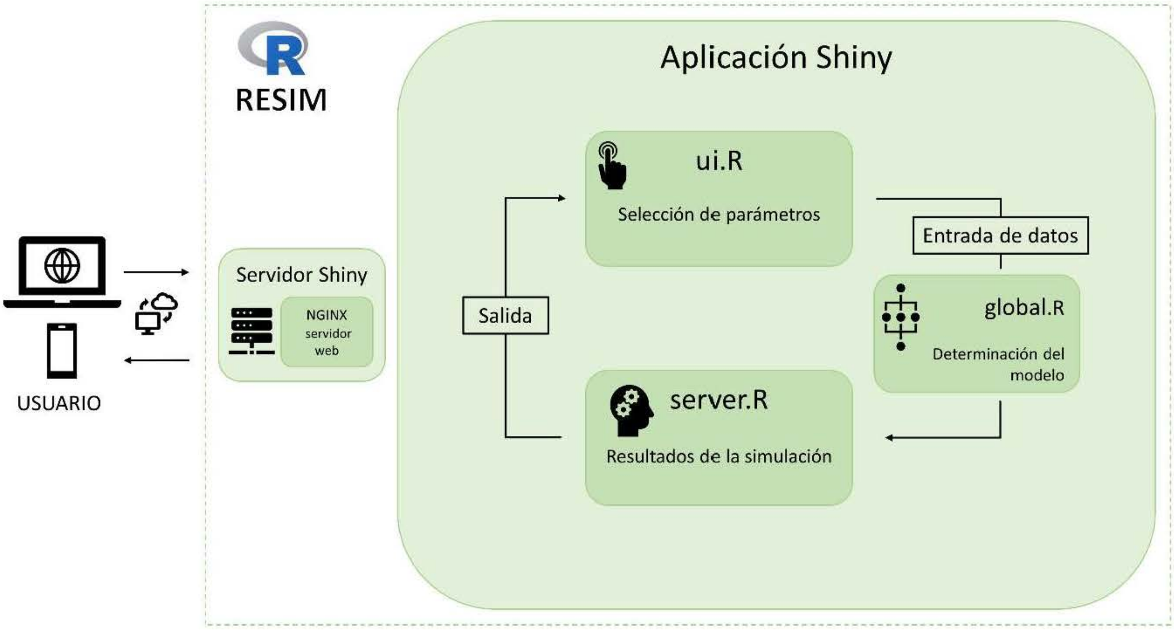


Figura 2. Flujo de la aplicación en la que se detallan la estructura general del módulo de Shiny.

7.3 IMPLEMENTACIÓN

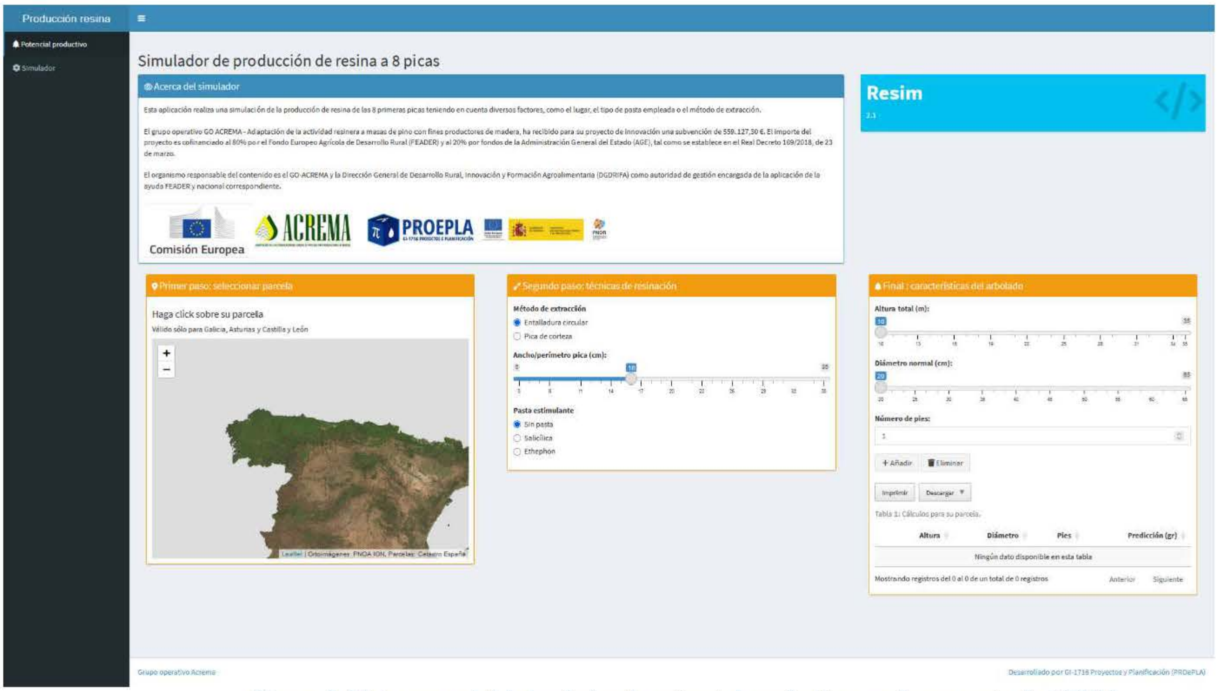
Una vez se ha realizado una breve descripción del esquema general de la aplicación web interactiva en la sección "7.2 Desarrollo", a continuación, se mostrará el funcionamiento de ésta, a la que se puede acceder de forma libre en la dirección web http://resim.proepla.com.

La aplicación consta de dos pantallas, una para cada tipo de modelo que se implementó, cuyos nombres son "Potencial productivo" y "Simulador".

Potencial productivo

En el caso de la pantalla correspondiente al modelo de potencial productivo se llama "Potencial productivo", y está compuesta de cuatro bloques bien diferenciadas (Figura 3):

- Acerca del simulador
- Primer paso: seleccionar parcela
- Segundo paso: técnicas de resinación
- Final: características del arbolado



Simulador de producción de resina a 8 picas

Acerca del simulador

Esta aplicación realiza una simulación de la producción de resina de las 8 primeras picas teniendo en cuenta diversos factores, como el lugar, el tipo de pasta empleada o el método de extracción.

El grupo operativo GO ACREMA - Adaptación de la actividad resinera a masas de pino con fines productores de madera, ha recibido para su proyecto de innovación una subvención de 559.127,30 €. El importe del proyecto es cofinanciado al 80% por el Fondo Europeo Agrícola de Desarrollo Rural (FEADER) y al 20% por fondos de la Administración General del Estado (AGE), tal como se establece en el Real Decreto 169/2018, de 23 de marzo.

El organismo responsable del contenido es el GO ACREMA y la Dirección General de Desarrollo Rural, Innovación y Formación Agroalimentaria (DGDRIFA) como autoridad de gestión encargada de la aplicación de la ayuda FEADER y nacional correspondiente.

Primer paso: seleccionar parcela

Haga click sobre su parcela
Válido sólo para Galicia, Asturias y Castilla y León

Segundo paso: técnicas de resinación

Método de extracción
● Entalladura circular
○ Pica de corteza

Ancho/perímetro pica (cm): 16

Pasta estimulante
● Sin pasta
○ Salicílica
○ Ethephon

Final : características del arbolado

Altura total (m): 10

Diámetro normal (cm): 20

Número de pies: 1

+ Añadir | Eliminar | Imprimir | Descargar

Tabla 1: Cálculos para su parcela.

Altura	Diámetro	Pies	Predicción (gr)
Ningún dato disponible en esta tabla			

Mostrando registros del 0 al 0 de un total de 0 registros — Anterior — Siguiente

Figura 3. Vista general del simulador de potencial productivo que forma parte de RESIM.

Bloque "Acerca del simulador de potencial productivo"

En esta sección se realiza una breve explicación del funcionamiento de la aplicación. También se cita el nombre del proyecto competitivo que sirvió como fuente de financiación para la realización de esta aplicación informática (GO ACREMA - Adaptación de la actividad resinera a masas de pino con fines productores de madera), así como el importe total recibido para la realización del proyecto, el organismo financiador y el grupo de investigación al que pertenecemos los investigadores encargados de la realización de dicho proyecto.

Bloque "Primer paso: seleccionar parcela"

El primer paso consiste en seleccionar la parcela en la cual se quiere predecir la producción potencial de resina. Para ello, integra un visor SIG web (Figura 4) en el que está cargada la ortofoto de máxima actualidad del PNOA (Plan Nacional de Ortofotografía Aérea), así como el parcelario de catastro. Para seleccionar la localización únicamente se debe de pinchar sobre la parcela, y a continuación aparecerán las coordenadas de dicho punto.

Primer paso: seleccionar parcela

Haga click sobre su parcela

Válido sólo para Galicia, Asturias y Castilla y León

Coordenadas: -4.73959254155707 , 41.4702063166465

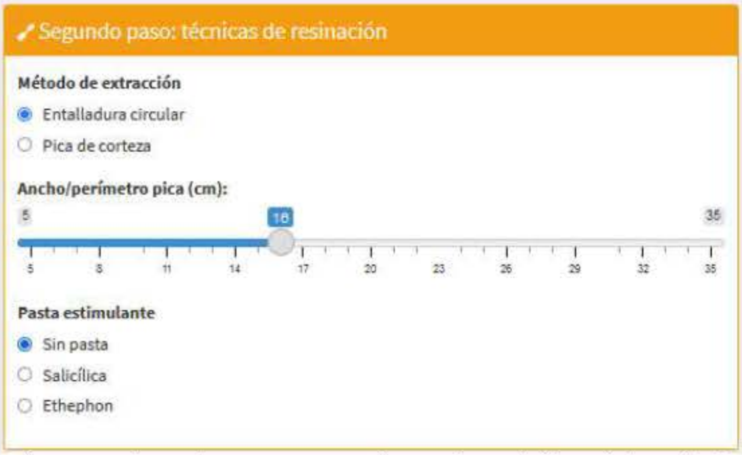
Figura 4. Visor SIG web de la aplicación que permite localizar la parcela e integra la ortofoto de máxima actualidad de PNOA y la cartografía catastral.

Bloque "Segundo paso: técnicas de resinación"

El segundo paso es el correspondiente a la selección de técnicas de resinación. Para ello se ofrecen diferentes combinaciones de métodos de extracción y pastas estimulantes (Figura 5).

Lo primero que permite seleccionar es el método de extracción que se vaya a emplear en el resinado. Ofrece dos opciones, el método de pica de corteza o entalladura tradicional, y el método de entalladura circula o método de entalladura circular mecanizada. En el ***Capítulo 5- Resin yield response to different tapping methods and stimulant pastes in Pinus pinaster Ait.*** de esta tesis se explican las diferencias entre estos dos métodos de extracción. Tras la selección del método de extracción se debe seleccionar el ancho o perímetro de la pica, en función de si se emplea la pica de corteza o la entalladura circular, fijada por defecto a 16 cm, cifra que se empleó en este proyecto como longitud óptima para el noroeste peninsular.

Tras la selección de los parámetros referidos al método de extracción, hay que seleccionar que estimulante químico en forma de pasta se desea utilizar. La aplicación da tres opciones: no aplicar pasta estimulante, aplicar la pasta estimulante con base de ácido salicílico o ASACIF o utilizar una pasta estimulante con base de ácido sulfúrico o Ethephon. La composición y efectividad de ambas pastas se encuentra detallado también en el capítulo 5.



Segundo paso: técnicas de resinación

Método de extracción

● Entalladura circular
○ Pica de corteza

Ancho/perímetro pica (cm): 16

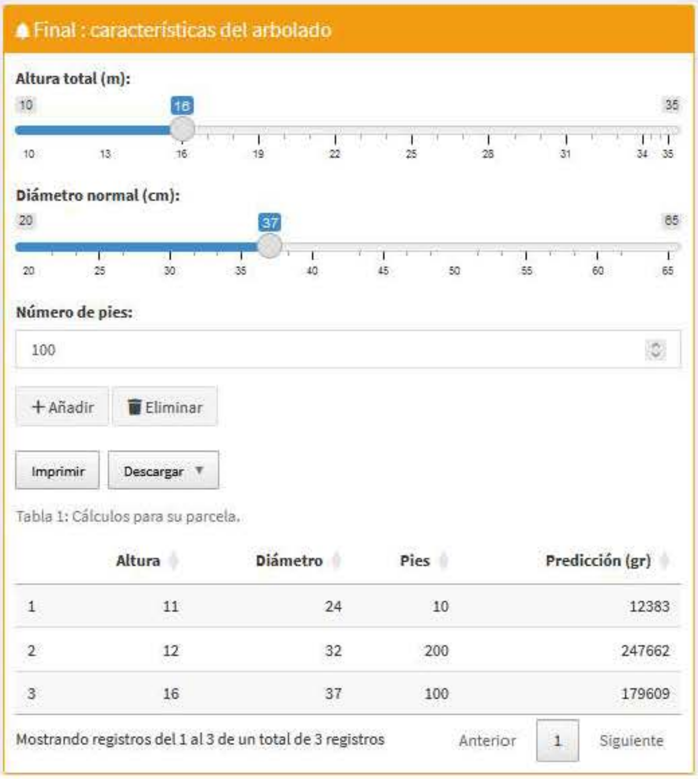
Pasta estimulante

● Sin pasta
○ Salicílica
○ Ethephon

Figura 5. Ventana de captura de parámetros correspondiente a las variables relativas al método de extracción.

Bloque "Final: características del arbolado"

El último paso a seguir para obtener una estimación de la producción de resina es el correspondiente a la caracterización dasométrica de la masa. Para ello se ha habilitado un cuadro en el que se pueden introducir dichas variables (Figura 6). En él se pueden indicar la altura total del árbol, su DBH y el número de pies a los que se refieren dichos valores. Toda la masa puede ser caracterizada mediante este bloque y obtener una predicción para la misma. Estas predicciones se pueden imprimir o exportar en formato PDF, Excel o CSV.



Final : características del arbolado

Altura total (m): 16

Diámetro normal (cm): 37

Número de pies: 100

Tabla 1: Cálculos para su parcela.

	Altura	Diámetro	Pies	Predicción (gr)
1	11	24	10	12383
2	12	32	200	247662
3	16	37	100	179609

Mostrando registros del 1 al 3 de un total de 3 registros

Figura 6. Ventana de captura de los datos dasométricos de la masa.

Simulador

La pestaña correspondiente al modelo desarrollado en el capítulo 6 se denomina "Simulador", y está compuesta, nuevamente, de cuatro bloques bien diferenciados (Figura 7):

- Acerca del simulador
- Elija la técnica de resinación
- Parámetros de cálculo
- Resultado de la predicción

Simulador de producción de resina en un momento dado

Acerca del simulador

Esta aplicación es capaz de estimar la producción que potencialmente obtendrá el usuario (sólo para Galicia) en un momento t después del inicio de la campaña (t0), a partir de los datos de producción medios por árbol individual. Para ello se hacen uso de modelos invariantes en función de la edad desarrollados por los autores de la aplicación tal y como se detalla en el artículo Base-age invariant models for predicting individual tree accumulated annual resin yield using two tapping methods in maritime pine (Pinus pinaster Ait.) forests in north western Spain

El grupo operativo GO ACREMA - Adaptación de la actividad resinera a masas de pino con fines productores de madera, ha recibido para su proyecto de innovación una subvención de 556.127,30 €. El importe del proyecto es cofinanciado al 80% por el Fondo Europeo Agrícola de Desarrollo Rural (FEADER) y al 20% por fondos de la Administración General del Estado (AGE), tal como se establece en el Real Decreto 169/2018, de 23 de marzo.

El organismo responsable del contenido es el GO-ACREMA y la Dirección General de Desarrollo Rural, Innovación y Formación Agroalimentaria (DGDRIFA) como autoridad de gestión encargada de la aplicación de la ayuda FEADER y nacional correspondiente.

Elija la técnica de resinación

Método de extracción
● Entalladura circular
○ Pica de corteza

Parámetros de cálculo

Días desde el comienzo de la campaña (momento actual): 1

Producción en el momento actual (gr): 1

Día para el que se quiere calcular la producción (desde el momento actual): 1

Resultado de la predicción

Se producirían 3 gr

Grupo operativo Acrema

Desarrollado por GI-1716 Proyectos y Planificación (PROePLA)

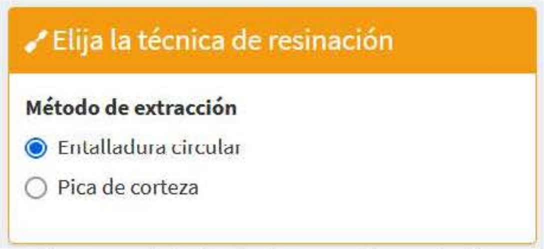
Figura 7. Vista general de la ventana "Simulador" que forma parte de RESIM

Bloque "Acerca del simulador de potencial productivo"

En esta ventana se realiza una breve explicación del funcionamiento de la aplicación, que en el caso de los modelos de esta pestaña fueron desarrollados específicamente para Galicia, así como la referencia al artículo original donde se desarrollan los modelos, el nombre del proyecto y los organismos públicos que financiaron la construcción de dicha aplicación.

Bloque "Elija la técnica de resinación"

Para realizar estimaciones de la cantidad de resina que un propietario puede obtener a final de campaña en función a datos de producción acumulada de árboles de su propia parcela, lo primero que debe de hacer es seleccionar el método que está empleando en el SAD. En la actualidad se encuentran implementados en la aplicación modelos correspondientes a los dos métodos más empleados para la producción de resina en España, el método de pica de corteza y el método de entalladura circular (Figura 8).


Elija la técnica de resinación

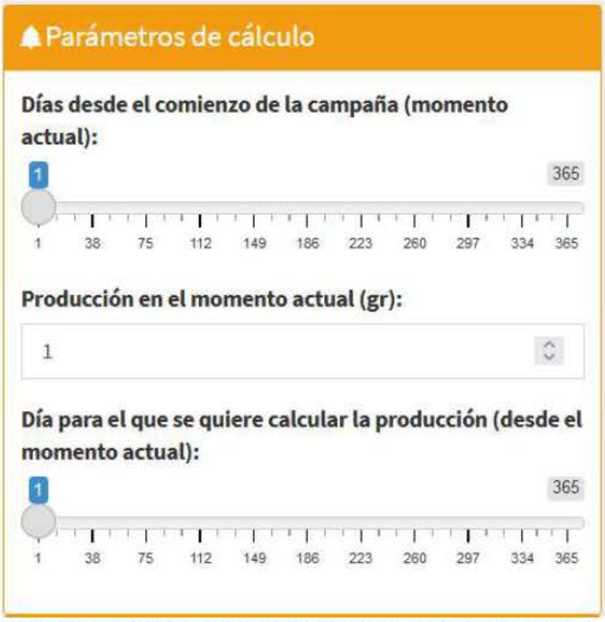
Método de extracción

● Entalladura circular
○ Pica de corteza

Figura 8. Ventana de captura del método de extracción empleado por el usuario.

Bloque "Parámetros de cálculo"

Tras seleccionar el método de extracción, el usuario tiene que introducir los datos actuales de su aprovechamiento resinero (Figura 9). Estos valores se corresponden con el momento de la campaña en el que se encuentra actualmente, medidos en días desde el comienzo, y la producción acumulada hasta ese momento de un pie o la media de los pies de los que está compuesta la masa. Una vez introducidos estos valores ha de indicar en la barra de desplazamiento inferior el número de días para el que quiere realizar la predicción, contados desde el momento actual.


Parámetros de cálculo

Días desde el comienzo de la campaña (momento actual): 1

Producción en el momento actual (gr): 1

Día para el que se quiere calcular la producción (desde el momento actual): 1

Figura 9. Ventana de captura de datos relativos a las producciones actuales y al momento que se quiere predecir.

Resultado de la predicción

Una vez se han realizado los pasos previos, en esta ventana (Figura 10) aparecerá la estimación de la producción en gramos que potencialmente podrá obtener en base a los datos previamente introducidos.


Resultado de la predicción

Se producirían 1544 gr

Figura 10. Ventana en la que aparece la predicción de resina en función a los datos aportados por el usuario.

8 DISCUSIÓN GENERAL

En esta tesis se presenta el proceso metodológico y las técnicas utilizadaspara modelizar la producción de resina de *Pinus pinaster* Ait. en el noroeste de la Península Ibérica, así como desarrollar un SAD que sirva como una herramienta para todos los actores involucrados en el sector de la resina. El proceso de modelización se dividió en tres fases principales correspondientes a cada uno de los capítulos centrales del documento (Capítulos 4, 5 y 6), así como en una cuarta fase (Capítulo 7), en la que se explica el trabajo llevado a cabo para la construcción de la aplicación web interactiva e integración de los modelos de producción potencial, cuya principal función es servir de SAD. Todas estas fases se llevaron a cabo con el fin de alcanzar un objetivo único y siendo totalmente necesarias para lograr el objetivo final de la investigación. En cada uno de estos capítulos se encuentra explicada la metodología que se empleó para lograr las metas propuestas al inicio de la investigación, con el fin accesorio de que sea reproducible en otros territorios nacionales o internacionales que posean un potencial subyacente para la producción de resina.

En el **Capítulo 4 - *Resin tapping: A review of the main factors modulating pine resin yield***, se realizó una revisión del estado del arte relacionada con los factores implicados en la producción de resina. Para ello, se revisaron los artículos científicos publicados hasta el año 2023 que abordaron de alguna manera temas relacionados con la producción de resina, como pueden ser las especies más empleadas a nivel mundial y sus particularidades (producción esperada, composición química de la resina, heredabilidad…), los factores bióticos o abióticos que median en la producción de resina y de qué manera intervienen, o los modelos estadísticos desarrollados capaces de predecir la producción de este PFNM.

Una vez realizada la selección de los artículos de acuerdo con la metodología descrita en los Capítulos 3 y 4, se recopilaron un total de 205 artículos. Tras conformar una base de datos con la información más relevante de cada una de las publicaciones, se procedió al análisis de la secuencia temporal de los trabajos con el fin de examinar su evolución a lo largo de los años. Los resultados derivados de este análisis indicaron que el interés por los factores implicados en la producción de la resina de pino, reflejado en el número de publicaciones anuales relacionadas con el ámbito de estudio, ha experimentado un crecimiento sostenido durante los últimos diez años hasta la actualidad (Figura 2, Capítulo 3). Este dato hay que tratarlo con precaución, ya que en los últimos años la dinámica general en el número de publicaciones de casi cualquier área de investigación es ir en aumento. Es por ello por lo que se debe de poner en contexto, y comparar estos resultados con el incremento experimentado por los artículos publicados en otros temas o áreas de conocimiento. Para esto se calculó la proporción que representan los artículos relacionados con resina de pino frente al total de publicaciones en revistas de impacto internacional con revisión por pares relacionadas con el género *Pinus* en Web of Science. El resultado obtenido fue que la proporción de artículos relacionados con la resina de pino aumentó frente al total de publicaciones relacionadas con las del género *Pinus*. Estos resultados indican que el interés científico por este PFNM sigue una tendencia creciente en los últimos años.

Cuando se analizó la procedencia de los estudios publicados, se relacionaron dichas procedencias con la producción total de resina de cada uno de los países (Figura 3, Capitulo 3). Los resultados demuestran que, salvo excepciones como España y Estados Unidos de América (EE. UU.), tres de los cinco países con el mayor número de publicaciones son también los tres mayores productores mundiales de resina. Estos países se tratan de China, Brasil e Indonesia, los cuales producen el 90% de la resina de pino mundial. El primero de ellos, China, se trata del mayor productor mundial de resina, que obtiene una producción mediade 420000 Mg/año, y aportó al estudio un total de más de 30 publicaciones. Brasil se trata del segundo productor mundial, produce un total de 210000 Mg/año, y contribuyó con un total de 16 publicaciones al documento. El tercer país con mayor producción mundial de resina es Indonesia, el cual produce 90000 Mg/año y aportó un total de 11 publicaciones a la revisión bibliográfica. Después de las tres potencias mundiales en lo que a producción se refiere, se agrupan el resto de los países productores, entre los cuales se encuentra España. Estos países producen alrededor del 10% de la producción mundial, siendo México (25000 Mg/año) y la India (23000 Mg/año) los mayores productores de este grupo. Tras estos dos países aparecen aquellos que producen menos de 10000 Mg/año, entre los que se encuentran los países mediterráneos, España, Portugal, y Francia, o EE. UU. En lo que aporte de publicaciones a la revisión bibliográfica de estos países se refiere, entre ellos se encuentran los dos países que más referencias aportaron, España y EE. UU. España, a pesar de no ser el país con más producción de resina, se trata del país que más literatura científica genera alrededor de esta temática con 43 publicaciones. Por su parte, EE. UU. aporta un total de 35 publicaciones a la lista de referencias del artículo en cuestión. Que estos dos países se encuentren a la cabeza en el número de publicaciones, se puede explicar en el caso de España debido al gran número de proyectos de investigación que se están llevando a cabo en los últimos años con el fin de impulsar el sector. En el caso de EE. UU., las publicaciones se concentran durante el siglo pasado, y están mayormente relacionadas con los ataques tan pronunciados que sufrieron en esa época a causa del escarabajo de la corteza.

Al analizar las especies más utilizadas en los estudios científicos, se observa que las más frecuentes fueron el *Pinus pinaster*, el *Pinus elliottii*, el *Pinus taeda*, el *Pinus massoniana* y el *Pinus merkusii* (Figura 4, Capítulo 3). En esta lista de especies se refleja claramente lo señalado en el párrafo anterior, que las especies originarias de países como España y EE. UU. aparecen junto aquellas empleadas para la extracción de resina en los principales países productores a nivel mundial (*e. g. P. elliottii* (Brasil y China), *P. massoniana* (China) y *Pinus merkusii* (Indonesia)), que en conjunto representan el 82% de la producción mundial de resina (Tabla 1, Capítulo 3). Las producciones que se pueden llegar a obtener de estas especies son muy variables inter-especies e intra-especies. Por ejemplo, el *P. halepensis* fue la especie que se reportó que más producía, llegando a alcanzar una producción de hasta 13.5 kg, pero también obtuvo producciones por debajo del 1 kg anual. Otro ejemplo es el *P.yunnanensis*, cuya producción máxima fue de 12 kg y cuya producción mínima fue de 2 kg por árbol. En el caso de la especie más empleada del mundo, el *P. elliottii,* de la cual se extrae el 48% de la producción mundial, puede llegar a producir entre 3 y 8 kg de resina.

De manera similar a las producciones, la composición química de la resina varía entre las diferentes especies, e incluso entre individuos de la misma especie en función de la localización geográfica de los pies resinados. La composición principal de la resina son monoterpenos (α-pineno, β-pineno, mirceno, etc.) y diterpenos (ácido isopimárico, ácido abiético, ácido neoabiético, etc.), los cuales tiene una proporción que varía en función de la especie. Por ejemplo, en el caso del *P. elliottii* el porcentaje de monoterpenos oscila entre un 43.42 y un 45.32 %, mientras que el de diterpenos entre un 50.41 y un 53 %. Por su parte, los porcentajes de monoterpenos y diterpenos en árboles de la especie *P. pinaster* varía entre 23.01 y 25.68% y 61.36 y 66.85%, respectivamente.

Tras revisar la procedencia de los artículos, las especies más empleadas a nivel mundial, sus producciones, y las características de su resina, se recopilaron los factores que potencialmente más influyen en la producción. Para ello se decidió agrupar los artículos seleccionados en función de la temática que abordan y su relación con la producción de resina. Como resultado, se formaron 6 grupos principales de factores que afectan a la producción: variación genética intraespecífica, factores climáticos, fisiográficos y edáficos, rasgos dasométricos, rasgos anatómicos, incendios y plagas, y factores derivados del método de extracción. Además de los seis bloques temáticos principales, se reportaron un cierto número de trabajos que abordaban la producción de resina desde una perspectiva diferente a la de estas agrupaciones. Un ejemplo de estos trabajos fueron los realizados por Gómez-García et al. (2022) y Nanos et al. (2000), los cuales estudiaron las funciones de distribución entre parcelas de experimentación y cuáles son las que mejor se ajustan a la producción de resina. Otro posible enfoque de la caracterización de la producción de resina fue el que siguieron Nanos et al. (2001), los cuales emplearon la geoestadística para modelizar la producción de resina.

El primero de los bloques temáticos de la revisión se dedicó a la variación genética de los individuos resinados. En este bloque se abordan los resultados de las investigaciones incluidas en la revisión bibliográfica sobre la genética detrás de la producción de resina que existen entre las diferentes especies y poblaciones de pinos. Este bloque fue uno de los que más importancia tuvo, ya que todo apunta a que la producción de resina es un rasgo fuertemente ligado con la herencia genética del individuo o la población. Una de las conclusiones que se puede obtener de los artículos consultados, es que, entre individuos de la misma especie, pero que proceden de diferentes poblaciones, o de diferentes especies existe una variación en la producción de resina que mayormente es heredada, ya que este rasgo posee una heredabilidad de moderada a alta. Pudiendo ser estas variaciones debidas a las diferentes condiciones ambientales a las que se fueron sometidas durante cientos de años las plantas en las diferentes localizaciones dentro de su gradiente ambiental (Tabla3, Capitulo 3). Este apartado de la revisión sugiere que existe un gran potencial para realizar una selección genética y obtener material de reproducción mejorado para la producción de resina, generando así una de las posibles vías para mejorar el sector.

El segundo de los bloques de los que se compone la revisión bibliográfica es el dedicado a cómo afectan los factores climáticos, fisiográficos y edáficos a la producción de resina. En relación con este grupo de factores, se puede afirmar que los que mayor influencian tienen sobre la producción de resina, ya que obtuvieron mayores valores de las correlaciones en los distintos artículos (Tabla 4, Capitulo 3), son la temperatura y aquellas variables relacionadas con el contenido de humedad, observándose en ciertos estudios que las producciones aumentan bajo un déficit hídrico moderado. Por otra parte, las variables fisiográficas relacionadas con la producción de resina fueron la altitud, que obtuvo resultados contradictorios, y la pendiente, la cual influyó positivamente. Se debe de señalar que el número de artículos relacionados con los factores fisiográficos es mucho menor que los relacionados con las variables climáticas. Por último, en el caso de las variables edáficas, la hipótesis inicial de los estudios consultados era que suelos con mayor contenido de nutrientes debían de afectar positivamente a la producción de resina, ya que se trata de un proceso en el que el árbol debe de movilizar una gran cantidad de recursos para su producción. Pero los resultados de los estudios analizados fueron en gran medida inconclusos, ya que se obtuvieron resultados contradictorios sobre cómo afectan a dicha producción.

En el tercer bloque se sintetizó la información de los artículos que relacionan la producción de resina con variables dendrométricas. Una vez finalizada la revisión se podría decir que los factores dasométricos que más influencian la producción de resina son el diámetro a la altura del pecho (DBH) y la altura total (HT) del árbol (Tabla 5, Capítulo 3). Otros trabajos también encontraron relaciones estadísticamente significativas entre el ratio de copa, el índice de competencia o el incremento del área basal y la producción de resina. A diferencia de las variables de los bloques anteriores, con las de este grupo los autores fueron un paso más allá e intentaron obtener modelos capaces de predecir la producción de resina en base a ellas. En el caso de las regresiones lineales simples, el DBH fue la variable más empleada, aunque también se empleó la HT, el área basal, el incremento del área basa o el espesor de la corteza (Tabla 6, Capítulo 3). De entre las variables anteriores, la que obtuvo unos mejores resultados fue el incremento del área basal, con un r^2 de 0.84, seguido del DBH, que obtuvo un r^2 con 0.46.

Además de los modelos anteriormente mencionados, ciertos autores ajustaron regresiones lineales múltiples empleando de manera conjunta variables dasométricas y ambientales como variables predictoras. Entre estos modelos, el que obtuvo un mejor resultado fue el estudio llevado a cabo por Wang et al. (2006), que logró un r^2 de 0.91 empleando la temperatura, la precipitación y el DBH como variables independientes del modelo de producción para *P. kesiya*. En el caso del *P. pinaster*, especie que, como se dijo anteriormente, es empleada para la producción de resina en España, Portugal y Francia, Zas et al. (2020) obtuvieron un r^2 de 0.45 empleando la edad y la esbeltez del árbol como variables predictoras del modelo.

El cuarto bloque se centra en la influencia de los factores anatómicos en la obtención de resina. Estos elementos están estrechamente vinculados con la producción de este PFNM, ya que los canales resiníferos son las estructuras encargadas de transportar la resina a través del interior del árbol. Además, la formación de estas estructuras en torno a la entalladura constituye una de las respuestas del árbol ante el traumatismo que se le inflige para posibilitar la recolección de resina. Por lo tanto, se pueden distinguir dos tipos de canales resiníferos, aquellos generados de manera natural por el árbol, y los inducidos como resultado de traumatismos, tales como la entalladura empleada en el proceso de resinado. Los resultados de las correlaciones y de las regresiones lineales entre diferentes medidas relacionadas con los canales resiníferos (frecuencia, diámetro, volumen…) y la producción de resina están comprendidos tienen una variabilidad muy elevada. Por ejemplo, para la especie *P. pinaster* en el ensayo llevado a cabo por Garcia-Forner et al. (2021) en Portugal (Tabla 7, Capítulo 3) se obtuvieron valores en el rango 0.03 a 0.70, dependiendo de la localización y de la estructura anatómica a medir. Además de los canales resiníferos en sí, existen otras características relacionadas con estos factores anatómicos que afectan a la producción de resina, como pueden ser la viscosidad o la presión de la resina en el interior de los canales. El contenido del cuarto bloque está estrechamente relacionado con el quinto bloque, ya que el efecto de los incendios forestales y de las plagas hacen que aumente el flujo de resina, en el caso de los incendios forestales, o en la generación de nuevos canales resiníferos, en el caso de las plagas.

Por último, en el sexto bloque se trataron los diferentes aspectos relacionados con las metodologías de extracción de resina, las cuales son unas de los principales factores moduladores de la producción. De manera general, para poder extraer la resina, se debe de retirar la corteza y el cambium del árbol dejando expuesta la madera. Esto hace que se genere un traumatismo que activa los mecanismos de defensa del árbol y le hace reaccionar frente a esta agresión comenzando a producir resina para de esta manera sellar la herida, y así impedir que agentes externos puedan dañarlo. Para que el proceso de sellado natural del árbol no cauterice la herida y haga que deje de expulsar resina, en muchos de los métodos se aplica un estimulante químico con base a diferentes ácidos que alarga este proceso, permitiendo recolectar mayores cantidades de resina. A nivel mundial existen diferentes métodos de extracción, si nos ceñimos a los que emplean estimulantes químicos, el más empleado es el sistema americano o "bark streak", que es ampliamente usado en países de Sudamérica, y su variante llamada "pica de corteza", que se emplea en la Península Ibérica y Francia. Por otro lado, está el método "chino", el cual se emplea principalmente en China y no utiliza ningún tipo de estimulante químico. Como una evolución den los métodos tradicionales, en los últimos años han comenzado a aparecer nuevas alternativas a los métodos clásicos de resinado, los cuales incluyen el uso de taladros u otros dispositivos con el fin de mecanizar una actividad que mayoritariamente se hace de forma manual, como pueden ser el método "Borehole" o el "Eurogem". Además, estos dos métodos tienen la particularidad que recogen la resina en envases cerrados, evitando de esta manera que puedan entrar impurezas a la resina, cosa que sí que ocurre en el caso de los sistemas tradiciones de envase abierto.

Una vez revisado el estado del arte sobre los factores moduladores de la producción de resina, así como las variables más empleadas en la literatura científica para modelizar la producción de este PFNM, se llevó a cabo un estudio que tuvo en cuenta la variabilidad de estos factores con el fin de poder caracterizar la producción de resina en el noroeste de la Península Ibérica. El resultado está contenido en el **Capítulo 5 -** ***Resin yield response to different tapping methods and stimulant pastes in Pinus pinaster Ait.*** En este estudio, se evaluó el efecto que tienen en la producción de resina de árboles individuales dos métodos de extracción y dos tratamientos estimulantes diferentes en masas de *P. pinaster*, situadas en el noroeste y el centro de la Península Ibérica.

En este estudio se obtuvieron por primera vez resultados concluyentes sobre el grado de influencia que posee sobre el potencial productivo de resina la combinación de emplear los dos métodos más usados hoy en día en la producción de resina en España, el método de "pica de corteza" y de entalladura circular, junto con las dos pastas estimulantes seleccionadas para este estudio, Ethephon y ASACIF. Caracterizar las producciones de estos dos métodos es fundamental para poder optimizar los protocolos de resinado en el noroeste de España y adaptarlos a las particularidades de la zona, una de esas adaptaciones es el método de entalladura circular, el cual se diseñó *ad hoc* para esta región, ya que se trata de una región en la que las precipitaciones anuales son más altas y las temperaturas medias anuales más bajas que las del centro de España. Para posibilitar la comparación entre las producciones obtenidas mediante cada una de las metodologías, al tratarse de dos métodos diferentes, se propuso una unidad de medida para la producción, nombrada producción de resina estándar (SRY). Esta nueva unidad de medida pondera la producción de resina producida por cada árbol en función del método, en el caso de la entalladura tradicional depende de la longitud de la pica, y en el caso de la entalladura circular depende del perímetro cortado por la corona empleada para realizar la perforación.

Con motivo de comprobar si existían diferencias estadísticamente significativas entre la SRY de cada uno de los métodos de extracción se realizó el test no paramétrico de Mann-Whitney (Figura 3, Capítulo 5), que obtuvo un *p-valor* menor a 0.05, umbral empleado en la prueba como valor de significación, indicando que sí existieron diferencias estadísticamente significativas entre las producciones de estos dos métodos. Cuando se evaluó el tamaño del efecto mediante el coeficiente de correlación biserial de rango de Glass, se obtuvo que este tamaño se podía considerar como medio según Vargha y Delaney (2000). Los resultados obtenidos se alinean con los de Pinillos et al. (2009), que reportaron como, de media, el sistema de pica tradicional producía un kilo más de resina por árbol que el método "Eurogem". El cual se trata de un método de entalladura circular patentado en Francia que sigue una lógica similar al método de entalladura circular empleado en este estudio.

En el análisis comparativo de la SRY en función de los estimulantes químicos, las producciones obtenidas en este estudio demostraron que el uso de pasta estimulante es totalmente necesario para la actividad resinera, ya que aumentó entre 4.12 y 6.26 veces la producción de los árboles estimulados frente a la obtenida por los árboles de control, dependiendo del método empleado. Los aumentos productivos alcanzados en este artículo fueron superiores a los reportados por Neis et al. (2018), que obtuvieron un aumento de 2.15

veces la producción de los árboles de control en un estudio llevado a cabo en Brasil empleando *P.*elliottii. En el caso de los resultados obtenidos por Liu et al. (2022), los aumentos en la producción también fueron menores, ya que obtuvieron un incremento de la producción de 2.14 veces la producción de control en un estudio localizado en China en *P. elliottii x P. caribaea*. Que el porcentaje de resina respecto al de los árboles de control sea mayor que en los artículos antes mencionados, puede ser explicado por los siguientes supuestos: la Hipótesis de la Disponibilidad de Recursos (HDR) (Endara & Coley, 2011); que los árboles empleados en este estudio tienen como objetivo principal el maderero. La relación entre la HDR y que los árboles empleados tengan como destino principal el maderero es que, según esta hipótesis, los pies con crecimientos más elevados, como es el caso de la mayoría de los pertenecientes a este estudio, producen una menor cantidad de resina constitutiva que aquellos que poseen crecimientos más lentos, pero son capaces de generar una mayor cantidad de resina cuando existe algún agente que los induce a ello (Zas et al., 2020). Esto es una posible explicación de por qué se incrementó más en proporción la producción de resina en este estudio que en otros de similares características.

Al comparar las producciones obtenidas mediante los distintos métodos de extracción en las diversas localizaciones del estudio (Figura 5, Capítulo 5), se observa que en la entalladura tradicional se presenta un fenómeno que no se da en la entalladura circular: la parcela situada en Coca muestra un comportamiento distinto al de las demás parcelas. En el caso en que no se aplicó tratamiento estimulante, esta parcela registró diferencias estadísticamente significativas con respecto a las cuatro parcelas restantes. En cuanto a la aplicación de la pasta estimulante Ethephon, la parcela de Coca presentó diferencias estadísticamente significativas con todas las parcelas, excepto con la situada en Godos. Finalmente, cuando se aplicó la pasta estimulante ASACIF, la parcela de Coca mostró nuevamente diferencias con la parcela ubicada en Godos. Este fenómeno puede ser explicado nuevamente con la HDR, ya que Coca se encuentra en una región en donde la disponibilidad de recursos, así como las condiciones climatológicas son más exigentes para los árboles, ya que deben soportar mayores temperaturas y las precipitaciones anuales son menores, incrementando por lo tanto el déficit hídrico en los meses centrales del año, haciendo que tengan crecimientos menores y, por lo tanto, generando una mayor cantidad de resina constitutiva. Además, al estar Coca situada en la zona donde históricamente se practicó la resinación en España, la selección genética de árboles para la producción de resina mediante la selvicultura aplicada pudo intervenir en que se obtuviesen mayores rendimientos en control en esta parcela, ya que este rasgo tiene una heredabilidad media-alta. Este fenómeno se diluye una vez se aplican las pastas estimulantes, pudiendo estar relacionado a lo comentado en el párrafo anterior sobre la HDR. En el caso de la entalladura circular hubo un comportamiento prácticamente uniforme independientemente de la localización geográfica. Esto hace indicar que el método de entalladura circular hace que la producción de resina sea más homogénea entre las diferentes localizaciones, aunque en términos de producción esta sea menor. Esto puede ser debido a la especialización de los resineros, ya que se trata de un método reciente aparición y en el que los operarios que realizaron los trabajos tenían todos el mismo grado de especialización, a diferencia de con el método de "pica de corteza", en el cual el resinero de la parte central de España poseía mucha más experiencia.

La eficacia de las pastas estimulantes varió en función del método de extracción empleado (Figura 4, Capítulo 5), ya que, aunque en ambos métodos el test de Welch mostró que existían diferencias estadísticamente significativas entre los dos grupos de producciones, en el método de pica de corteza la pasta que más produjo de media fue Ethephon, mientras que en el método de entalladura tradicional fue la pasta ASACIF la que obtuvo la mayor producción. Este fenómeno podría explicarse por la respuesta más favorable de la pasta ASACIF cuando se aplica en un ambiente cerrado, como el del dispositivo instalado en el árbol, que también es el lugar donde se coloca la bolsa destinada a recoger la resina en el sistema de entalladura circular. Cuando se estudió el patrón que siguen las series temporales de las producciones en función de las pastas estimulantes (Figura 5, Capítulo 5), se puede observar como las parcelas de control siguen tendencias muy similares a otros trabajos realizados en la misma especie (Zas et al., 2020a; Touza et al., 2021), obteniendo su máximo productivo en torno a los 100 días posteriores al comienzo del resinado. De manera general, se puede observar cómo existe una bajada en la producción alrededor de la quinta pica, la cual coincidió con la máxima temperatura media registrada en cada una de las localizaciones (Figura S1, Anexo II). Por último, se detectó que el comportamiento que tuvo la pasta ASACIF al final de la campaña no fue el habitual y esperado, ya que las producciones suelen decrecer hacia el final de temporada coincidiendo con la bajada de las temperaturas (Hood y Sala, 2015; Neis et al., 2018; Rodrigues-Corrêa y Fett-Neto, 2013), aunque en este caso la trayectoria de la producción tendió a incrementarse hacia el final de la campaña.

Por último, se pudo observar como la producción de resina en los árboles de control pareció que mostraba correlaciones estadísticamente significativas con árboles menos esbeltos, aunque éstas fueron bajas. Estos resultados están alineados con los resultados obtenidos por Zas et al. (2020a), los cuales establecieron que para la producción de resina el tamaño del árbol no contribuye significativamente, y que su esbeltez contribuye negativamente a la producción. Esto es coherente ya que, los árboles más esbeltos se relacionan con masas más densas, en las que la competición por los recursos es mayor, y pueden destinar menor número de recursos a la defensa (Hood y Sala, 2015; Miina et al., 2020).

La siguiente fase de esta investigación se basó en modelizar cómo evoluciona la producción de resina a lo largo de la campaña de resinado. El desarrollo de esta parte de la tesis se encuentra en el **Capítulo 6 - *Base-age invariant models for predicting individual tree accumulated annual resin yield using two tapping methods in maritime pine (Pinus pinaster Ait.) forests in north-western Spain***. En este capítulo se demostró por primera vez que es posible emplear la metodología de modelos invariantes con la edad para modelizar el comportamiento que muestra la producción acumulada de resina a lo largo de la campaña. Además, se trata del primer trabajo científico que, aun existiendo una gran variabilidad entre árboles individuales en el rendimiento de este PFNM, establece que la producción acumulada de resina se comporta de manera similar a otros procesos biológicos, y se puede predecir empleando las metodologías de enfoque de diferencias algebraicas (ADA) y de diferencias algebraicas generalizadas (GADA).

De entre los modelos base empleados para modelizar la producción de resina acumulada, aquellos que tuvieron un mejor desempeño, independientemente del método de extracción, fueron los basados en la ecuación de Bertalanffy-Richards. El rendimiento del modelo ajustado para el método de pica de corteza mostró resultados superiores en términos de estadísticos de bondad del ajuste que el modelo ajustado para la metodología de entalladura circular. Esto se puede deber a que el método tradicional de pica de corteza posee un pico de producción más pronunciado que el método de entalladura circular entorno al momento central de la campaña, esto hace que si se representa la producción acumulada de resina a lo largo de la campaña tenga una forma sigmoidea y un punto de inflexión más pronunciado que el caso del método de entalladura circular. Las predicciones realizadas con los modelos desarrollados están en promedio por debajo del 30%. En el caso del método tradicional el porcentaje de acierto medio es de 76.81% y en el caso de la entalladura circular mecanizada es de 70.76%. Los resultados obtenidos por los modelos ajustados en este estudio son similares a los alcanzados por otros trabajos en los que modelizan el crecimiento de especies de turnos largos, como el roble pedunculado (Gómez-García et al., 2015), y ligeramente más discretos que los obtenidos en especies de crecimiento rápido (Diéguez-Aranda et al., 2005, Seki & Sakici, 2017) o el crecimiento en espesor del corcho (Sánchez-González et al., 2008). Si se evalúa la precisión de los modelos en función del número de días que es capaz de predecir con antelación la producción, se puede observar como para un periodo de 85 días, el cual es el tiempo que se puede considerar la mitad de la campaña, el error medio de los modelos es del 35%. Que no alcancen los valores de los estadísticos de bondad del ajuste de los modelos desarrollados para otras producciones forestales, puede ser debido a la gran variabilidad productiva que poseen los pies individuales de pino resinero, o a un efecto derivado de la necesidad de aumentar el tamaño de la muestra de este estudio preliminar.

Este trabajo se trata de un estudio pionero en el que se demuestra que es posible modelar la tendencia que sigue la producción de resina acumulada a lo largo de la campaña, pudiendo incluir este PFNM entre aquellos procesos que es posible modelizarlos mediante la ecuación de Bertalanffy-Richards. Más allá de los buenos resultados obtenidos, para hacer estos modelos herramientas realmente útiles para los gestores forestales que producen resina, así como para los resineros, la industria transformadora o para la propia comunidad científica, es necesario profundizar más en ellos, y realizar un muestreo más amplio en el que estén representados a una mayor escala todos los factores que *a priori* influyen en la producción de resina y que se comentaron en los capítulos 4 y 5 de esta tesis. Además, este tipo de modelos tienen el potencial se servir como una herramienta a investigadores para obtener las producciones intermedias o imputar datos perdidos, ya que el coste de obtener este tipo de datos es muy elevado (Calama et al., 2011). Por último, estos modelos también se presentan como una herramienta extremadamente útil en la gestión multifuncional de los montes, ya que son capaces de generar una estimación de la producción que potencialmente pueden alcanzar los productores forestales, permitiéndoles así poder estimar los ingresos que podrían llegar a ingresar por la venta de la resina y optimizar cada la duración de esta.

Finalmente, en el **Capítulo 7 - *RESIM: Simulador de la producción de resina en proyectos de nueva implantación***, capítulo no perteneciente al compendio de artículos, se desarrolló una aplicación web interactiva capaz de generar una estimación de la producción de resina que el usuario potencialmente podrá obtener de parcelas situada en el noroeste de la Península Ibérica. Esta aplicación se trata de la primera aplicación capaz de estimar la producción de resina basada dos metodologías diferentes, una que integra un proceso bietápico que integra diferentes modelos de machine learning, y otra que emplea los modelos desarrollados en el capítulo 6. El desarrollo de esta aplicación se enmarcó en el proyecto "GO Acrema - Adaptación de la actividad resinera a masas de pino con fines productores de madera", el cual se trató de un proyecto interautonómico en el que se buscó optimizar la producción de resina en pinares cuyo principal objetivo es el maderero, compatibilizando ambas producciones y valorizando la madera de estas masas para su uso como madera de calidad.

Como se comentó anteriormente, uno de los modelos de los que se compone la aplicación se basa en un proceso de dos etapas. En la primera de ellas, a cada dato se le asigna la pertenencia a un clúster empleando el modelo de clasificación que se ha desarrollado. Este modelo emplea el algoritmo XGBoost en base a la localización, los métodos de extracción y la caracterización dasométrica aportada por el usuario. En la segunda de las etapas se calcula una estimación de la producción potencial de resina para la localización seleccionada por el usuario. Para ello se emplean diferentes modelos ajustados específicamente para cada uno de los clústeres en los que se ha clasificado los datos en el paso número uno. Los modelos de esta segunda etapa emplean las mismas variables que el modelo de asignación de clúster. Tanto la metodología empleada para construir el modelo de asignación, como la que se ha usado en la construcción de los modelos de predicción, se trata de la primera vez que se usan para modelizar la producción de resina, no habiendo trabajos previos que relacionen a este PFNM con técnicas de machine learning o aprendizaje automático.

Las técnicas de modelización en dos etapas, aunque no son empleadas en la predicción de la producción de resina, si son más comunes en la modelización de otros fenómenos naturales complejos. Normalmente, este tipo de metodologías son empleadas junto con técnicas de machine learning para la construcción de modelos funcionales. Un ejemplo del uso de estas técnicas en la modelización de otros fenómenos puede ser el descrito por Garroussi et al. (2022). En este trabajo los autores utilizan un proceso bietápico en el que en la etapa de clusterización emplean el método de k-means y un Modelo Mixto Gaussiano para agrupar los datos, para posteriormente modelizar las crecidas del rio Garona. Otro ejemplo del empleo de un proceso de modelización en dos pasos en el que primero se agrupan los datos, y después se modeliza, solo que aplicado a otro fenómeno natural puede ser el desarrollado en Aono et al. (2022). En este trabajo los autores utilizaron la metodología de "divide y vencerás" para predecir el genoma de árboles del caucho empleando una clusterización jerárquica completa basada en distancias euclídeas y machine learning. Es por esto por lo que la metodología empleada para ajustar los modelos que se emplean en las predicciones que realiza la aplicación interactiva RESIM se trata de un conjunto de técnicas que están en la vanguardia de la modelización de fenómenos naturales.

La integración de los modelos desarrollados en el capítulo 6 en la aplicación informática, permite a los usuarios realizar predicciones de la cantidad de resina que potencialmente podrán obtener a partir de sus propios datos de producción acumulada una vez comenzada la campaña. Para realizar estas estimaciones, los usuarios deben de escoger el método de resinado que estén empleando en su explotación, pica de corteza o entalladura circular mecanizada. En función de la metodología de extracción que hayan seleccionado, la aplicación empleará el modelo que mejores resultados obtuvo en el capítulo 6 para cada uno de los métodos, y realizará las estimaciones en función de los datos que el usuario le suministre.

Actualmente, esta herramienta es la única aplicación web interactiva que permite obtener estimaciones de la producción de resina que potencialmente se podrá obtener de montes del noroeste peninsular, aunque existen otras herramientas web que sirven como un apoyo a los productores forestales e industrias que pretendan obtener beneficios asociados con este PFNM. Uno de estos ejemplos es el desarrollado por el grupo operativo "GO-RESINLAB, Red de Territorios para el impulso de la actividad resinera", el cual creó una red de territorios interesados en crear valor entorno a la resina en las provincias de Extremadura, Castilla La Mancha y Castilla y León. Desde este grupo operativo implementaron dos herramientas web gratuitas relacionadas con la actividad resinera para estos tres territorios. La primera de ellas es la "Herramienta de toma de decisiones", esta herramienta funciona como un compendio de información técnica y herramientas útiles para los tres principales agentes implicados en la producción de la resina: el gestor propietario, el resinero y la industria. Otra de las herramientas desarrolladas por este grupo operativo son las "Calculadoras de rentabilidad". Estas herramientas permiten tanto al resinero como al propietario forestal calcular la rentabilidad de sus explotaciones en función de los datos que estos poseen de acuerdo con su experiencia. Por último, está la aplicación ResinApp, desarrollada por el proyecto SustForest Plus, un proyecto transnacional cofinanciado por el Programa Interrreg Sudoe a través del Fondo Europeo de Desarrollo Regional (FEDER). Esta aplicación se trata de un sistema de trazabilidad de la resina que permite verificar la procedencia de este producto, así como otras funcionales como la gestión empresarial o la promoción comercial de los productos.

Todas estas herramientas están desarrolladas para hacer crecer el sector, fomentar esta actividad en zonas rurales en riesgo de despoblamiento o muy envejecidas, y la generación de empleos ligados a estas zonas. El conjunto de estas aplicaciones abarca diferentes puntos del ciclo de vida de la producción de resina, que incluye desde la selección de un lugar óptimo para la extracción de resina, así como la formación y apoyo al resinero, al gestor forestal y al propietario. En este sentido, RESIM es la única aplicación de entre las nombradas anteriormente que es capaz de proporcionar una estimación numérica de la producción de resina que sirva de apoyo a todos los agentes implicados anteriormente nombrados.

9 CONCLUSIONES

Generales

A continuación, se destacan los avances que este trabajo introduce, por primera vez, en el ámbito científico de la investigación sobre la producción de resina:

1. En el trabajo de revisión bibliográfica se recopiló un enfoque integral sobre la producción de resina, abarcando aspectos tales como: las principales especies productoras, la variación genética, y los factores climáticos, fisiográficos, edáficos, dendrométricos y anatómicos que influyen en su producción. Además, se analizó el impacto de los incendios y las plagas, así como los métodos empleados en la extracción de resina.

2. Se llevó a cabo una caracterización del efecto del método de entalladura circular mecanizada, en combinación con el uso de dos pastas estimulantes, comparada con el método tradicional de pica de corteza, en la producción de resina.

3. Se modelizó la producción acumulada de resina a lo largo de una campaña de resinado empleando la ecuación de Bertalanffy-Richards y la metodología de los modelos invariantes con la edad.

4. Se creó un modelo capaz de predecir la producción potencial de resina empleando una metodología bietápica basada en técnicas de machine learning.

5. Se creó el primer sistema de apoyo a la decisión diseñado para proporcionar estimaciones de la producción que potencialmente el usuario podrá obtener, basándose en los modelos desarrollados en el transcurso del trabajo.

Conclusiones de la Metodología

6. El proceso empleado para determinar el potencial productivo de la especie *Pinus pinaster* en relación con la producción de resina, y su posterior integración en un sistema de apoyo a la decisión, posibilita la identificación de los factores clave que inciden de manera más significativa en este proceso. Este enfoque permite, asimismo, caracterizar dichos factores y desarrollar modelos robustos que faciliten su utilización como herramienta funcional para la estimación de la producción de este PFNM.

7. La principal ventaja de la metodología empleada en este estudio radica en su facilidad de aplicación y replicabilidad en otros territorios en los que se empleen, otras especies, otros métodos de extracción y/o otras pastas estimulantes. Adicionalmente, se caracteriza por su alta capacidad de adaptación a las particularidades de cada región.

8. Una de las principales limitaciones de esta metodología radica en el coste asociado a la obtención de los datos de campo, dado que se trata de un proceso costoso y prolongado en el tiempo. Esto se debe a que es necesario realizar visitas periódicas a cada parcela por persona experimentado durante el periodo definido como campaña, con el fin de efectuar una nueva entalladura y pesar la producción acumulada. Este enfoque dificulta la creación de una red de parcelas permanentes más amplia que permita monitorizar la evolución de la producción de resina tanto a lo largo de la campaña como en los años posteriores.

Conclusiones de los Resultados

9. Tras llevar a cabo el análisis bibliográfico, se observó un notable aumento en el interés hacia la producción de resina en los últimos años. Asimismo, se identificaron como factores determinantes en dicho proceso los factores ambientales y los fenotípicos, así como la influencia de los métodos y las pastas estimulantes.

10. Como resultado de la revisión, también se evidenció una carencia en la cantidad de modelos desarrollados para este aprovechamiento forestal no maderero, así como una insuficiencia de recursos que faciliten el trabajo de las personas interesadas en producir resina. Fruto de estos resultados determinaron los objetivos específicos de este trabajo.

11. Derivada de la revisión bibliográfica, se detectó una inconsistencia en las unidades de medida de la producción que imposibilita comparar las cantidades obtenidas por diferentes métodos. Por ello se propuso el empleo de la unidad de medida de la producción estandarizada, la cual facilitó la comparación entre los dos métodos de resinado.

12. En términos generales, se puede concluir que el método de pica de corteza produce cantidades de resina superiores que el método de entalladura circular mecanizada. Lo cual demuestra que, el método tradicional es más eficiente en la producción de resina, mientras que el método circular es más eficiente en términos de coste, donde la mano de obra es el factor limitante.

13. La pasta estimulante Ethephon generó mayores cantidades de resina en comparación con la pasta ASACIF, aunque las diferencias observadas no fueron estadísticamente significativas. Esto demuestra que la proporción de ácido sulfúrico determina en gran medida la capacidad de obtención de resina de las pastas estimulantes, pero a su vez está condicionada desde el punto de vista medioambiental.

14. Se concluyó que las variables dasométricas por sí solas no son suficientes para explicar la producción de resina. Sin embargo, los árboles con mayor diámetro en relación con su altura mostraron correlaciones leves con la producción. Este resultado es especialmente interesante para regiones como Galicia, que regulan el comienzo del resinado y lo retrasan hasta los últimos años del turno, donde los pinos resinados pueden tener dimensiones y volúmenes elevados.

15. La localización de las parcelas ejerció una influencia leve en las producciones obtenidas, aunque las diferencias observadas no fueron estadísticamente significativas. Esto

contradice la creencia popular de que hay zonas más productoras que otras, ya que una vez se aplica pasta estimulante estas diferencias se minimizan.

16. En la modelización de la producción acumulada durante la campaña la ecuación de Bertalanffy-Richards fue la que arrojó mejores resultados de entre todos los modelos probados. Una vez más esta ecuación, que es empleada en un amplio espectro de ámbitos, demostró una vez más su prevalencia.

17. La ecuación ajustada para el método de pica de corteza obtuvo mejores resultados que el modelo para el método de entalladura circular mecanizada modelizando la producción acumulada. Esto es debido a como se distribuye la producción de cada uno de los métodos a lo largo de la serie temporal.

18. El desarrollo de una aplicación que integre los modelos elaborados, así como que permita a los usuarios emplearlos, facilita la transferencia del conocimiento generado a distintos públicos. Estas herramientas son esenciales para la transferencia de los avances científicos al conocimiento técnico, y de esta manera generar valor económico al sector.

Líneas de Futuro

Este trabajo, en cierta medida pionero, es de esperar que sirva para dar continuidad al desarrollo del sector resinero. En este sentido, se considera que estos deben ser los ejes principales que deben impulsar los futuros trabajos.

1. Es necesario crear una red de parcelas de experimentación más amplia que permita realizar un seguimiento de un mayor número de poblaciones a lo largo de un período de tiempo más extenso, con el fin de evaluar de manera más exhaustiva todos los factores que influyen en la producción de resina.

2. Resulta fundamental crear modelos técnico-económicos que integren las actividades realizadas por los resineros con el fin de poder optimizar las labores que realizan y ajustar la duración de la campaña para conseguir un máximo de rentabilidad. Consideramos que en un futuro la variable a optimizar será el coste por kilogramo de resina extraído.

3. Resulta crucial llevar a cabo una adecuada difusión de los beneficios asociados a la actividad resinera y desmentir los mitos infundados que la rodean.

CONCLUSIONS

General

The scientific advancements that this work introduces for the first time in the scientific field of resin production research:

1. In the literature review, a comprehensive approach to resin production was compiled, covering aspects such as the main resin-producing species. Their genetic variation, and the climatic, physiographic, edaphic, dendrometric, and anatomical factors that influence its production. Additionally, the impact of fires and pests and methods used in resin extraction were analyzed.

2. A characterization on the effect on resin production of the mechanized circular tapping method was carried out, in combination with the use of two stimulating pastes, compared to the traditional bark tapping method.

3. The accumulated resin production throughout a resin tapping campaign was modelled using the Bertalanffy-Richards equation and the methodology of base age-invariant models.

4. Was used to develop a model to predict the potential resin using a two-step methodology based on machine learning techniques.

5. The first decision support system was created, to provide estimates of the production that users could potentially achieve, based on the models developed throughout the work.

Conclusions from the Methodology

6. The process used to determine the productive potential of the *Pinus pinaster* species in relation to resin production, and its subsequent integration into a decision support system, enables the identification of the most significant factors that influence this process. This approach also allows for the characterization of these factors and the development of robust models that facilitate their use as functional tools for estimating the production of this NTFP.

7. The main advantage of the methodology employed in this study is its ease of application and replicability in other regions where different species, extraction methods, and/or stimulating pastes are used. Additionally, the methodology is characterized by its high adaptability to the specific conditions of each region.

8. One of the main limitations of this methodology is the cost associated with obtaining field data, as it is an expensive and time-consuming process. This is due to the need for periodic visits to each plot by an experienced person throughout the defined campaign period, in order to carry out new scoring and weigh the accumulated production. This approach makes it difficult to establish a broader network of permanent plots to monitor the evolution of resin production both during the campaign and in the subsequent years.

Conclusions from the Results

9. After conducting the bibliographic analysis, a notable increase in interest in resin production in recent years was observed. Additionally, environmental and phenotypic factors were identified as key determinants in this process, along with the influence of methods and stimulating pastes.

10. As a result of the bibliographic review, a lack of developed models for this non-timber forest product exploitation was also evident, as well as an insufficiency of resources to assist those interested in resin production. These findings led to the determination of the specific objectives of this work.

11. Derived from the bibliographic review, an inconsistency in the units of measurement for production was detected, which makes it impossible to compare the quantities obtained by different methods. Therefore, the use of a standardized production measurement unit was proposed, which facilitated the comparison between the two resin tapping methods.

12. In general terms, it can be concluded that the "pica de corteza" method produces higher resin quantities than the mechanized circular tapping method. This demonstrates that the traditional method is more efficient in resin production, while the circular method is more cost-efficient, where labour is the limiting factor.

13. The stimulating paste Ethephon generated higher resin quantities compared to the ASACIF paste, although the observed differences were not statistically significant. This demonstrates that the sulfuric acid content largely determines the resin extraction capacity of the stimulating pastes, the use of sulfiric acid is restricted by environmental legislation.

14. It was concluded that dasometric variables alone are not sufficient to explain resin production. However, trees with a larger diameter relative to their height showed weak correlations with production. This result is particularly interesting for regions like Galicia, where resin tapping is regulated to start in the later years of the rotation period, when the tapped pines may have larger dimensions and volumes.

15. The location of the plots had a slight influence on the production obtained, although the observed differences were not statistically significant. This contradicts the common belief that some areas are more productive than others, as these differences are minimized once stimulating paste is applied.

16. In the modelling of accumulated production during the season, the Bertalanffy-Richards equation provided the best results among all the models tested. This equation, which is utilised in a broad range of fields, has once again substantiated its preeminence.

17. The equation fitted for the "pica de corteza" method obtained better results than the model for the mechanized circular tapping method in modelling the accumulated production. This is due to how the production of each method is distributed throughout the time series.

18. The development of an application that integrates the models developed, facilitates the transfer of the knowledge generated to different audiences. These tools are essential for the transfer of scientific advances to technical knowledge, thus generating economic value for the sector.

Future Lines

This work is, to innovative and should serve to provide continuity to the development of the resin sector. In this sense, it is considered that the following should be the main axes that should drive future work:

1. It is necessary to establish a larger network of experimental plots in order to assess all factors influencing resin production in a more comprehensive manner. This would enable the monitoring of a larger number of populations over a longer period of time.

2. It is essential to create technical-economic models that integrate the activities carried out to optimise the work of resin workers and adjust the duration of the campaign to achieve maximum profitability. In the future the variable to be optimised will be the cost per kilogram of resin extracted.

3. It is vital to ensure that the benefits of resin production are disseminated effectively and this will contribute to debunking the myths resin production around.

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ANEXO I

Material suplementario correspondiente al artículo incluido en el **Capítulo 4 -** ***Resin tapping: A review of the main factors modulating pine resin yield.***


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Supplementary data

Table S 1. Documents used in the review process are classified by their main subject according to the classification groups. Years are grouped in pairs from 2000 onwards. The categories of dendrometry and anatomical traits are grouped together. The Species group is included because there were papers that were used only for the species used. There are publications that are not in this table because they do not have a specific topic, they are of general knowledge.

Year\Topic	Species	Intraspecific genetic variation	Climatic, physiographic and edaphic	Dendrometry and anatomical	Fires and Pests	Extraction method
<2000	Jantan and Ahmad (1999); Song et al. (1995); McReynolds and Gansel (1985)	McReynolds (1971); Mergen et al. (1955)	Lorio and Sommers (1986); Lorio and Hodges (1968); Lombardero et al. (2000); Warren et al. (1999); Kytö et al. (1998); Tisdale and Nebeker (1992)	Wu and Hu (1997); Blanche et al. (1992); Brito et al. (1982); Hodges et al. (1981); Krekling et al. (2000)		Hodges (1995); Ruel et al. (1998); Parham (1976)
2001-2002	Arrabal et al. (2002)	Strom et al. (2002); Tadesse et al. (2001)		Lin et al. (2002); Tadesse et al. (2001)	Santoro et al. (2001); Wolter et al. (1980)	
2003-2004		Roberds et al. (2003); Romanelli and Sebbenn (2004)		Rigling et al. (2003)	Wallin et al. (2003)	
2005-2006	Arrabal et al. (2005); Kim et al. (2005); Wiyono et al. (2006); Chen et al. (2006)	Rezzi et al. (2005)	Zas et al. (2005)	Kim et al. (2005)	Roberds and Strom (2006); Lombardero et al. (2006); Franceschi et al. (2005); Nagy et al. (2006); Luchi et	Silverman et al. (2005); Franceschi et al. (2005); Wang et al. (2006)

Year\Topic	Species	Intraspecific genetic variation	Climatic, physiographic and edaphic	Dendrometry and anatomical	Fires and Pests	Extraction method
					al. (2005); Perrakis and Agee (2006)	
2007-2008	Silvestre and Gandini (2008)		Knebel et al. (2008); Gaylord et al. (2007)	Rodrigues et al. (2008); McDowell et al. (2007)		Rodrigues et al. (2008)
2009-2010	Spanos et al. (2010); Cannac et al. (2009)	Sampedro et al. (2010)	Rodrigues-Corrêa and Fett-Neto (2009)	Tomusiak and Magnuszewski (2009)	Eyles et al. (2010); Kane and Kolb (2010)	Rodrigues-Corrêa and Fett-Neto (2009)
2011-1012	Palma et al. (2012)	Assis and Resende (2011); Li et al. (2012)	Novick et al. (2012)	Silva Rodrigues-Corrêa and Fett-Neto (2012); Krokene and Nagy (2012); Esteban et al. (2012)	Davis et al. (2011)	Rodrigues-Corrêa et al. (2011)
2013-2014		Salto et al. (2014); Zeng et al. (2013); Susilowati et al. (2013); Liu et al. (2013); Westbrook et al. (2013)	Wei et al. (2014)	Rodríguez-García et al. (2014); K. R. Sharma et al. (2013)		K. R. Sharma et al. (2013); Serrano et al. (2013); S. C. Sharma et al. (2013); Torrijos et al. (2013); Jimeno and Crespo (2013); Martínez et al. (2013); Silva Rodrigues-Corrêa and Fett-Neto (2013)
2015-2016	HaiLin et al. (2015); Sukarno et al. (2015)	Westbrook et al. (2015); Zhang et al. (2016); Santos et al. (2016) Liu et al. (2015)	Hood and Sala (2015); Chen et al. (2015); Rodríguez-García et al. (2015); Sukarno et al. (2015)	Hadiyane et al. (2015); Rissanen et al. (2016); Palma et al. (2016); HaiLin et al. (2015)	Hood et al. (2015)	Füller et al. (2016); Rodríguez-García et al. (2016); Sukarno et al. (2015)

Year\Topic	Species	Intraspecific genetic variation	Climatic, physiographic and edaphic	Dendrometry and anatomical	Fires and Pests	Extraction method
2017-2018	Lauture (2017)	Yi et al. (2018); Lai et al. (2017); Jansson et al. (2017)	K. R. Sharma et al. (2018); Neis et al. (2018); Maaten et al. (2017)	Gajšek et al. (2018)	Rodríguez-García et al. (2018); Prasetya et al. (2017)	S. C. Sharma et al. (2018); Neis et al. (2018); Williams et al. (2017); Gómez-García et al. (2017)
2019-2020	Lai et al. (2020); Dutt et al. (2020); Neis et al. (2019)	Vázquez-González et al. (2019); Lai et al. (2020); Dutt et al. (2020); Liu et al. (2019); Liu et al. (2020); López-Goldar et al. (2019)	Zas et al. (2020b); Reyes-Ramos et al. (2019); Torre et al. (2019)	Zas et al. (2020); Abdillah et al. (2020); Lukmandaru et al. (2020); Reyes-Ramos et al. (2019); Egloff et al. (2019); Sood et al. (2019); Neis et al. (2019); Rissanen et al. (2019); Martínez-Chamorro et al. (2019)	Vazquez-Gonzalez et al. (2020); Kolb et al. (2019)	García-Méijome et al. (2020); García-Meijome et al. (2019); Hartiningtias et al. (2020)
2021-2022	Zaluma et al. (2022); Rubini et al. (2022); Garcia-Forner et al. (2021); Luan et al. (2022); Liu et al. (2022); Aloui et al. (2022); Rubini et al. (2021)	Suárez-Vidal et al. (2021); Ramírez-Valiente et al. (2022); Mei et al. (2021a); Fabián-Plesníková et al. (2022); Vázquez-González et al. (2021); Mei et al. (2021b); Nugrahanto et al. (2022); Rissanen et al. (2021); Shi et al. (2021); Govina et al. (2021)	Lukmandaru et al. (2021); Michavila et al. (2021); Yi et al. (2021)	Rissanen et al. (2021); Garcia-Forner et al. (2021); Zeng et al. (2021); Cabrita (2021)	Valor et al. (2021)	Touza et al. (2021); Heinze et al. (2021); Candaten et al. (2021); Gurau et al. (2021); López-Villamor et al. (2021); Yovi et al. (2021); Vázquez-González et al. (2022)


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ANEXO II

Material suplementario correspondiente al artículo incluido en el **Capítulo 5 - *Resin yield response to different tapping methods and stimulant pastes in Pinus pinaster Ait.***


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Supplementary data

Resin yield response to different tapping methods and stimulant pastes in *Pinus pinaster* Ait.

Journal name: European Journal of Forest Research

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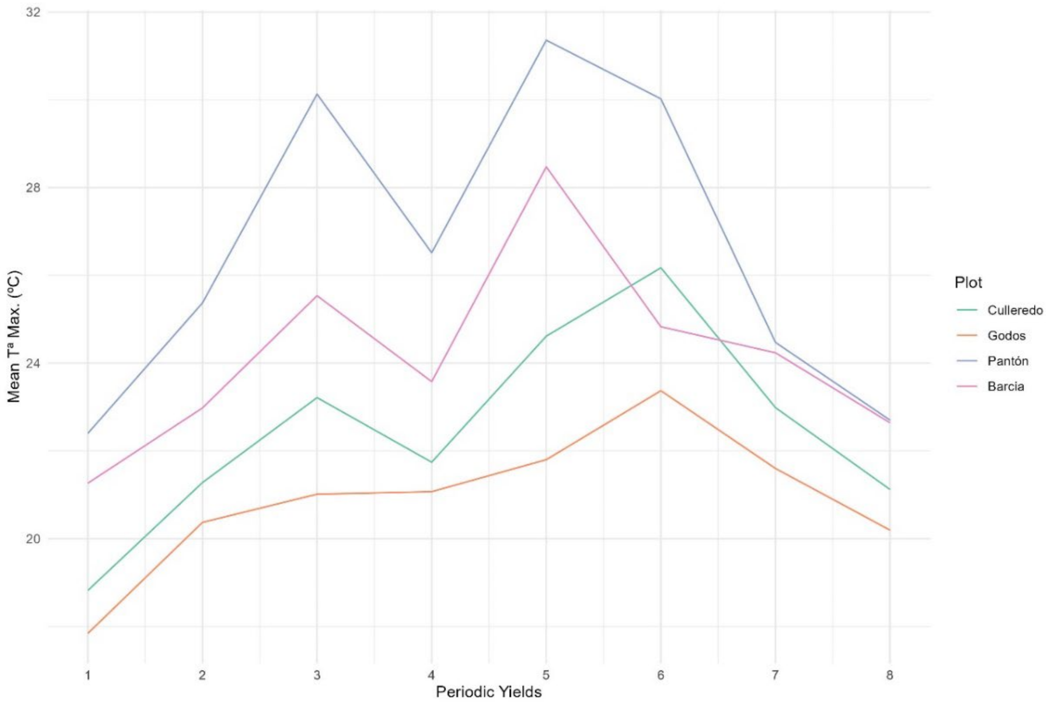

Fig S 1. Average of the maximum temperatures during the grooving period carried out in each of the plots

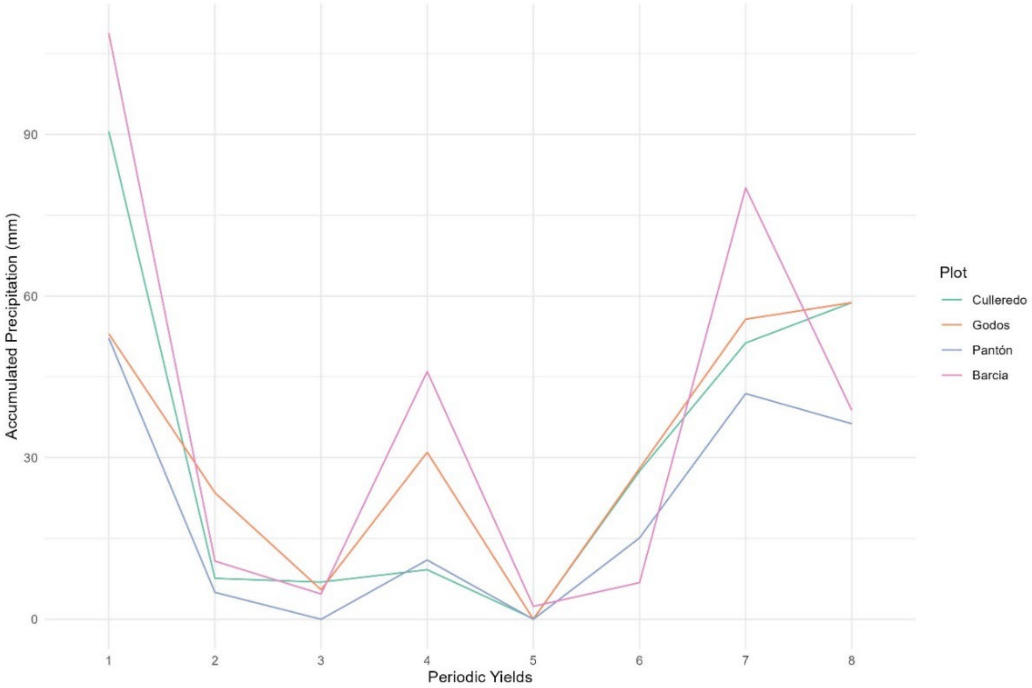

Fig S 2. Accumulated precipitation during the grooving period carried out in each of the plots.

Table S 1: Summary of closest weather stations to the plots consulted from two sources of information, the Spanish State Meteorological Agency (AEMET)(www.aemet.es) and the Galician Meteorologial Service (MeteoGalicia)(www.meteogalicia.gal). ID: MeteoGalicia and AEMET station id; Altitude: stations altitude (m); T^{a} min: average minimum temperatures (ºC); T^{a} mean: average mean temperatures (ºC); T^{a} max: average maximun temperatures (ºC); Precipitation: average accumulated precipitation (mm).

Plot	Meteorological Service	ID	Altitude (m)	T^{a} min (ºC)	T^{a} mean (ºC)	T^{a} max (ºC)	Precipitation (mm)
Culleredo	AEMET	1387E	98	9.4	13.8	18.1	1105.5
Pantón	MeteoGalicia	10171	286	10.6	14.1	18.3	1236.4
Godos	MeteoGalicia	19056	52	9.3	14.2	19.6	1156.6
Busfrio	AEMET	1212E	127	9.8	13.4	17	1018.8
Coca	AEMET	2465	1005	6.9	12.5	18	479.4


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En esta tesis se presenta el flujo de trabajo y las metodologías empleadas para determinar el potencial productivo de resina de la especie *Pinus pinaster* Ait., integradas en un sistema de apoyo a la decisión. El trabajo se ha estructurado en cuatro fases: (i) identificación de los principales factores que influyen en la producción en base a bibliografía; (ii) caracterización la producción en la zona de estudio; (iii) modelización de la producción acumulada a lo largo de la campaña utilizando modelos invariantes con la edad y la ecuación de Bertalanffy-Richards; (iv) estimación de la producción potencial de resina, empleando una metodología bietápica basada en técnicas de aprendizaje automático, y creación del primer sistema de apoyo a la decisión.