



FACULTAD DE CIENCIAS NATURALES Y EXACTAS
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**EVALUACIÓN DE LA RECUPERACIÓN POST-INCENDIO A
CORTO PLAZO EN BOSQUES MEDITERRÁNEOS DE CHILE
CENTRAL BAJO DIFERENTES NIVELES DE SEQUÍA
UTILIZANDO TELEDETECCIÓN**

Tesis para optar al grado de Doctor en Ciencias Ambientales

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Dedicatoria

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Resumen

La recuperación de la vegetación en los ecosistemas mediterráneos tras incendios se ha vuelto un tema de gran relevancia, especialmente en el contexto del cambio climático. Estos ecosistemas, caracterizados por su alta biodiversidad y adaptaciones a condiciones climáticas extremas, enfrentan desafíos importantes debido a la intensificación de perturbaciones naturales como incendios y sequías. Comprender los procesos de recuperación forestal es crucial no solo para la preservación de la biodiversidad, sino también para mantener servicios ecosistémicos esenciales, como la captura de carbono y la regulación del ciclo hidrológico. La presente tesis doctoral se enfoca en analizar cómo diversos factores ambientales (impulsores) influyen en la recuperación a corto plazo (5 años) de la productividad del bosque Mediterráneo de Chile Central tras incendios, evaluado a partir del Índice de Vegetación de Diferencia Normalizada (NDVI) obtenido mediante imágenes satelitales.

Para este propósito, la investigación comienza con una introducción general sobre los efectos del cambio climático en los regímenes de perturbación y su impacto en la recuperación de los ecosistemas mediterráneos. Se busca contrastar un modelo que propone que las interacciones entre sequías prolongadas e incendios forestales disminuyen significativamente la recuperación del bosque, pudiendo alcanzar puntos de inflexión ecológica.

El tercer capítulo se centra en analizar las diferencias en la respuesta de productividad entre tres tipos forestales del bosque mediterráneo, en tres condiciones de sequía (No Sequía, Mega Sequia e Hiper Sequia), así como la severidad del incendio (media y alta). Los resultados indican diferencias significativas en la recuperación de los tres tipos de bosque analizados a lo largo de los gradientes de sequía durante el período de Hiper Sequía. El bosque xerófilo, compuesto principalmente por *Quillaja saponaria* y *Lithrea caustica*, mostró efectos de interacción significativos entre los niveles de sequía y la severidad del incendio, mientras que en el bosque espinoso y matorral no se

observaron interacciones significativas. El bosque mésico, dominado por *Cryptocarya alba* y *Peumus boldus*, mostró diferencias significativas adicionales en su recuperación entre los períodos de Hiper Sequía y Mega Sequía, así como efectos de interacción significativos. Estos hallazgos resaltan la importancia de las sequías prolongadas y severas en la dinámica de recuperación forestal y la necesidad de comprender estos patrones para fortalecer la resiliencia futura de los bosques bajo condiciones cada vez más áridas.

El cuarto capítulo aborda la importancia relativa y el efecto de las condiciones ambientales, tanto las relacionadas con el incendio como las condiciones climáticas posteriores, en la recuperación de la vegetación en los tres principales tipos del bosque esclerófilo mediterráneo de Chile. Para ello, se desarrollaron modelos predictivos de Random Forest en dos variables de respuesta, una la métrica de recuperación relativa de NDVI (NDVIrec), así como al NDVI absoluto. Los valores medios del R-cuadrado obtenidos en estos modelos oscilaron entre 0.7 y 0.9 según el tipo de bosque. Los resultados subrayan que la severidad de la sequía es el principal factor limitante en la recuperación post-incendio para los modelos asociados a NDVIrec, impactando negativamente en la recuperación de la vegetación. Y el verdor previo de la vegetación como el principal factor en los modelos asociados a NDVI, con una relación positiva en la capacidad de recuperación de la productividad.

En consecuencia, esta investigación contribuye a una comprensión más profunda de los efectos de las sequías prolongadas y severas, así como de otros factores impulsores, en la recuperación y capacidad regenerativa potencial de los bosques mediterráneos. Comprender mejor la respuesta de las diferentes formaciones vegetacionales ante estos impulsores de la recuperación post-perturbación puede facilitar el desarrollo de estrategias de conservación y manejo más efectivas y eficientes, orientadas a promover la resiliencia de estos bosques altamente presionados. Estos hallazgos forman parte integral del Doctorado en Ciencias Ambientales, en la línea de investigación “Desafíos ambientales globales, medio ambiente, sociedad y organismos” ya que proporcionan

información valiosa para abordar los desafíos que enfrenta la gestión forestal en un contexto de cambio climático.

Palabras Clave: Cambio climático, perturbaciones naturales, sequía, incendio, bosque Mediterráneo, sensoramiento-remoto.

Abstract

Vegetation recovery in Mediterranean ecosystems after fires has become a topic of great relevance, particularly in the context of climate change. These ecosystems, characterized by high biodiversity and adaptations to extreme climatic conditions, face significant challenges due to the intensification of natural disturbances like fires and droughts. Understanding forest recovery processes is crucial not only for biodiversity conservation but also for maintaining essential ecosystem services, such as carbon sequestration and hydrological cycle regulation. This doctoral thesis focuses on analyzing how various environmental factors influence the short-term (5-year) productivity recovery of the Mediterranean forest in central Chile following fires, assessed using the Normalized Difference Vegetation Index (NDVI) derived from satellite imagery.

For this purpose, the research begins with a general introduction to the effects of climate change on disturbance regimes and their impact on the recovery of Mediterranean ecosystems. It seeks to test a model proposing that interactions between prolonged droughts and forest fires significantly reduce forest recovery, potentially reaching ecological tipping points.

The third chapter examines productivity response differences among three Mediterranean forest types under three drought conditions (No Drought, Mega Drought, and Hyper Drought) and two fire severity levels (moderate and high). Results indicate significant differences in the recovery of the three forest types across drought gradients during the Hyper Drought period. The xeric forest, primarily composed of *Quillaja saponaria* and *Lithrea caustica*, showed significant interaction effects between drought levels and fire severity, while the thorny forest and shrubland showed no significant interactions. The mesic forest, dominated by *Cryptocarya alba* and *Peumus boldus*, exhibited additional significant recovery differences between the Hyper Drought and Mega Drought periods, as well as significant interaction effects. These findings highlight the critical role of prolonged and severe droughts in shaping forest recovery dynamics and underscore the

need to understand these patterns to enhance future forest resilience under increasingly arid conditions.

The fourth chapter addresses the relative importance and effect of both fire-related and post-fire climatic conditions on vegetation recovery in the three main types of Mediterranean sclerophyllous forest in Chile. For this, predictive Random Forest models were developed with two response variables: a relative NDVI recovery metric (NDVIrec) and absolute NDVI. The mean R-squared values obtained for these models ranged from 0.7 to 0.9, depending on the forest type. Results underscore that drought severity is the main limiting factor for post-fire recovery in the NDVIrec models, negatively impacting vegetation recovery. In contrast, pre-fire vegetation greenness emerged as the main factor in the NDVI models, positively influencing productivity recovery capacity.

Consequently, this research contributes to a deeper understanding of the effects of prolonged and severe droughts, as well as other driving factors, on the recovery and potential regenerative capacity of Mediterranean forests. Improving knowledge of how different vegetation formations respond to these post-disturbance recovery drivers can aid in developing more effective and efficient conservation and management strategies to promote resilience in these highly pressured forests. These findings are an integral part of the PhD in Environmental Sciences within the research line "Global Environmental Challenges, Environment, Society, and Organisms," providing valuable insights to address the challenges facing forest management in a climate change context.

Keywords: Climate change, natural disturbances, drought, wildfire, Mediterranean forest, remote sensing.

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Capítulo I. Introducción General

Introducción General de la Investigación

Efecto del cambio climático en las perturbaciones naturales forestales

El mundo está experimentando una transformación acelerada, con cambios en el clima, los ecosistemas naturales y los suelos modificados por el ser humano a velocidades sin precedentes. Diversos informes destacan los efectos y posibles impactos de estos cambios abruptos tanto en los sistemas naturales como en los humanos (IPCC, 2022). Entre estos impactos, uno de los más relevantes es la transformación de los regímenes de perturbación, que, aunque fundamentales para la dinámica de los ecosistemas, no han sido suficientemente estudiados (Seidl et al., 2016; Turner, 2010).

Las perturbaciones naturales son un componente clave de la dinámica ecológica y su análisis proporciona información valiosa sobre los procesos y patrones a distintas escalas. Eventos como incendios, sequías, huracanes, erupciones volcánicas o plagas de insectos generan heterogeneidad espacial y temporal en los ecosistemas, alterando su estructura, composición y funcionamiento (Burton et al., 2020; White & Pickett, 1985). Además, estas perturbaciones dejan una huella duradera en la trayectoria de los ecosistemas, influyendo en su estado futuro (Scheffer et al., 2001). En el contexto del calentamiento global, las perturbaciones climáticas están mostrando un cambio significativo en sus patrones y características (Frenne et al., 2013; Thom et al., 2017). A diferencia de los eventos aislados, los regímenes de perturbación incluyen características espaciales y temporales como la frecuencia, severidad e interacción con otros eventos perturbadores (Veblen, 2000; White & Pickett, 1985).

El aumento de la frecuencia y severidad de estas perturbaciones en el marco del cambio climático ha elevado el riesgo de superar umbrales ecológicos, desencadenando cambios irreversibles en la estructura y función de los ecosistemas forestales (Seidl et al., 2017). Esto es especialmente evidente en las regiones mediterráneas, donde la intensificación de los regímenes de perturbación está transformando las interacciones ecológicas (Thom, 2023;

Turco et al., 2019). Estos disturbios no solo afectan la disponibilidad de recursos, sino que también generan mayor heterogeneidad en el paisaje, reorganizando las comunidades ecológicas (Liu et al., 2024).

Los puntos de inflexión en los ecosistemas forestales se están volviendo cada vez más frecuentes debido a la acumulación de efectos negativos asociados a perturbaciones como incendios y sequías prolongadas. Cuando estas perturbaciones alcanzan una intensidad o frecuencia crítica, pueden provocar un cambio irreversible en el ecosistema, reduciendo la biodiversidad y alterando la capacidad de estos sistemas para proporcionar servicios ecosistémicos clave, como la captura de carbono y la regulación del ciclo hidrológico (Scheffer et al., 2001; Thom et al., 2023). En los bosques mediterráneos, las interacciones entre sequías prolongadas e incendios forestales aumentan la probabilidad de alcanzar estos puntos de inflexión, al reducir la capacidad de los ecosistemas para recuperarse tras eventos de gran magnitud (Liu et al., 2024).

El estudio de las perturbaciones naturales como impulsores de puntos de inflexión es esencial para desarrollar estrategias de manejo y conservación adaptativas. Comprender cómo las perturbaciones interactúan entre sí y con otros factores ambientales permitirá prever las condiciones bajo las cuales los ecosistemas pueden perder su capacidad de recuperación. Esto es particularmente relevante en zonas mediterráneas donde la alta presión antropogénica y la variabilidad climática ya están poniendo en riesgo la estabilidad ecológica de los bosques (Gauquelin et al., 2018; Miranda et al., 2023; Sommerfeld et al., 2018).

Perturbaciones en ecosistemas mediterráneos

Los ecosistemas mediterráneos, que incluyen tanto bosques como matorrales, se caracterizan por una notable resistencia y resiliencia frente a perturbaciones naturales (Keeley, 1986; Naveh, 2007). La resistencia se refiere a la capacidad de un ecosistema para absorber una perturbación sin experimentar cambios drásticos en su estructura o función, mientras que la resiliencia alude a la

capacidad de recuperarse y restaurar su funcionalidad tras un disturbio (Lloret et al., 2011; White & Pickett, 1985). Estas características han sido fundamentales para mantener la estabilidad ecológica de estos ecosistemas, particularmente frente a perturbaciones como incendios y sequías.

Los ecosistemas mediterráneos tienen una relevancia especial en el monitoreo de cambios ecológicos debido a su considerable riqueza de especies y biodiversidad (Miranda et al., 2023). Estas regiones albergan una flora altamente adaptada a condiciones climáticas extremas, con especies que han desarrollado mecanismos de resistencia frente al estrés hídrico y la recurrencia de incendios. Además, su ubicación cerca de zonas semiáridas las convierte en áreas particularmente vulnerables a las respuestas inducidas por la sequía y los efectos del cambio climático, lo que subraya la importancia de su estudio. La alta biodiversidad y endemismo de estos ecosistemas los convierte en un foco clave para la conservación, pero también en áreas altamente susceptibles a las perturbaciones (Peñuelas & Sardans, 2021).

Distribuidos a lo largo de las costas de todos los continentes en latitudes entre los 32° y 45°, estos ecosistemas se caracterizan por inviernos fríos y húmedos y veranos cálidos y secos, con una notable variabilidad estacional (Di Castri & Mooney, 2012). Esta variabilidad climática, dominada por largos periodos de sequía, ejerce un fuerte estrés hídrico en la vegetación durante la temporada de crecimiento, lo que ha llevado a la evolución de adaptaciones clave en las plantas. Entre estas adaptaciones se incluyen la capacidad de rebrotar tras incendios, la acumulación de agua en tejidos leñosos y el desarrollo de sistemas radiculares profundos, que permiten acceder a fuentes de agua subterráneas (Tognetti et al., 2019). Estas estrategias han sido esenciales para la supervivencia de especies vegetales en estos entornos, lo que ha contribuido a la resiliencia de los ecosistemas mediterráneos frente a perturbaciones moderadas.

Sin embargo, el aumento en la frecuencia y severidad de las perturbaciones está llevando a estos ecosistemas al límite de su capacidad de regeneración (McDowell et al., 2020; Seidl et al., 2017). La interacción entre diferentes tipos de perturbaciones, como los incendios recurrentes y las sequías prolongadas, está agotando los nutrientes del suelo y reduciendo la capacidad de recuperación de las especies vegetales, afectando la composición de las comunidades ecológicas (Thom, 2023). Además, la fragmentación del paisaje, impulsada por la expansión agrícola y urbana, está dificultando la conectividad entre los fragmentos de bosque, lo que limita la dispersión de especies y reduce su capacidad de recolonización tras un disturbio (Baudena et al., 2020).

La relevancia de los ecosistemas mediterráneos no solo radica en su biodiversidad y riqueza de especies, sino también en su vulnerabilidad a los impactos del cambio climático. Las proyecciones sugieren que las perturbaciones como las sequías e incendios seguirán aumentando, comprometiendo la capacidad de estos ecosistemas para regenerarse y mantenerse estables a largo plazo (Liu et al., 2024). Esto destaca la necesidad de implementar estrategias de manejo que promuevan la conectividad del paisaje y la diversidad funcional para aumentar la resiliencia de los ecosistemas mediterráneos frente a futuros disturbios (Sommerfeld et al., 2018; Thom, 2023).

Sequía: Expansión de la aridez, sequías más prolongadas y calientes

El cambio climático ha intensificado los patrones de aridez y ha extendido la duración de las sequías en muchas regiones mediterráneas del mundo, incluida América del Sur (Garreaud et al., 2017). Las sequías prolongadas y más intensas están ejerciendo una presión considerable sobre los ecosistemas forestales mediterráneos, limitando la disponibilidad de recursos hídricos esenciales para el mantenimiento de la vegetación y la biodiversidad (Liu et al., 2024; Parra & Moreno, 2018; Trambly et al., 2020). medida que los periodos secos se extienden, las plantas no solo deben lidiar con la falta de agua, sino también con un aumento en las temperaturas que exacerba el estrés hídrico.

La megasequía en Chile central es uno de los ejemplos más extremos de cómo la aridez está afectando los ecosistemas mediterráneos de América del Sur (Garreaud et al., 2017). Durante más de una década, esta región ha experimentado una disminución sostenida en las precipitaciones, lo que ha reducido drásticamente la capacidad de las especies vegetales para realizar funciones vitales, como la fotosíntesis y la producción de biomasa. Esta disminución en la disponibilidad de agua ha afectado particularmente a las especies menos adaptadas a la sequía, como muchas especies de árboles que dependen de fuentes superficiales de agua para sobrevivir (Tognetti et al., 2019).

Las proyecciones climáticas sugieren que las sequías en las regiones mediterráneas continuarán aumentando en severidad y duración, lo que podría comprometer la capacidad de regeneración de los bosques tras eventos perturbadores como incendios (Batllori et al., 2019; Essa et al., 2023; Rundel et al., 2018). La combinación de sequías prolongadas e incendios recurrentes plantea una amenaza significativa para la biodiversidad, ya que muchas especies no tendrán tiempo suficiente para recuperarse entre eventos perturbadores. Además, el aumento de la aridez está asociado con una mayor degradación del suelo, lo que a su vez reduce la capacidad de los ecosistemas para sostener procesos de regeneración a largo plazo (Hinojosa et al., 2012; Peñuelas & Sardans, 2021).

La expansión de la aridez también está afectando la productividad primaria neta de los ecosistemas mediterráneos. A medida que disminuye la disponibilidad de agua, la vegetación experimenta una reducción en su capacidad de capturar carbono, lo que tiene implicaciones directas para la mitigación del cambio climático (Xu et al., 2024). Estos cambios en los patrones de productividad y regeneración están transformando la estructura de los ecosistemas mediterráneos, favoreciendo la expansión de especies más resistentes a la sequía, pero menos eficientes en la captura de carbono y otros servicios ecosistémicos (Pugh et al., 2019).

Incendios: cambios en el régimen de incendios

El cambio climático ha incrementado significativamente la frecuencia y severidad de los incendios forestales en los ecosistemas mediterráneos (Turco et al., 2018). Las temperaturas más altas y las condiciones más secas han creado un ambiente propicio para la propagación de incendios, exacerbando los impactos sobre la biodiversidad y la estructura del paisaje (Jolly et al., 2015; Jones et al., 2022). En Chile central, los incendios están afectando áreas más grandes y de manera más frecuente, lo que está limitando la capacidad de regeneración de los bosques nativos (de la Barrera et al., 2018; González et al., 2018; Smith-Ramírez et al., 2022). Estos incendios, conocidos como "mega-incendios", tienen el potencial de transformar permanentemente el paisaje, favoreciendo la expansión de especies de matorrales más resistentes al fuego, pero menos eficientes en términos de captura de carbono (Peñuelas & Sardans, 2021; Xu et al., 2024). Los cambios en los regímenes de incendios también están alterando los ciclos de nutrientes del suelo, afectando la regeneración vegetal y reduciendo la productividad de los ecosistemas (Nolan et al., 2021).

La interacción entre incendios y otros disturbios, como la sequía, genera efectos sinérgicos que amplifican los impactos negativos. Las sequías prolongadas, al reducir la humedad del suelo, incrementan la inflamabilidad de la vegetación, elevando la probabilidad de incendios más severos y recurrentes (Liu et al., 2024). Este escenario plantea desafíos adicionales para la conservación y gestión forestal, ya que los regímenes de incendios en combinación con otros factores de estrés están creando nuevas dinámicas en los ecosistemas mediterráneos, comprometiendo su resiliencia a largo plazo.

Cambio de régimen de Perturbación por forzantes climáticos

Una de las tendencias más preocupantes asociadas al cambio climático es la transición de las perturbaciones naturales de eventos discretos a condiciones crónicas. La megasequía en Chile central es un ejemplo claro de cómo una perturbación, que en el pasado podía considerarse puntual, ha evolucionado

hacia una condición permanente que afecta de manera constante la capacidad de los ecosistemas para regenerarse (Rillig et al., 2023; Seidl et al., 2017). Estas interacciones en nuevas condiciones entre estresores ambientales (mayor aridez, mayor temperatura e incendios) tiene serias implicaciones para la biodiversidad y el funcionamiento de los ecosistemas. Además, la combinación de sequía prolongada, fragmentación del hábitat y cambios en el uso del suelo está creando un nuevo régimen de perturbaciones que limita la capacidad de los ecosistemas mediterráneos para recuperarse (Miranda et al., 2023; Seidl et al., 2017). A medida que estas condiciones se vuelven más persistentes, los ecosistemas pierden su capacidad de resistencia y resiliencia frente a nuevos disturbios. En muchos casos, el resultado es la transformación de paisajes forestales en áreas dominadas por matorrales o pastizales, con menor capacidad para proveer servicios ecosistémicos clave, como la captura de carbono (Liu et al., 2024; Xu et al., 2024). La transformación de las perturbaciones naturales en condiciones permanentes plantea nuevos desafíos para la gestión ambiental. Es esencial entender cómo estos cambios alteran las dinámicas ecológicas para implementar estrategias de manejo adaptativas que puedan responder a estas nuevas condiciones y asegurar la sostenibilidad de los ecosistemas mediterráneos a largo plazo (IPBES, 2019; Keeley, Bond, et al., 2011).

Factores impulsores de la recuperación de la vegetación post-incendio

La recuperación de la productividad de la vegetación después de los incendios en los ecosistemas mediterráneos depende de una variedad de factores biológicos, climáticos y ecológicos. La disponibilidad de agua y nutrientes es un factor crucial en la regeneración post-incendio. En ecosistemas donde el acceso a estos recursos es limitado, la recuperación se ve significativamente retrasada, afectando la capacidad de los ecosistemas para restaurar su productividad y su rol en la captura de carbono (Schenk et al., 2008). La capacidad de rebrote de las especies también juega un papel importante en la recuperación de la vegetación (Montenegro et al., 2004). Las especies esclerófilas, típicas de los ecosistemas mediterráneos, tienden a rebrotar rápidamente después de un

incendio, lo que acelera la restauración de la biomasa. Sin embargo, la magnitud y frecuencia de los incendios son factores determinantes. Incendios recurrentes en intervalos cortos pueden agotar los nutrientes del suelo y dificultar la regeneración vegetal, reduciendo la productividad y aumentando la vulnerabilidad del ecosistema a futuras perturbaciones (Castillo et al., 2020; Smith-Ramírez et al., 2021).

Además, las condiciones climáticas posteriores a los incendios, como la cantidad de precipitaciones y las temperaturas, también afectan la velocidad de recuperación. Escenarios de cambio climático que proyectan condiciones más secas y cálidas podrían inhibir la recuperación de la vegetación, prolongando el tiempo necesario para que los ecosistemas restauren su funcionalidad completa (Xu et al., 2024). Estos desafíos destacan la necesidad de desarrollar estrategias de manejo adaptativas que consideren tanto la prevención de incendios como la restauración post-incendio para promover la resiliencia de los ecosistemas mediterráneos.

Evaluación de la recuperación de la vegetación post-incendio mediante teledetección

La teledetección ha emergido como una herramienta clave para evaluar la recuperación de los ecosistemas forestales tras incendios, proporcionando datos precisos y espacialmente explícitos que permiten un seguimiento continuo a lo largo del tiempo (Cohen et al., 2010; Hislop et al., 2018; Kennedy et al., 2012). El uso de imágenes satelitales y de índices de vegetación, como el Índice de Vegetación de Diferencia Normalizada (NDVI), ha permitido a los científicos monitorear la dinámica de recuperación de la vegetación y evaluar tanto la severidad del daño inicial como la tasa de recuperación post-incendio (Frazier et al., 2018; Meng et al., 2015; Viana-Soto et al., 2020).

El NDVI es particularmente útil en la detección de cambios en la cobertura vegetal y en la productividad primaria neta, ya que proporciona un indicador cuantitativo

del vigor de la vegetación. En los primeros años tras un incendio, se suele observar un rápido rebrote de la vegetación en algunas áreas, lo que se refleja en un aumento del NDVI (Meng et al., 2015). Sin embargo, en ecosistemas mediterráneos, la velocidad y efectividad de esta recuperación pueden verse influenciadas por factores climáticos como la disponibilidad de agua, la frecuencia de los incendios y las temperaturas posteriores al evento perturbador (Blanco-Rodríguez et al., 2023; Fernández-Guisuraga et al., 2023).

En ecosistemas mediterráneos de América del Sur, la evaluación de la recuperación post-incendio mediante teledetección es especialmente relevante debido a la variabilidad en las respuestas de la vegetación. Algunos estudios han mostrado que, aunque ciertas especies vegetales pueden recuperarse relativamente rápido, otras requieren más tiempo y recursos, lo que sugiere la necesidad de monitorear a largo plazo para entender completamente las dinámicas de recuperación (Hermosilla et al., 2015). La integración de datos de teledetección con estudios de campo y modelos ecológicos permite no solo cuantificar los patrones de recuperación, sino también identificar áreas que requieren intervenciones de manejo o restauración más intensivas (Collins et al., 2009; Roche et al., 2024).

A pesar de los avances logrados en este campo, los ecosistemas mediterráneos del hemisferio sur siguen estando subrepresentados en estudios sobre recuperación post-incendio (Xu et al., 2024). Esto resalta la necesidad de realizar evaluaciones regionales más exhaustivas que permitan ajustar las estrategias de manejo forestal en función de las características particulares de estos ecosistemas. La aplicación de tecnologías de teledetección avanzadas puede proporcionar información crucial para diseñar estrategias de restauración ecológica más efectivas, mejorando la resiliencia de los bosques mediterráneos frente a futuros disturbios y al cambio climático.

El monitoreo continuo y la implementación de modelos de predicción basados en teledetección también pueden ayudar a identificar áreas vulnerables a futuros

incendios o sequías, permitiendo a los gestores del territorio actuar de manera preventiva para mitigar los impactos de las perturbaciones (Roche et al., 2024). A medida que los incendios y otros disturbios se vuelven más frecuentes y severos bajo escenarios de cambio climático, el uso de estas herramientas se vuelve indispensable para la gestión adaptativa de los ecosistemas forestales.

Capítulo II. Hipótesis y Objetivos

Hipótesis

La recuperación a corto plazo (5 años) de la productividad del bosque Mediterráneo de Chile Central post-incendio se encuentra influenciada por factores relacionados con la severidad del incendio, condiciones climáticas posteriores al incendio y otros factores ambientales como la topografía. Entre estos factores, la severidad de la sequía actúa como la principal limitante, afectando negativamente a la recuperación de la productividad del bosque, medida a través de la capacidad fotosintética de la Vegetación.

Objetivo General

Analizar el efecto de los factores ambientales que modulan la recuperación a corto plazo (5 años) de la productividad del bosque Mediterráneo de Chile Central post-incendio utilizando herramientas de teledetección.

Objetivos Específicos

O1: Caracterizar y comparar la recuperación del bosque a corto plazo después de un incendio medida por el NDVI, considerando la condición de sequía, la severidad del incendio y el subtipo de bosque.

O2: Identificar la importancia relativa y los efectos de factores ambientales clave (severidad del fuego, condiciones climáticas post incendio, topografía) involucrados en la recuperación post-incendio, a partir de modelos predictivos de regresión.

Capítulo III. Effects of Drought and Fire Severity Interaction on Short-Term Post-Fire Recovery of the Mediterranean Forest of South America

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Article

Effects of Drought and Fire Severity Interaction on Short-Term Post-Fire Recovery of the Mediterranean Forest of South America

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Abstract: Wildfires and drought stressors can significantly limit forest recovery in Mediterranean-type ecosystems. Since 2010, the region of central Chile has experienced a prolonged Mega Drought, which intensified into a Hyper Drought in 2019, characterized by record-low precipitation and high temperatures, further constraining forest recovery. This study evaluates short-term (5-year) post-fire vegetation recovery across drought gradients in two types of evergreen sclerophyllous forests and a thorny forest and shrubland, analyzing Landsat time series (1987–2022) from 42 wildfires. Using the LandTrendr algorithm, we assessed post-fire forest recovery based on NDVI changes between pre-fire values and subsequent years. The results reveal significant differences in recovery across drought gradients during the Hyper Drought period, among the three forest types studied. The xeric forest, dominated by *Quillaja saponaria* and *Lithrea caustica*, showed significant interaction effects between levels of drought and fire severity, while the thorny forest and shrubland displayed no significant interaction effects. The mesic forest, dominated by *Cryptocarya alba* and *Peumus boldus*, exhibited additional significant differences in recovery between the Hyper Drought and Mega Drought periods, along with significant interaction effects. These findings underscore the critical role of prolonged, severe drought in shaping forest recovery dynamics and highlight the need to understand these patterns to improve future forest resilience under increasingly arid conditions.

Keywords: Chile; Mediterranean; NDVI; forest recovery; drought; wildfire; fire severity; remote sensing; disturbance; stressors interaction

1. Introduction

Natural disturbances, such as wildfires and droughts, play a crucial role in the ecological dynamics of forest ecosystems by shaping their structure, composition, and function [1,2]. These disturbances leave long-lasting imprints on forest trajectories, influencing their future states [3,4]. However, anthropogenic climate change and land-use practices

Resumen

Los incendios forestales y la sequía podrían limitar significativamente la recuperación de los bosques en ecosistemas de tipo mediterráneo. Desde 2010, la región del centro de Chile ha experimentado una prolongada "Mega Sequía", que se intensificó en una "Hiper Sequía" en 2019, con precipitaciones extremadamente bajas y temperaturas altas, restringiendo aún más la recuperación de los bosques. Este estudio evalúa la recuperación de la vegetación post-incendio a corto plazo (5 años) a través de gradientes de sequía en dos tipos de bosques esclerófilos siempreverdes y en un bosque y matorral espinoso, analizando series temporales de Landsat (1987–2022) para 42 incendios. Usando el algoritmo LandTrendr, evaluamos la recuperación forestal post-incendio basándonos en los cambios en el NDVI entre los valores previos al incendio y los años posteriores. Los resultados revelan diferencias significativas en la recuperación durante el período de Hiper Sequía en los tres tipos de bosque estudiados. El bosque xerófilo, dominado por *Quillaja saponaria* y *Lithrea caustica*, mostró efectos de interacción significativos entre los niveles de sequía y la severidad del incendio, mientras que el bosque espinoso y el matorral no presentaron efectos de interacción significativos. El bosque mésico, dominado por *Cryptocarya alba* y *Peumus boldus*, exhibió diferencias significativas adicionales en la recuperación entre los períodos de Hiper Sequía y Mega Sequía, junto con efectos de interacción significativos. Estos hallazgos resaltan el papel crítico de las sequías prolongadas y severas en la configuración de la dinámica de recuperación forestal y destacan la necesidad de comprender estos patrones para mejorar la resiliencia futura de los bosques bajo condiciones cada vez más áridas.

Palabras clave: Chile; Mediterráneo; NDVI; recuperación forestal; sequía; incendios forestales; severidad del incendio; teledetección; perturbación; interacción de estresores.

Abstract

Wildfires and drought stressors can significantly limit forest recovery in Mediterranean-type ecosystems. Since 2010, the region of central Chile has experienced a prolonged Mega Drought, which intensified into a Hyper Drought in 2019, characterized by record-low precipitation and high temperatures, further constraining forest recovery. This study evaluates short-term (5-year) post-fire vegetation recovery across drought gradients in two types of evergreen sclerophyllous forests and a thorny forest and shrubland, analyzing Landsat time series (1987–2022) from 42 wildfires. Using the LandTrendr algorithm, we assessed post-fire forest recovery based on NDVI changes between pre-fire values and subsequent years. The results reveal significant differences in recovery across drought gradients during the Hyper Drought period, among the three forest types studied. The xeric forest, dominated by *Quillaja saponaria* and *Lithrea caustica*, showed significant interaction effects between levels of drought and fire severity, while the thorny forest and shrubland displayed no significant interaction effects. The mesic forest, dominated by *Cryptocarya alba* and *Peumus boldus*, exhibited additional significant differences in recovery between the Hyper Drought and Mega Drought periods, along with significant interaction effects. These findings underscore the critical role of prolonged, severe drought in shaping forest recovery dynamics and highlight the need to understand these patterns to improve future forest resilience under increasingly arid conditions.

Keywords: Chile; Mediterranean; NDVI; forest recovery; drought; wildfire; fire severity; remote sensing, disturbance; stressors interaction

Introduction

Natural disturbances, such as wildfires and droughts, play a crucial role in the ecological dynamics of forest ecosystems by shaping their structure, composition, and function (Turner, 2010; White & Pickett, 1985). These disturbances leave long-lasting imprints on forest trajectories, influencing their future states (Scheffer et al., 2001; Seidl et al., 2014). However, anthropogenic climate change and land-use practices have significantly altered these disturbances' frequency, intensity, and interactions (Frenne et al., 2013; Seidl et al., 2017; Thom et al., 2017). As climate-related disturbances increase in both duration and intensity, they may transition from isolated incidents to persistent stressors, exemplified by extended drought conditions (Rillig et al., 2023). These persistent stressors can severely limit vegetation recovery and elevate the risk of surpassing ecological thresholds, potentially leading to irreversible changes in forest structure and function (Bendall et al., 2022; Seidl et al., 2017). This vulnerability is particularly pronounced in Mediterranean regions, where the interaction between wildfires and droughts can push ecosystems toward critical thresholds (Turco et al., 2017), potentially reducing forests' capacity to provide essential services such as carbon sequestration and hydrological regulation (Scheffer et al., 2001; Thom, 2023). Comprehensive assessments of post-fire vegetation recovery under these stressors are essential for understanding how these ecosystems could change. Such evaluations also help to anticipate the broader impacts of environmental changes, ensuring the continued provision of ecosystem functions, including resource supply, biodiversity conservation, and ecosystem service maintenance.

Among Mediterranean ecosystems, central Chile faces intensified environmental stressors (Carrasco-Escaff et al., 2024; Garreaud et al., 2017). Located along the southern Pacific coast of South America, central Chile presents a unique opportunity to study the effects of shifting disturbance regimes and the interactions between wildfires and drought. The region is recognized for its high level of endemism, making it one of the world's biodiversity hotspots (Myers et al., 2000). Central Chile has been undergoing a significant dry period since 2010,

characterized by rising temperatures and a long-term decline in rainfall (Boisier et al., 2016; Garreaud et al., 2020; Miranda et al., 2020), with a persistent precipitation deficit ranging from 25% to 45% for over a decade, referred to as the Mega Drought (Alvarez-Garreton et al., 2021; Garreaud et al., 2017; Garreaud et al., 2020). The 'Mega Drought' intensified in 2019 and 2021, with rainfall dropping to less than 30% of climatological records and temperatures elevating during the spring and summer seasons (Arroyo et al., 2020). This phase, termed a Hyper Drought, marked the peak of an extended drought that has persisted for over a decade. During this time, the region showed an abrupt decline in vegetation productivity compared to the 2000–2010 baseline period (Miranda et al., 2023).

These severe drought conditions have coincided with an increase in wildfire frequency and magnitude, exacerbated by climatic conditions favorable to the spread of fires, posing substantial risks to native vegetation (Carrasco-Escaff et al., 2024; González et al., 2018; González, 2020; Holz et al., 2012; Urrutia-Jalabert et al., 2018). Similar to other Mediterranean ecosystems, the historical transformation of land use in central Chile has significantly reduced the extent of original forests, leaving remaining forests mostly confined to slopes and limited access to water. These forests, mainly found in mesic, south-facing areas, consist of three forests with different species compositions (forest subtypes): degraded thorny shrublands dominated by *Vachellia caven* & *Maytenus boaria* located in xeric areas; coastal Mediterranean forests primarily covered by *Cryptocarya alba* & *Peumus boldus* located in mesic conditions; and Andean Mediterranean forests dominated by *Quillaja saponaria* & *Lithrea caustica* established in drier, xeric locations (Donoso, 1982; Luebert & Plischoff, 2017; Rodriguez et al., 2018). However, dense canopy coverage areas are mostly restricted to topographically water-accumulating sites or microclimates that favor their persistence. Evergreen sclerophyllous forests in central Chile are adapted to withstand low soil water potential and fire (Rundel et al., 2016), and natural ignitions are rare in central Chile due to infrequent lightning-producing storms without rain (Ganteaume et al., 2013). Many tree and shrub species in central Chile's Mediterranean forests

exhibit resilience by regenerating primarily through resprouting, while some species maintain seeds even after low-intensity fires (Armesto et al., 2009; Becerra et al., 2018; Montenegro et al., 2004).

Post-fire and drought recovery in these forests frequently rely on stored resources within survival structures and the varying ability of basal buds, such as lignotubers, roots, rhizomes, and nodes, to sprout (Montenegro et al., 2004). While resprouting from underground structures is possible if sufficient carbon reserves are available, it may fail due to hydraulic limitations, making forest recovery uncertain if drought conditions persist and water balance declines (Nolan et al., 2021). Moreover, seedling recruitment after disturbances in Chile's sclerophyllous forests is limited by the rapid establishment of exotic species and the high abundance of herbivores (Holmgren et al., 2000). It remains unclear how different forests, and their dominant species, respond to post-fire recovery under drought-driven declines in productivity.

Remote sensing is a widely used tool for monitoring post-disturbance vegetation recovery (Kurbanov et al., 2022; Pérez-Cabello et al., 2021). Analysis of time-series vegetation indices derived from satellite imagery, such as the Normalized Difference Vegetation Index (NDVI), helps track vegetation recovery and photosynthetic capacity after events like wildfires (Abdel Malak & Pausas, 2006; Ireland & Petropoulos, 2015; Meng et al., 2018). However, the effects of the interaction of long-term drought, Hyper Drought, and wildfire have been poorly documented because they rarely occur in extensive areas, high intensity, and decadal long periods. The Landsat program has been instrumental in offering high-resolution imagery, supporting advanced research using techniques like LandTrendr (Kennedy et al., 2010), which enable in-depth analysis of vegetation changes following disturbances (Verbesselt et al., 2010; Viana-Soto et al., 2022; Wang et al., 2022). The NDVI has been widely used as a reliable proxy for assessing post-fire vegetation productivity recovery (Kurbanov et al., 2022; Veraverbeke et al., 2012; Vicente-Serrano et al., 2011). NDVI is closely associated with photosynthetic capacity, as its greenness primarily indicates

chlorophyll content (Pettorelli et al., 2005; Xu et al., 2024). By integrating advanced remote sensing techniques with analytical models (Bright et al., 2019; Smith-Ramírez et al., 2021; White et al., 2022), we enhanced our ability to characterize, assess, and monitor forest responses to fire, providing robust insights to inform conservation and management strategies effectively.

Given the expected increase in aridity for this region and the higher frequency of extreme events (Bozkurt et al., 2018; Garreaud et al., 2021), comprehensive assessments at both regional and local scales were crucial for enhancing our understanding of vegetation recovery. While recent studies have begun to explore the complex relationships between forests, drought, and wildfires in central Chile (Carrasco-Escaff et al., 2024; Chávez et al., 2022; González et al., 2018; Smith-Ramírez et al., 2022), to our knowledge, no studies have directly addressed the specific effects of post-fire recovery in these ecosystems. Mediterranean forests in the Southern Hemisphere, particularly in central Chile, remain underrepresented in global analyses despite their ecological importance (Xu et al., 2024). As a result, there is a need for targeted research to better assess the dynamics of vegetation recovery in response to increasing climate stressors and fire severity.

Given the context described above, this research aims to characterize and compare short-term (5-year) forest recovery following wildfire, as measured by NDVI. We focused on recovery variability across different levels of drought and fire severity between forests of different species compositions (forest subtypes). Specifically, we sought to answer the following questions: Are there significant differences in forest recovery across levels of drought and fire severity, based on forest composition? Are there interaction effects between drought and fire severity that shape forest recovery? By addressing these questions, our research provides initial insights into how drought and fire severity shape recovery patterns within central Chile's Mediterranean ecosystems, establishing a foundation for further investigation into these dynamics.

Material and Methods

Study area

The study area is situated in central Chile, spanning from the Pacific coast to the Andean foothills, between 71.5° W and 70.0° W, and from 32.0° S to 36.0° S (Figure III.1). This region encompasses Chile's Mediterranean sclerophyllous shrublands and forests, stretching from coastal zones to the pre-Andean mountains. The area is a Mediterranean ecosystem, characterized by winter precipitation and a prolonged dry summer season, heavily influenced by the El Niño-Southern Oscillation (ENSO) (Garreaud et al., 2020). Annual precipitation ranges from approximately 220 mm in the central valley to around 700 mm along the coast, while mean annual temperatures range between 12 °C and 15.1 °C (data obtained from <http://explorador.cr2.cl/> accessed on 17 Jun 2024). Although this ecosystem typically endures one to two years of drought, since 2010 it has been experiencing an unprecedented, prolonged drought that continues to the present (Figure III.2), leading to a marked decline in vegetation productivity (Miranda et al., 2023).

Selection of Burned Forest Areas

We used fire perimeter and severity data from a previous study in the area (Miranda et al., 2022b). Forest spatial distribution and type were obtained from the official vegetation map provided by the National Forest Service (CIREN-CONAF, 2013, 2016; CONAF, 2022). From this dataset, which covers the four administrative regions of the study area and includes more than 5533 wildfires, we applied a multi-criteria filter for vegetation attributes considering natural forest, the main subtypes of Mediterranean sclerophyllous forest and shrublands (*Q. saponaria* & *L. caustica*, *V. caven* & *M. boaria*, and *C. alba* & *P. boldus*), and dense canopy cover. The selection of dense canopy cover prevented the retrieval of a combined spectral response. We avoided areas with multiple fires and ensured that there were no changes in land cover, such as urban development, plantations, or agricultural expansion, by evaluating five years before and after

the wildfires. This was performed using the LandTrendr change detection algorithm (Kennedy et al., 2018) and visually confirmed with Google Earth imagery. Consequently, 44,108 pixels from 42 wildfires, spanning 1992 to 2017, met the vegetation, wildfire, and land-use criteria (Figures III.1 and III.2, and Table III.S1). The total number of burned pixels selected varied annually, with the largest number being in 2017 due to the mega-fire season (Figure III.2) (Bowman et al., 2019).

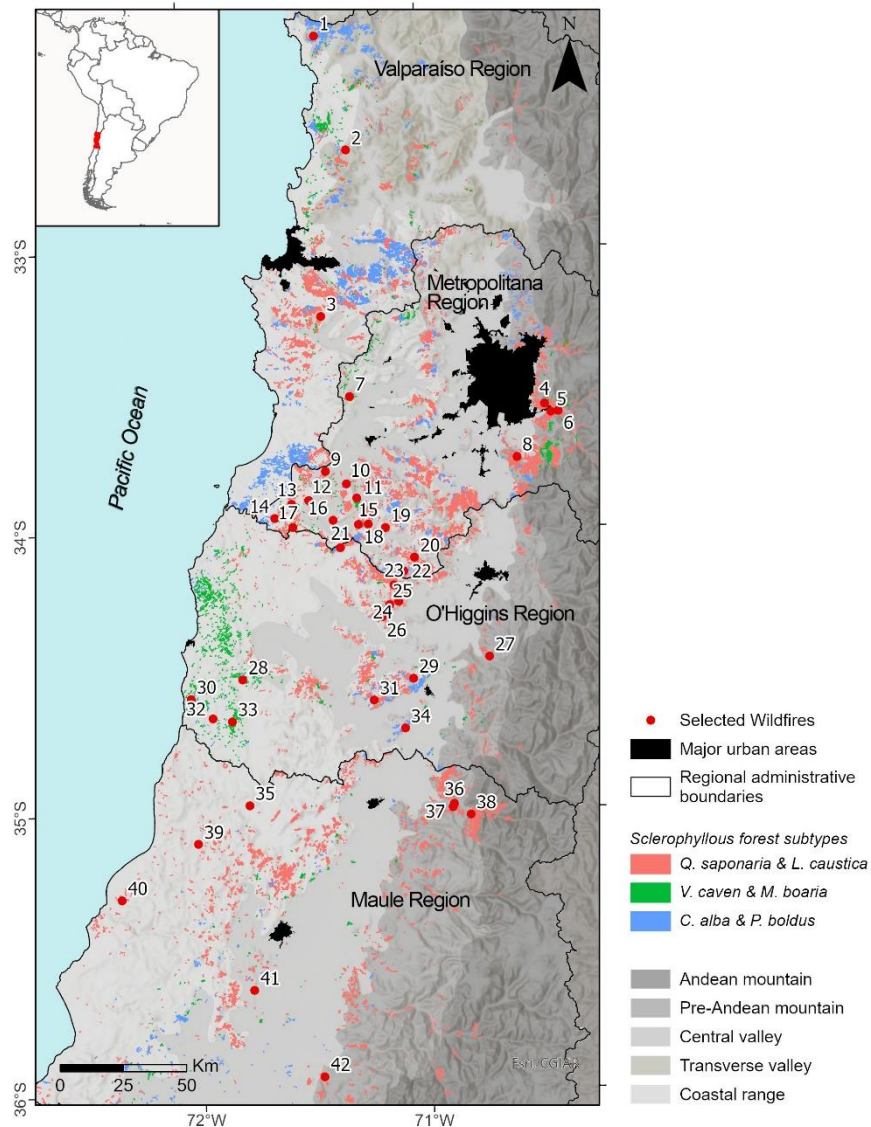


Figure III.1. Study area. Locations of the wildfires analyzed in central Chile, occurring between 1992 and 2017, based on data from Miranda et al. (Miranda et al., 2022b) and vegetation maps from CIREN-CONAF and CONAF (CIREN-CONAF, 2013, 2016; CONAF, 2022). Numbers in the figure indicate the fire ID used in this study; see details in Table S1.

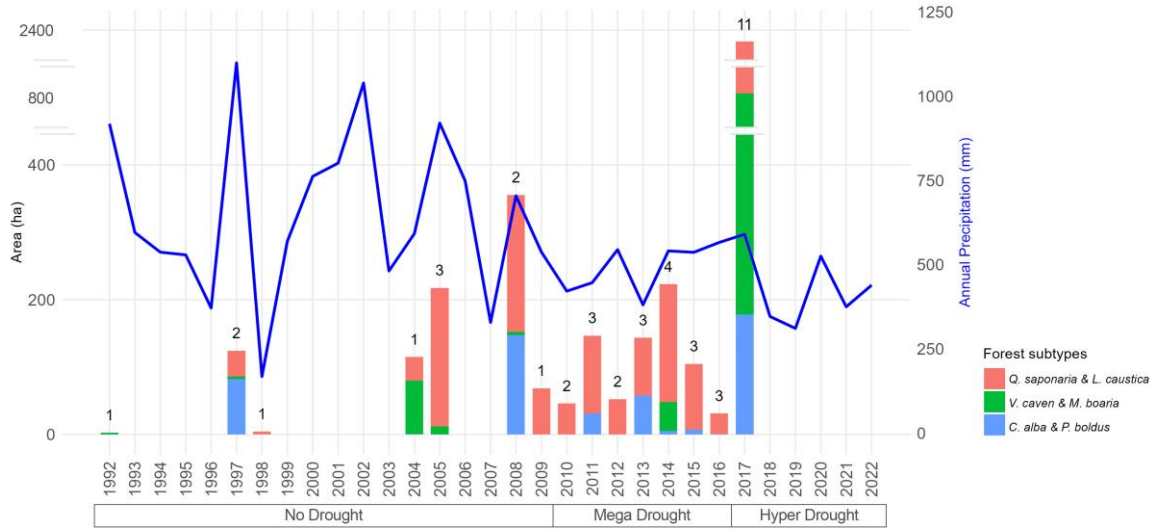


Figure III.2. Temporal distribution of burned areas analyzed by forest subtype. Above the bars are indicated the number of selected wildfires by year. The blue line represents the annual precipitation from TerraClimate data (Abatzoglou et al., 2018), describing the three distinct drought periods analyzed in this study.

Landsat Time Series for Post-Fire Recovery

We implemented all our input data and processing in Google Earth Engine (GEE), an open cloud-computing platform designed for geospatial analysis. GEE provides access to a comprehensive public catalog comprising satellite imagery, topographical data, and climate and environmental datasets (Gorelick et al., 2017). Prolonged periods of consistent satellite data were essential to assess interannual changes. We used NDVI to characterize the trajectory and spectral response post-fire. NDVI time series was derived using the LandTrendr spectral-temporal segmentation algorithm (Kennedy et al., 2018), which was proposed by Kennedy et al. (2010). This algorithm adopts a singular perspective based on a pixel's spectral history. It undergoes a systematic procedure to discern breakpoints that delineate intervals of sustained alterations or constancy in spectral trajectories. The identified breakpoints, characterized by the year of occurrence and spectral index value, represent a pixel's spectral history as a sequence of vertices bounding line segments. The outcome is an idealized trajectory-based time series devoid of noise, where each observation is situated within the framework of a spectral-temporal trend. In this study, LandTrendr

contributes to two methodological steps. The first is detecting land use changes for selecting burned areas, and the second is collecting noise-reduced NDVI time series to evaluate the post-fire forest response. We opted for this adjusted data format instead of using unmodified surface reflectance to minimize the impact of minor fluctuations in time series data attributed to instabilities in climate, atmospheric conditions, phenology, solar angle, and limitations in available images, on the determination of post-fire NDVI recovery.

The dataset included images that had already undergone atmospheric and geometrical corrections. We utilized all available TM/ETM+/OLI/OLI2 Level-2, Collection 2, Surface Reflectance Tier 1 images from Landsat 5, 7, 8, and 9 (for details on pre-processing images, see Supplementary Materials), spanning the period from 1987 to 2022. Our focus was on the local summer season (21 December–31 March). In instances where cloud-free pixels were limited, the season was extended to ensure a representative summer composition, extending up to one month beyond the typical summer season if necessary (see cases in Table S2). This summer period was selected to minimize the presence of herbaceous vegetation from the wet season, thereby reducing potential confusion in post-wildfire forest recovery and concentrating on the regeneration of trees and shrubs. The result was a single cloud-free NDVI-band image per year, representing the median NDVI values for the summer season.

Post-fire Recovery Percentage

To evaluate forest recovery, we independently calculated the relative change in NDVI for each year following the wildfire, up to year 5, between pre-fire values for each fire (Equation (1), Figure III.S1). This calculation was repeated annually to create a 5-year time series, using the recovery index proposed by Lloret et al. (2011). This approach, focusing on recovery variability, provides a metric that captures the degree of recovery concerning the extent of damage experienced during a disturbance event and pre-disturbance levels. We explain this metric using our spectral index converted to a percentage, calculated as:

$$\%NDVI_{rec_i} = \frac{NDVI_{yi} - NDVI_{y1}}{NDVI_{pre} - NDVI_{y1}} \times 100 \quad (\text{Eq. 1})$$

where $NDVI_{yi}$ is the value of NDVI in the year of post-fire observation, $NDVI_{y1}$ is the value next to the disturbance at year 1 (we expect a lower value than pre-disturbance), and $NDVI_{pre}$ is the weighted NDVI value for the 5 years before the wildfire, with greater weight given to the pre-fire years. For $NDVI_{rec}$, values closer to 1 show greater recovery (1 = full recovery), values close to 0 show less recovery, and negative values show a decrease in recovery. This value allows comparison of recovery between forest subtypes and wildfires. We selected $NDVI_{y1}$ as a surrogate for post-fire vegetation conditions; this could represent both open-growing canopy recovery and the presence of a remnant or recovery of overstory trees (Collins & Roller, 2013; Donato et al., 2009).

Statistical Analysis of Recovery Differences in Drought Levels and Fire Severity

We structured our analysis by categorizing drought conditions into three distinct levels: No Drought (1992–2009) as the climate reference (González et al., 2018), the Mega Drought (2010–2016) (Boisier et al., 2016; Garreaud et al., 2020), and the Hyper Drought (2017–2022), which represents the most severe stage of the prolonged drought, including 2019 and 2021, the driest and warmest years on record during this period (Miranda et al., 2020). Additionally, we classified fire severity using Relative Delta Normalized Burn Ratio (RdNBR) (Miller & Thode, 2007) (Equation (2)), and classified it into two categories: medium severity (316–640 RdNBR) and high severity (≥ 641 RdNBR). We excluded low-severity (69–315 RdNBR) pixels because there were fewer than 200 observations, which were concentrated in *Q. saponaria* & *L. caustica*. We ran a subsample selection to avoid slight differences being considered statistically significant due to the large sample sizes (Figure III.2). For resampling, pixels were split into groups by combining drought level and fire severity. Within each group, pixels were drawn using stratified random sampling, ensuring samples were proportional to the

strata (Table S3). All statistical analyses were performed in R software version 4.4.1 (Team, 2020).

$$\text{RdNBR} = \frac{\text{PreFireNBR} - \text{PostFireNBR}}{\sqrt{\text{ABS}(\text{PreFireNBR})}} \quad (\text{Eq. 2})$$

We examined the effects of drought and fire severity on the recovery of the three forest subtypes following fire disturbances, as well as potential interactions between these factors. We conducted a two-way analysis of variance (ANOVA) to determine significant differences in post-fire vegetation recovery among drought levels and fire severity categories for each forest subtype, and to test for factor interactions. Factor interaction refers to the case where each factor not only exerts an effect on the response variable (described as main effects), but also influences the other factor, resulting in additional joint effects on the response variable (known as interaction effects). We utilized type III and II approaches for calculating sums of squares in two-way ANOVA, depending on the presence or absence of interactions between factors and the imbalance of the data (Langsrud, 2003). When a significant difference was detected in the ANOVA, we conducted a post hoc analysis using Tukey's Honestly Significant Difference (HSD) test to identify specific differences between groups. If the interaction was significant, we explored which factor was significant at each level of the other factor. In cases where the interaction was not significant, we focused on examining the main effects. Before conducting the ANOVA, we assessed the assumptions of normality and homoscedasticity by inspecting the residuals of each model. To evaluate normality, we applied the Kolmogorov–Smirnov test with the Lilliefors correction, while homoscedasticity was evaluated using the Levene test.

To describe drought periods, we used the annual Palmer Drought Severity Index (PDSI) from TerraClimate data (Abatzoglou et al., 2018), a widely recognized metric for assessing drought intensity that integrates temperature and precipitation data to estimate relative soil moisture levels (Palmer, 1965). Negative PDSI values indicate drier conditions, while positive values suggest

wetter conditions, offering insights into the severity and duration of short-term and prolonged drought periods.

Result

The NDVI recovery five years post-fire exhibited differences across forest subtypes. In *Q. saponaria* & *L. caustica*, significant effects were identified for drought level (ANOVA: $F = 203.518$, $df = 2$, $p < 2.2 \times 10^{-16}$), fire severity (ANOVA: $F = 30.436$, $df = 1$, $p < 2.2 \times 10^{-16}$), and the interaction between these factors on NDVI recovery at year five (ANOVA: $F = 3.263$, $df = 2$, $p = 0.038$). We observed the highest recovery under conditions of No Drought and High fire severity, while the lowest recovery occurred during Hyper Drought across both fire severity levels (Tukey's multiple comparison test, $p < 0.01$) (Figure III.3, Tables S5 and S6). Given the interaction between factors (Figures III.3 and III.S2), the significance of the interaction of fire severity for each drought level group was evaluated, showing significance only for No Drought and Mega Drought conditions ($p < 0.01$). For the *V. caven* & *M. boaria*, we noted significant effects for drought level (ANOVA: $F = 173.88$, $df = 2$, $p < 2.2 \times 10^{-16}$), while fire severity did not show significant effects (ANOVA: $F = 8.829$, $df = 1$, $p = 0.003$), nor did the interaction between these factors on NDVI recovery at year five (ANOVA: $F = 0.276$, $df = 2$, $p = 0.759$). The highest recovery rates were recorded under both No Drought and Mega Drought conditions, whereas the lowest recovery occurred under Hyper Drought at high severity ($p < 0.01$) (Figure III.3 and Table III.S4). In the case of *C. alba* & *P. boldus*, significant effects were found for both drought level (ANOVA: $F = 186.892$, $df = 2$, $p < 2.2 \times 10^{-16}$) and fire severity (ANOVA: $F = 73.491$, $df = 1$, $p < 2.2 \times 10^{-16}$), along with their interaction (ANOVA: $F = 15.102$, $df = 2$, $p = 3.3 \times 10^{-07}$). The highest recovery was observed under No Drought conditions across all fire severity levels, with the lowest recovery noted during Hyper Drought ($p < 0.01$). The interactions between fire severity were found to be significant for each drought level, affecting NDVI recovery ($p < 0.01$) (Figure III.3, Table III.S5).

A descriptive analysis of the overall means indicating marked differences among forest subtypes showed the highest recovery in high severity than medium severity (Figures III.3 and III.S3, Table III.S6). For high severity, *C. alba* & *P. boldus* achieved the highest recovery during No Drought levels, averaging

approximately 100%. This was followed by *Q. saponaria* & *L. caustica* at 89.8%, and *V. caven* & *M. boaria* at 63.0%. Under Mega Drought, recovery was higher for *Q. saponaria* & *L. caustica* (80.2%), and *V. caven* & *M. boaria* (65.6%), whereas *C. alba* & *P. boldus* declined to 55.8%. As drought intensity increased to Hyper Drought, recovery converged to 39%, 30.5%, and 27.9% for *C. alba* & *P. boldus*, *Q. saponaria* & *L. caustica*, and *V. caven* & *M. boaria*, respectively. For medium fire severity, variability among the three forest subtypes was reduced under No Drought and Mega Drought conditions (69.2% to 45.3%), with the lowest recovery rates observed under Hyper Drought (21.1% to 30.3%). The confidence interval is shown in Table III.S6.

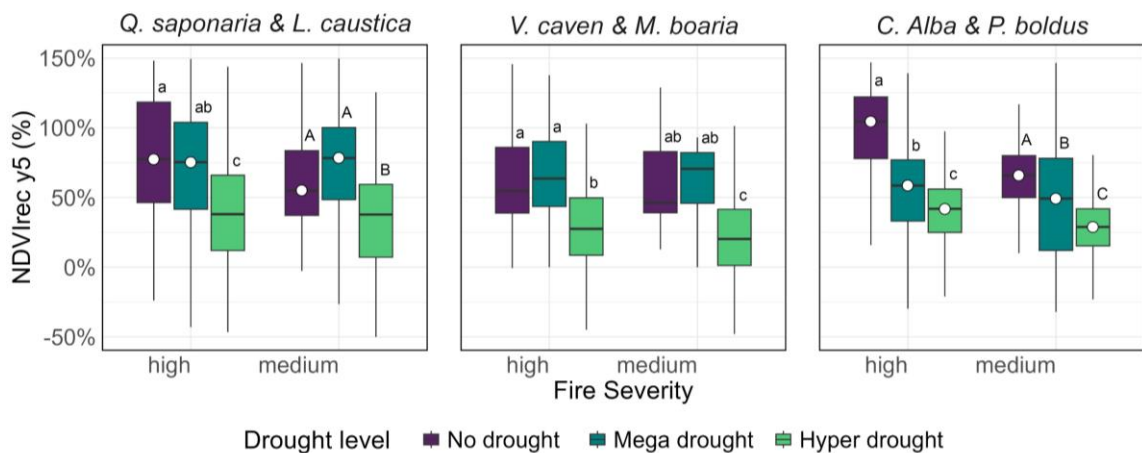


Figure III.3. The boxplots display the mean percentage of NDVI recovery five years post-fire. Uppercase and lowercase letters represent different groups analyzed due to interaction effect ($p < 0.01$). Into each group, different letters indicate significant differences between means, while the same letters are not significantly different from each other. A white point marks significant interaction effects of fire severity with each drought level ($p < 0.01$).

When considering the No Drought period as a reference for post-fire vegetation recovery, the results reveal notably lower recovery percentages across all forest subtypes during the Hyper Drought level, regardless of fire severity. Hyper Drought, both in high and medium fire severity, shows a significant difference relative to No drought ($p < 0.01$) (Figure III.4). Additionally, *C. alba* & *P. boldus* show significant differences for Mega Drought ($p < 0.01$) and lower relative recovery percentages compared to *Q. saponaria* & *L. caustica* and *V. caven* and *M. boaria*.

An analysis of the recovery trajectory from year one to year five revealed distinct differences based on drought level and fire severity. Wildfires occurring under the No Drought condition showed continuous recovery each year. In contrast, Mega Drought and Hyper Drought conditions exhibited interrupted recovery phases, particularly for *Q. saponaria* & *L. caustica* and *V. caven* & *M. boaria*. The Hyper Drought condition was notably associated with more pronounced disruptions in recovery, corresponding to the increased severity of drought and productivity decline observed in year 3 (Figure III.5 and Figure III.6).

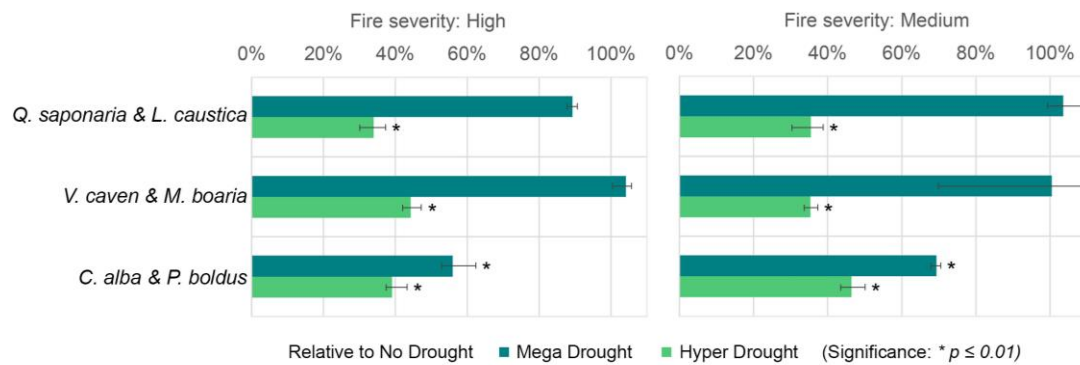


Figure III.4. Mean percentages of NDVIrec for Mega Drought and Hyper Drought relative to No Drought values as a reference period for high and medium severity. The asterisk shows significant differences.

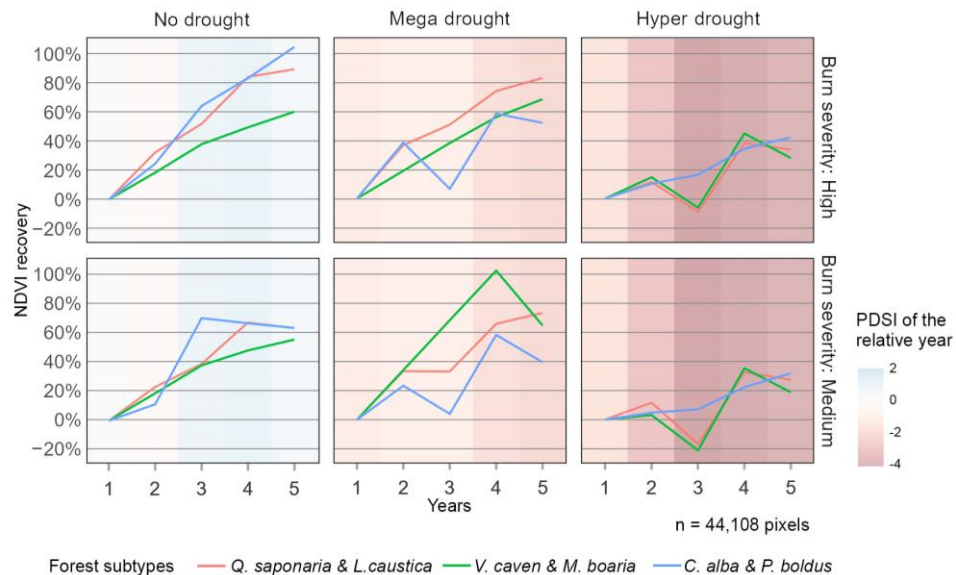


Figure III.5. The trajectory of mean NDVI recovery values from year 1 to year 5 for all forest subtypes and burn severity. The background color represents the average of the Palmer Drought Severity Index (PDSI) for each relative year after the fire derived from TerraClimate data (Abatzoglou et al., 2018).

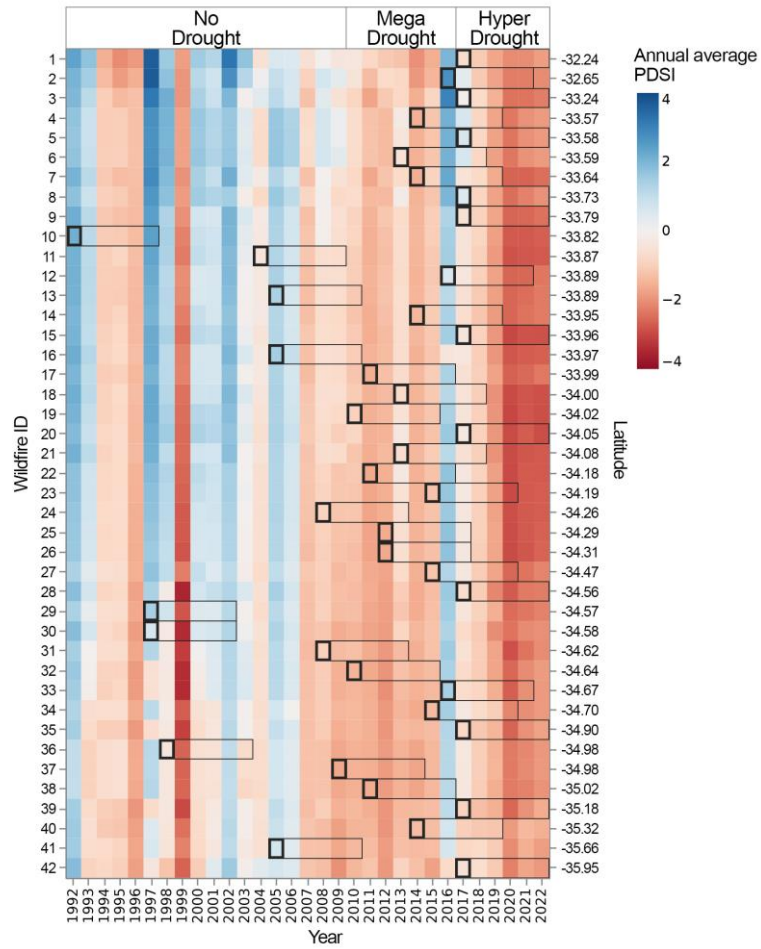


Figure III.6. Annual Palmer Drought Severity Index (PDSI) for each wildfire, derived from TerraClimate data (Abatzoglou et al., 2018). The bold squares indicate the year of wildfire occurrence, and the rectangles represent the short-term recovery period from year 1 to year 5 post-wildfire. Wildfires are arranged by latitude, from north to south.

Discussion

Understanding ecosystem responses to environmental variables is essential for effective conservation management and planning (IPBES, 2019; Jolly et al., 2015). In the case of Mediterranean vegetation ecosystems, evidence suggests their evolution is closely tied to a climatic history of increasing aridity throughout the Cenozoic (Rundel et al., 2016). This trend has been accompanied by persistent fire disturbances, resulting in a range of fire-adapted tolerance and reproduction mechanisms associated with fire ecology (Rundel et al., 2018). However, Chile represents an exception, where localized regional climatic changes linked to the Andean uplift during the Miocene led to a suppression of fires compared to other Mediterranean climate regions (Rundel et al., 2018; Rundel et al., 2016). Therefore, examining fire tolerance responses in the flora of central Chile provides a unique opportunity to understand the adaptive capacity of an ecosystem that evolved under the stress of climate-induced drought but now faces increasing wildfire pressure (Keeley, Bond, et al., 2011). This analysis can help predict potential ecological trajectories and alternative states for this ecosystem (Falk et al., 2022).

Our analysis revealed statistically significant differences in short-term post-fire recovery based on drought levels, fire severity, and interaction effects (Figure III.3). We observed disparity in recovery across forest subtypes, underscoring their distinct resilience capacities. Specifically, *C. alba* & *P. boldus*, which exhibited higher average recovery percentages under No Drought conditions, demonstrated increased vulnerability to increasing drought levels. In contrast, *Q. saponaria* & *L. caustica*, along with *V. caven* & *M. boaria*, showed greater recovery. However, under extreme and prolonged drought conditions, all forest subtypes experienced a significant decline in recovery. These findings suggest that, regardless of forest subtype or fire severity (which appeared to have a lesser effect than drought), a critical threshold of drought level substantially compromised forest recovery.

In other Mediterranean regions, such as Southern California and the Mediterranean Basin, severity and extended drought periods, especially in the early state post-fire, can significantly reduce soil moisture content, hindering seed germination and seedling establishment in vegetation (Blanco-Rodríguez et al., 2023; Dong et al., 2019; Vidal-Macua et al., 2017). This diminished water availability limits the capacity of Mediterranean plant species to initiate the regrowth process after a fire event, thereby impeding post-fire recovery (Rossetti et al., 2022). Blanco-Rodríguez et al. (Blanco-Rodríguez et al., 2023) report that the effect of drought duration on post-fire vegetation recovery varied depending on the aridity level, intensifying at extremes of aridity gradient (for semi-arid and humid areas) in the western Mediterranean Basins. In arid environments, the adverse effect of drought on recovery aligns with contemporary findings suggesting that adaptations to drought (for example, embolism resistance) may act antagonistically to the post-fire recovery process (Resco de Dios et al., 2018).

The higher recovery rates observed in *Q. saponaria* & *L. caustica*, as well as *V. caven* & *M. boaria*, during the Mega Drought likely stemmed from their greater adaptation to limited water availability compared to *C. alba* & *P. boldus*, which are typically associated with more humid environments (Miranda et al., 2020). Moreover, *Q. saponaria* & *L. caustica*, particularly those on northern slopes, frequently coexisted with xeric species well adapted to drought conditions. However, during the Hyper Drought, *Q. saponaria* & *L. caustica* exhibited lower recovery rates than *C. alba* and *P. boldus*. This discrepancy may relate to the browning phenomenon reported in sclerophyllous forests of central Chile in 2020 (Miranda et al., 2023), an event not directly analyzed here but potentially insightful for interpreting our results. Prior research noted that the xeric forest subtype, particularly in the Andean range and the northern extent of its distribution, demonstrated a more pronounced decline in productivity relative to other forest types, aligning with our observations (Miranda et al., 2020). It is possible that species in xeric forests are nearing a threshold of adaptive capacity under such

extreme conditions, where they increasingly reduce foliage in summer or activate alternative drought-adaptive strategies.

In thorny forests and shrublands, we observed relatively lower recovery rates of 27.9% and 21.1% for areas with high and medium fire severity, respectively. This outcome can be attributed to the traits (from plant to ecosystem) exhibited by *Vachellia caven* which are involved in its recovery dynamics. This species can regenerate rapidly through vegetative means, such as resprouting from stumps and roots, which is especially vigorous after disturbances such as grazing (Mochi et al., 2023). Its presence is associated with anthropogenic activities (e.g., overgrazing) (Velasco et al., 2023), rather than solely with the degradation of forest ecosystems under desertification, as previously suggested (Root-Bernstein et al., 2017). However, even with its drought tolerance (Fagg & Stewart, 1994), *V. caven* shows susceptibility to present hydraulic failure under extreme seasonal drought (Sepulveda M. et al., 2018). Thus, under hyper-drought conditions, extreme water deficits further restrict soil moisture availability, impeding both vegetative resprouting and seed germination. Seed germination, in particular, may depend on conditions such as the presence of grazing animals, which facilitate seed dispersal to suitable sites. Despite its prolific seed production, fire can destroy seed banks or severely impact germination success (Torres et al., 2014). Furthermore, the degraded state of these shrublands exacerbates soil erosion, altering soil properties and potentially limiting recovery potential under severe drought conditions (Lucas-Borja et al., 2019). While *V. caven* demonstrates considerable ecological resilience, its slower recovery during hyper-drought likely reflects a complex interplay between adaptive strategies and intense environmental stressors. Future studies should explore longer-term recovery dynamics to capture more nuanced recovery trends.

The analysis of post-fire NDVI recovery trajectories over the five years revealed significant differences based on drought levels and fire severity (Figure III.5). Forests experiencing No Drought conditions demonstrated consistent and positive recovery across all forest subtypes, indicating strong resilience.

Supporting field observations (Keeley et al., 2011) suggested that initial increases in NDVI were primarily driven by resprouting rather than new seedling growth, particularly under No Drought conditions. However, recovery was notably disrupted during the Mega and Hyper Drought periods, with setbacks observed across every forest subtype. Consistent with the recovery patterns observed in year five, the NDVI_{rec} trajectories during the Mega Drought showed that *C. alba* & *P. boldus* and *Q. saponaria* & *L. caustica* experienced a considerable decline in recovery by years three and five. This decline was particularly abrupt for *C. alba* & *P. boldus*, whose recovery percentages returned to similar levels in year one. These findings support that, for these forest subtypes, more severe drought conditions—evidenced by the continuity of drought—significantly impacted post-fire recovery. In Hyper Drought conditions, these setbacks became even more pronounced for *Q. saponaria* & *L. caustica* and *V. caven* & *M. boaria*, with recovery values reaching negative levels by year three (−20%). This decline was related to the persistence of drought conditions and an increase in drought severity, as indicated by more negative precipitation anomalies across all drought levels (Arroyo et al., 2020; Carrasco-Escaff et al., 2024).

As an alternative interpretation, the observed drop in NDVI recovery during the third year could be indicative of an ecological succession event. This trend may indicate a shift in community structure, where the decline in photosynthetic productivity by year three could be linked more closely to the senescence or replacement of herbaceous vegetation than to any substantial loss in resprouting shrubs or trees. Consequently, this pattern may signal a transition from herbaceous-dominated to shrub or tree-dominated cover types, potentially driven by climatic events (e.g., dry episodes) that favor such successional dynamics. Similar patterns have been documented in other Mediterranean ecosystems, such as those in California (Keeley, 1986; Keeley & Keeley, 1981). Following this period of decline, a marked recovery was observed, which again fell by year five. This aligns with the NDVI trajectories observed, where rapid vegetative responses likely drove initial recovery under No Drought conditions. In contrast, drought

conditions severely hampered these processes, resulting in less recovery (Figure III.5).

Our observations revealed that only *C. alba* & *P. boldus* achieved an average recovery rate of 100% under No Drought conditions and high fire severity. In contrast, *V. caven* and *M. boaria* displayed the lowest recovery rate at 63.0% under the same conditions. The slower recovery observed in *V. caven* & *M. boaria* suggests that these species face greater challenges in regenerating and restoring pre-fire conditions in the short-term than other forest subtypes. However, rather than indicating a lower recovery of *V. caven* & *M. boaria*, these patterns may reflect a post-fire shift in community structure, where species dominance changes toward *V. caven* and *R. trinervia* rather than evergreen species such as *C. alba* or *P. boldus*, particularly in areas affected by repeated fires (Smith-Ramírez et al., 2021). This shift, along with slower biomass recovery, coupled with a less complex structural response, indicates that after a fire, *V. caven* & *M. boaria* may take longer to re-establish, potentially allowing for the invasion of exotic species or loss of vegetation cover, which could negatively affect the overall recovery (Montoya-Tangarife et al., 2017; Vita et al., 1997). Despite being a species more adapted to extreme drought conditions, *V. caven* shows limited post-fire recovery capacity in short terms, hindering its regeneration.

Previous studies in the Mediterranean region of Central Chile have reported long-term post-fire coverage recovery of dense vegetation by remote sensing, spanning approximately 10 years (Smith-Ramírez et al., 2022). However, these studies often included mixed observations of forest, shrubland, and forest plantation, and were based on vegetation coverage rather than photosynthetic productivity. In contrast, our study has demonstrated significant differences in short-term NDVI recovery between forest subtypes. Similar or slower recovery rates have been reported in other Mediterranean regions through studies utilizing remote sensing-based vegetation indices (Blanco-Rodríguez et al., 2023; Hislop et al., 2018; Hope et al., 2007; Meng et al., 2015; Viedma et al., 1997; Wittenberg et al., 2007) (Table III.S7). These findings highlight the importance of considering

forest subtype-specific responses and using photosynthetic productivity metrics in assessing post-fire recovery dynamics.

We observed variation in forest recovery by fire severity (Figures III.3–5). This result can be attributed to the fire-adapted characteristics of the Mediterranean forest type. Mechanisms such as lignotubers, which are located underground, and epicormic buds, which are latent buds found on the trunk or main branches of the plant, can activate to sprout when the plant has lost its foliage due to fire (Montenegro et al., 2004; Nolan et al., 2021). Field observations within the study area further supported these results, demonstrating rapid vegetation regrowth following fire, even in the face of high fire intensity and extensive damage (Castillo et al., 2020). These findings highlight the resilience of Mediterranean forests to wildfires and underscore the importance of understanding the adaptive mechanisms that drive recovery in these ecosystems. Recovery was especially notable for *Q. saponaria* & *L. caustica* and *C. alba* & *P. boldus* under No Drought conditions, where significant differences in recovery rates were observed based on fire severity. However, in these Mediterranean ecosystems, once drought severity exceeds certain thresholds, fire severity becomes a less influential factor. Overall, the results emphasize the intricate interplay between fire severity, drought intensity, and forest type in shaping post-fire recovery dynamics.

Our analysis did not determine whether post-fire changes occurred in the structure and composition of the forests. We assumed that tree and shrub regeneration in the short term primarily occurred through resprouting (Castillo et al., 2020; Smith-Ramírez et al., 2021) (Figure III.7). Generally, studies measuring photosynthetic activity and post-disturbance forest productivity often lack field validations that explore the composition and structure of the forest. This omission may result from the high costs associated with analyzing large areas (Garreaud et al., 2020; Hilker et al., 2014; Miranda et al., 2020; Zhou et al., 2014). This limitation can lead to confusion in interpreting results, particularly given the differences in plant community composition (Barbosa & Asner, 2017).



Figure III.7. Examples of post-fire resprouting and regeneration in sclerophyllous forests of Central Chile. (a) *Quillaja saponaria* three months after the wildfire that occurred in 2024; (b) *Q. saponaria* & *Lithrea caustica* forest subtype area on slope. (c) *Q. saponaria* & *Lithrea caustica* forest subtype area, both one year after the wildfire that occurred in 2019. Credit: a. Ana Hernández-Duarte. b.c. Jean Pierre Francois.

In our calculation of the recovery index, we chose to use the NDVI from year one instead of the immediate post-fire NDVI from year zero. This decision was based on the potential for NDVI values to continue declining throughout the first year after a fire disturbance. Even when vegetation survives the initial burn, it may experience gradual declines during the post-fire period due to stress factors and delayed mortality (Rossetti et al., 2022; Serra-Burriel et al., 2021; Solans Vila & Barbosa, 2010). Furthermore, significant shifts in species composition during this period can lead to fluctuations in NDVI values (Epting & Verbyla, 2005; Hope et al., 2007). Additionally, changes in surface reflectance caused by the leaching of burned residues can further influence NDVI measurements after a fire (Meng et al., 2015; Miller et al., 2013).

Remote sensing tools, particularly satellite-derived spectral indices, have increasingly proven essential for assessing post-fire vegetation recovery (Senf, 2022; Xu et al., 2024) (Table III.S7). In Mediterranean ecosystems like central

Chile, on-the-ground monitoring is limited (Miranda et al., 2020; Smith-Ramírez et al., 2021). By selecting NDVI as our primary metric due to its proven applicability in Mediterranean regions (Hope et al., 2007; Vicente-Serrano et al., 2011) and its effectiveness in capturing disturbances like drought (Miranda et al., 2020; Miranda et al., 2023), we provided valuable insights into vegetation conditions based on changes in cover density and photosynthetic activity following wildfire. However, we acknowledged that NDVI cannot detail vegetation composition and structure, highlighting the challenge of integrating field data with remote sensing for a comprehensive understanding of complex ecosystems (Blanco-Rodríguez et al., 2023; Meng et al., 2015). Our focus on NDVI aimed to establish a foundation for future investigations that could utilize advanced remote-sensing technologies to explore specific vegetation characteristics, such as LiDAR or airborne laser scanning (Fernández-García et al., 2023; Gao et al., 2020; Pérez-Cabello et al., 2021). Recovery metrics based on remote sensing are particularly relevant for planning and managing conservation areas, as they inform adaptive management practices by identifying regions where post-disturbance recovery is slow or incomplete (Chazdon, 2003; Holl & Aide, 2011).

This study encountered unique challenges compared to other Mediterranean regions, concerning the fragmentation of natural forests in central Chile. The presence of forest remnants limited the spatial scale of our analysis (Armesto, 2007; Miranda et al., 2020; Schulz et al., 2010). This fragmentation resulted in a reduced number of pixels in areas with dense vegetation coverage, potentially affecting the accuracy of our analysis. Moreover, the precision of our outcomes was influenced by the inherent limitations of the official vegetation map products, which reported an overall accuracy ranging between 75% and 83% for the most recent vegetation map of the study regions (CONAF, 2022). However, the advent of next-generation fire remote-sensing products and model methodologies based on machine learning and artificial intelligence holds promise for enhancing the quality and efficacy of post-fire recovery studies (Mamadaliev et al., 2024; Pérez-Cabello et al., 2021).

Despite the projected changes in disturbance regimes due to climate change, research on post-fire vegetation recovery in the context of drought within the Chilean Mediterranean ecosystem remains scarce. Extensive research has highlighted the profound impacts of climate change on forest structure, disturbance patterns, and carbon storage, particularly in Mediterranean regions (Allen, 2003; Anderegg et al., 2015; Lloret et al., 2012). The vulnerability of central Chile's Mediterranean forest to wildfires during prolonged droughts highlights the critical intersection between climate stressors and ecological resilience. Long-term observations suggest that climate change has reshaped natural disturbance regimes, increasing ecosystem susceptibility to severe disturbances like wildfires (Seidl et al., 2017; Sommerfeld et al., 2018; Thom, 2023). This is particularly evident in central Chile, where the interplay between the prolonged Mega Drought and subsequent Hyper Drought has intensified ecosystem vulnerability, compromising short-term vegetation recovery. Prolonged and severe droughts can deplete the soil seed bank and impair resprouting mechanisms, resulting in slower and less predictable recovery processes. Drier conditions may lower the threshold at which disturbances trigger shifts to alternative ecosystem states, as even minor changes in disturbance regimes can be transformative (Batllori et al., 2019; Batllori et al., 2020).

In this study, we adopted a categorical approach to classify drought conditions into three well-documented phases: No Drought (1992–2009) as the climate reference, Mega Drought (2010–2016), and Hyper Drought (2017–2022) (Alvarez-Garretón et al., 2021; Arroyo et al., 2020; Boisier et al., 2016; Garreaud et al., 2017; Garreaud et al., 2020; Miranda et al., 2023). This approach allowed us to analyze post-fire recovery across distinct drought periods. While it facilitated a landscape-level perspective on forest recovery, we acknowledge its limitations, particularly regarding potential boundary effects for fires occurring near period transitions and the absence of continuous drought measures such as the PDSI. These constraints may influence recovery trajectories, and our findings should therefore be viewed as initial insights into the complex interactions between

drought severity and post-fire recovery. Despite these limitations, our findings contribute to a better understanding of recovery thresholds in Mediterranean forests and how prolonged droughts may undermine these thresholds. Understanding the thresholds of forest resilience and resistance to climate extremes, such as droughts, is crucial for forest conservation and ecological restoration efforts (Holl & Aide, 2011). This study provides valuable insights into the complex interplay between drought and fire, emphasizing the need for integrating comprehensive vulnerability assessments into sustainable forest management. Given the shifts in fire regimes, post-disturbance ecosystem trajectories, and increasing aridity—especially in southern Mediterranean regions (Essa et al., 2023; Gill et al., 2017; Miranda et al., 2023)—our findings underscore the critical role of post-fire climate in vegetation recovery. The future resilience of Mediterranean forests may face increasing challenges due to the rising frequency of extreme droughts projected for this region, highlighting the need for further research on the long-term implications of these changes.

Conclusions

The interaction between drought and wildfire presents significant challenges for the recovery of Mediterranean forest ecosystems, particularly in central Chile, where the magnitude of these disturbances has been exacerbated in the last decades. The vulnerability of central Chile's Mediterranean ecosystems to prolonged droughts underscores the critical intersection between climate stressors and ecological resilience, emphasizing the need for targeted conservation strategies. This study highlights the urgent need for comprehensive monitoring of forest recovery dynamics in response to such disturbances. Our findings indicate that the level of drought plays a pivotal role in determining post-fire recovery rates. The observed variation in recovery rates among different forest subtypes under varying drought conditions and fire severity emphasizes the need for further investigation into the factors influencing post-fire recovery, as well as their complex interactions. These factors include species-specific traits, the duration of drought, and other ecological considerations. Understanding these dynamics is essential for forecasting future forest resilience in the face of climate change, particularly as drought frequency and intensity are expected to increase.

The insights gained from this study not only advance our understanding of Mediterranean forest recovery but also provide a valuable resource for policymakers and land managers aiming to mitigate the impacts of climate change on this forest.

Supplementary Materials

Methodology for Pre-processing Landsat images

The satellite images dataset was based on 30-meter spatial resolution Landsat images provided by the United States Geological Survey (USGS) obtained from the GEE platform (<https://developers.google.com/earth-engine/datasets/catalog/landsat>). Snow, clouds, and cloud shadow pixels have been masked from each image using the pixel quality band provided by Landsat surface reflectance dataset. This band contains pixel quality attributes generated from the CFMASK algorithm (Foga et al., 2017). We homogenized OLI and OLI+ bands to match the rest of the sensor data to allow inter-sensor compositing. The medoid pixel compositing method was used, whereby for a given image pixel, the medoid is the value numerically nearest to the median of all corresponding pixels among the considered images. Medoids are akin in concept to means or centroids; however, medoids are always members of the dataset (Flood, 2013). The medoid compositing was chosen for each year, considering all images from any sensor for the summer season to the years of the analyses. The medoid compositing method is a means of mitigating the variability that may arise from the use of maximum or minimum compositing methods while also preserving the original pixel values, in contrast to the summary statistics that are often derived from mean or median compositing methods (Bright et al., 2019).

Figures

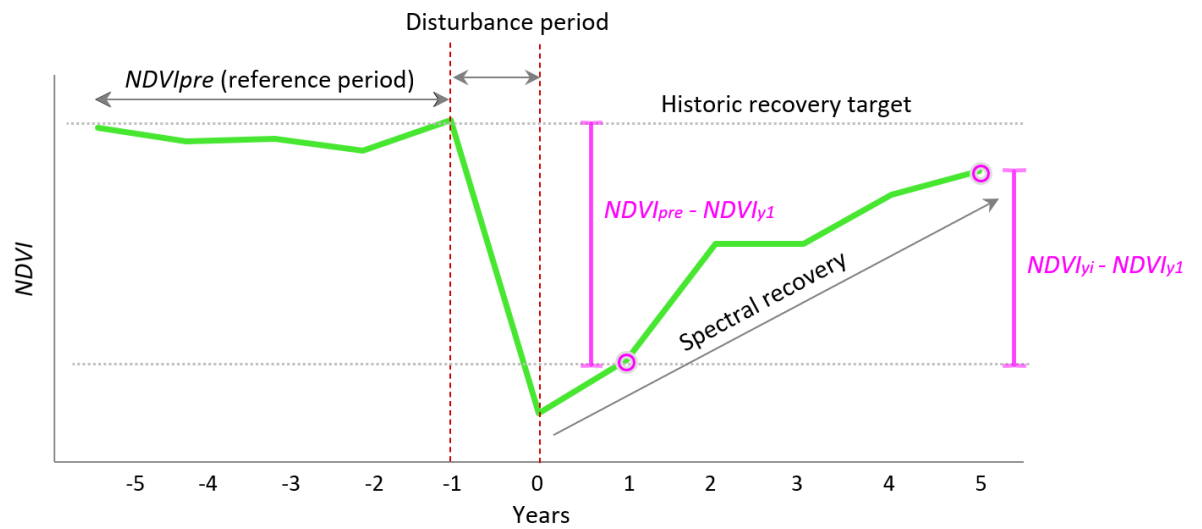


Figure III.S1. The spectral recovery metric scheme (NDVIrec) used in this research is described in Equation 1.

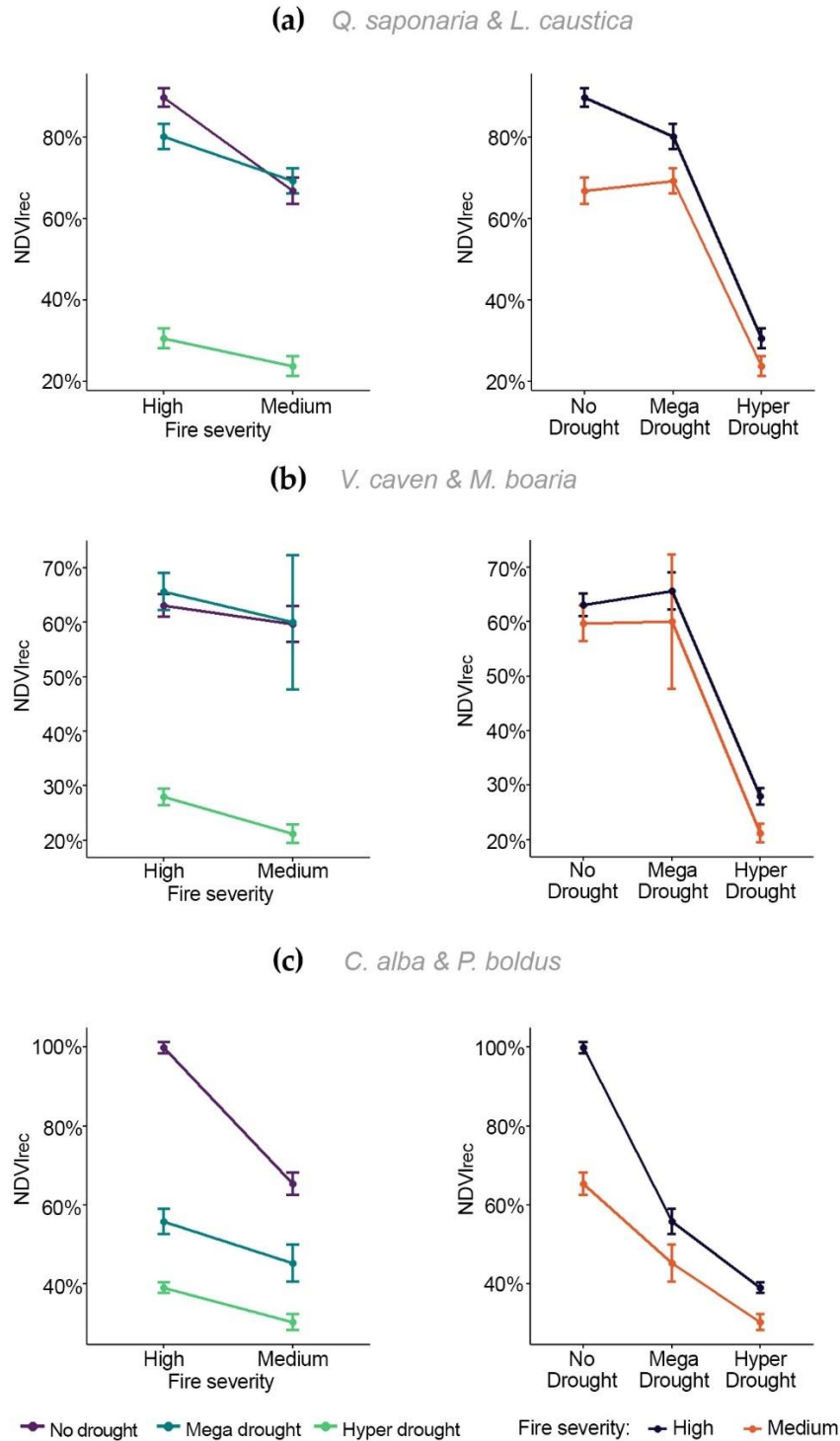


Figure III.S2. Interaction plot. For each forest subtype, the interaction plots illustrate the relationship between both factors, fire severity and drought levels (x-axis). The y-axis represents the response variable NDVIrec at year five. Parallel lines in the interaction plots suggest no interaction between factors, indicating similar recovery patterns across different levels of fire severity and drought. In this case, there is a significant interaction effect as the slopes are unequal. For (a) *Q. saponaria* & *L. caustica*. (b) *V. caven* & *M. boaria* and (c) *C. alba* & *P. boldus*.

		<i>Q. saponaria</i> & <i>L. caustica</i>			<i>V. caven</i> & <i>M. boaria</i>			<i>C. alba</i> & <i>P. boldus</i>		
		Drought severity			Drought severity			Drought severity		
		No Drought	Mega Drought	Hyper Drought	No Drought	Mega Drought	Hyper Drought	No Drought	Mega Drought	Hyper Drought
Fire Severity	High	90% -	80% 89%	31% 34%	63% -	66% 104%	28% 44%	100% -	56% 56%	39% 39%
	Medium	67% -	69% 104%	24% 35%	60% -	60% 100%	21% 35%	65% -	45% 69%	30% 46%

☐ Climatic Reference

Figure III.S3. Average NDVIrec values summarized by forest subtype at year 5. Bold values represent the mean percentage of NDVIrec, while regular values indicate the percentage of NDVIrec relative to the climatic reference.

Tables

Table III.S1. Wildfires selected in the study area and their characteristics.

ID	ID CONAF	Fire Name	Fire year	Administrative Region	Forest subtype	Wildfire area (ha)	Lat	Lon
1	ID189237	Santa Maria - Los Molles	2017	Valparaíso	Qs & Lc, Vc & Mb, Ca & Pb	1,190.30	-32.24	-71.49
2	ID189192	Madre del Agua	2016	Valparaíso	Qs & Lc	417.2	-32.65	-71.32
3	ID189119	Lo Orozco	2017	Valparaíso	Qs & Lc, Vc & Mb	169.9	-33.24	-71.42
4	ID169148	El Penon	2014	Metropolitana	Qs & Lc	606,3	-33.57	-70.51
5	ID189223	El Toyo	2017	Metropolitana	Qs & Lc	891,8	-33.58	-70.44
6	ID169133	El Manzano	2013	Metropolitana	Qs & Lc	445.4	-33.59	-70.41
7	ID169171	El Carrizo	2014	Metropolitana	Vc & Mb, Ca & Pb	14,173,5	-33.64	-71.37
8	ID189257	Rinconada de Pirque	2017	Metropolitana	Qs & Lc, Ca & Pb	3,228.20	-33.73	-70.58
9	ID189124	San Rafael De Puro	2017	Metropolitana	Qs & Lc	130	-33.79	-71.41
10	ID39037	Los Maitenes	1992	Metropolitana	Qs & Lc, Vc & Mb, Ca & Pb	497.2	-33.82	-71.34
11	ID112326	Cruce Las Aranas	2004	Metropolitana	Qs & Lc, Vc & Mb, Ca & Pb	1,911.40	-33.87	-71.33
12	ID189195	Quilamuta	2016	Metropolitana	Qs & Lc, Vc & Mb	511.2	-33.89	-71.50
13	ID118979	La Manga	2005	Metropolitana	Qs & Lc, Vc & Mb	2,057.20	-33.89	-71.61
14	ID169040	Corneche	2014	Metropolitana	Qs & Lc, Ca & Pb	255.8	-33.95	-71.63
15	ID189264	Lo Chacon	2017	Metropolitana	Ca & Pb	6,035.80	-33.96	-71.28
16	ID118915	Longovilo	2005	Metropolitana	Qs & Lc	344.8	-33.97	-71.40
17	ID151627	Quelentaro	2011	O'Higgins	Qs & Lc	94.2	-33.99	-71.56

ID	ID CONAF	Fire Name	Fire year	Administrative Region	Forest subtype	Wildfire area (ha)	Lat	Lon
18	ID169139	El Membrillo	2014	Metropolitana	Qs & Lc, Vc & Mb, Ca & Pb	1252.52	-34.00	-71.28
19	ID146674	Cuesta Alhue	2010	Metropolitana	Qs & Lc	1,020.00	-34.02	-71.20
20	ID189263	Talami	2017	Metropolitana	Qs & Lc, Va & Pb	7,747.70	-34.05	-70.99
21	ID169120	Cruce Santa Ines	2013	O'Higgins	Qs & Lc	217.1	-34.08	-71.37
22	ID151674	La Palmeria	2011	O'Higgins	Qs & Lc, Va & Pb	1,490.40	-34.18	-71.12
23	ID177153	La Palmeria 4	2015	O'Higgins	Qs & Lc	576,2	-34.19	-71.12
24	ID136426	Quebrada Quillyquen	2008	O'Higgins	Qs & Lc	126.4	-34.26	-71.61
25	ID157096	Rinconada de Idahue	2012	O'Higgins	Qs & Lc	71.1	-34.29	-71.15
26	ID157061	Pampa Idahue	2012	O'Higgins	Qs & Lc	52	-34.31	-71.17
27	ID177202	Las Nieves 4	2015	O'Higgins	Ca & Pb	688,9	-34.47	-70.75
28	ID189265	Rincon de Yaquil 4	2017	O'Higgins	Qs & Lc, Vc & Mb, Ca & Pb	40,366.70	-34.56	-71.28
29	ID68831	El Calabozo	1997	O'Higgins	Qs & Lc	1,636.10	-34.57	-71.04
30	ID68630	Las Cruces	1997	O'Higgins	Vc & Mb	66.4	-34.58	-71.98
31	ID136494	San Jose De Apalta	2008	O'Higgins	Qs & Lc	2,221.90	-34.62	-71.23
32	ID146656	Paredones	2010	O'Higgins	Vc & Mb	150.6	-34.64	-71.90
33	ID189226	Alto Nilahue	2016	O'Higgins	Vc & Mb	5,463.40	-34.67	-71.81
34	ID176579	Lo Orozco	2015	O'Higgins	Qs & Lc	19.1	-34.70	-71.07
35	ID189275	Las Cardillas	2017	Maule	Qs & Lc, Ca & Pb	52,908.60	-34.90	-71.99
36	ID73968	Los Maquis	1998	Maule	Ca & Pb	32.6	-34.98	-70.89
37	ID142593	La Aguadilla	2009	Maule	Qs & Lc, Vc & Mb, Ca & Pb	174.6	-34.98	-70.91
38	ID151664	Los Quenes	2011	Maule	Ca & Pb	424.5	-35.02	-70.81
39	ID189254	Tabunco-El Aguila Convenio	2017	Maule	Qs & Lc	3,215.10	-35.18	-71.99
40	ID169169	Quivolgo 1	2014	Maule	Ca & Pb	2,670,9	-35.32	-72.39
41	ID118965	Loncomilla	2005	Maule	Qs & Lc	742.2	-35.66	-71.76
42	ID189243	Llepo	2017	Maule	Qs & Lc	1,839.90	-35.95	-71.48

Abbreviation: Qs & Lc: *Quillaja saponaria* & *Lithrea caustica*, Vc & Mb: *Vachellia caven* & *Maytenus boaria*, Ca & Pb: *Cryptocarya alba* & *Peumus boldus*. Lat: Latitude, Lon: Longitude.

Table III.S2. Wildfire cases extending beyond the typical summer season.

ID	ID CONAF	Fire Name	Fire year	Extended time window in the analysis
10	ID39037	Los Maitenes	1992	one month after
30	ID68630	Las Cruces	1997	15 days before
18	ID169139	El Membrillo	2014	15 days after
3	ID189119	Lo Orozco	2017	15 days after

Table III.S3. Sample for two-way ANOVA.

Q. saponaria & L. caustica

Drought Level	Fire Severity	count	mean	median	sd	cv
Hyper Drought	high	386	0.31	0.36	0.49	1.58
Hyper Drought	medium	387	0.24	0.35	0.48	2.00
Mega Drought	high	386	0.80	0.80	0.61	0.76
Mega Drought	medium	386	0.69	0.79	0.62	0.90
No Drought	high	385	0.90	0.86	0.46	0.51
No Drought	medium	148	0.67	0.57	0.39	0.58
Total		2078				

V. caven & M. boaria

Drought Level	Fire Severity	count	mean	median	sd	cv
No Drought	high	228	0.63	0.55	0.32	0.51
No Drought	medium	85	0.60	0.46	0.30	0.50
Mega Drought	high	109	0.66	0.64	0.36	0.55
Mega Drought	medium	7	0.60	0.71	0.33	0.55
Hyper Drought	high	386	0.28	0.27	0.30	1.07
Hyper Drought	medium	341	0.21	0.20	0.31	1.48
Total		1156				

C. alba & P. boldus

Drought Level	Fire Severity	count	mean	median	sd	cv
No Drought	high	386	1.00	1.05	0.29	0.29
No Drought	medium	76	0.65	0.66	0.25	0.38
Mega Drought	high	174	0.56	0.59	0.41	0.73
Mega Drought	medium	104	0.45	0.48	0.48	1.07
Hyper Drought	high	360	0.39	0.42	0.24	0.62
Hyper Drought	medium	140	0.30	0.29	0.24	0.80
Total		1240				

Table III.S4. *Post-hoc*, Tukey's multiple comparison tests, confidence level 0.95, $p < 0.01$ (contrast).

Q. saponaria & L. caustica

High Fire Severity					
Drought Level	Estimate	SE	df	t ratio	p-value
No Drought -Mega Drought	0.096	0.0379	2072	2.525	0.031
No Drought -Hyper Drought	0.592	0.0379	2072	15.627	<.0001
Mega Drought - Hyper Drought	0.497	0.0379	2072	13.111	<.0001
Medium Fire Severity					
Drought Level	Estimate	SE	df	t ratio	p-value
No Drought -Mega Drought	-0.024	0.0509	2072	-0.471	0.885
No Drought -Hyper Drought	0.4318	0.0509	2072	8.487	<.0001
Mega Drought - Hyper Drought	0.4557	0.0509	2072	12.036	<.0001

V. caven & M. boaria

Drought Level : Fire Severity	Difference	Lower	Upper
Mega drought: high - No drought: high	0.025	-0.079	0.13
Hyper drought: high - No drought: high	-0.35	-0.43	-0.28
No drought: medium - No drought: high	-0.03	-0.15	0.08
Mega drought: medium - No drought: high	-0.03	-0.37	0.31
Hyper drought: medium - No drought: high	-0.42	-0.49	-0.34
Hyper drought: high - Mega drought: high	-0.38	-0.47	-0.28
No drought: medium - Mega drought: high	-0.05	-0.18	0.07
Mega drought: medium - Mega drought: high	-0.06	-0.40	0.29
Hyper drought: medium - Mega drought: high	-0.44	-0.54	-0.35
No drought: medium - Hyper drought: high	0.31	0.21	0.42
Mega drought: medium - Hyper drought: high	0.32	-0.01	0.66
Hyper drought: medium - Hyper drought: high	-0.06	-0.13	0.00
Mega drought: medium - No drought: medium	0.00	-0.34	0.35
Hyper drought: medium - No drought: medium	-0.38	-0.49	-0.28
Hyper drought: medium - Mega drought: medium	-0.38	-0.72	-0.05

C. alba & P. boldus

High Fire Severity					
Drought Level	Estimate	SE	df	t ratio	p-value
No Drought -Mega Drought	0.440	0.0283	1234	15.558	<.0001
No Drought -Hyper Drought	0.607	0.0227	1234	26.779	<.0001
Mega Drought - Hyper Drought	0.168	0.0286	1234	5.864	<.0001
Medium Fire Severity					
No Drought -Mega Drought	0.200	0.0467	1234	4.290	0.0001
No Drought -Hyper Drought	0.350	0.0441	1234	7.929	<.0001
Mega Drought - Hyper Drought	0.149	0.0441	1234	3.726	0.0006

Table III.S5. Post-hoc pairs tests for drought level within each category of fire severity.

Q. saponaria & L. caustica

Drought Level	df1	df2	F ratio	<i>p</i>-value
No Drought	1	2072	20.297	<0.0001
Mega Drought	1	2072	8.379	0.0038
Hyper Drought	1	2072	3.288	0.0699

C. alba & P. boldus

Drought Level	df1	df2	F ratio	<i>p</i>-value
No Drought	1	1234	78.806	<0.0001
Mega Drought	1	1234	7.561	0.0061
Hyper Drought	1	1234	7.997	0.0048

Table III.S6. A confidence interval of ANOVA (Confidence level used: 0.95).

Q. saponaria & L. caustica

High Fire Severity					
Drought Level	Mean	SE	df	Lower	Upper
No Drought	0.898	0.0268	2072	0.845	0.950
Mega Drought	0.802	0.0268	2072	0.749	0.855
Hyper Drought	0.305	0.0268	2072	0.253	0.358
Medium Fire Severity					
No Drought	0.668	0.0433	2072	0.583	0.753
Mega Drought	0.692	0.0268	2072	0.640	0.745
Hyper Drought	0.237	0.0268	2072	0.184	0.289

V. caven & M. boaria

High Fire Severity					
Drought Level	Mean	SE	df	Lower	Upper
No Drought	0.630	0.0207	1150	0.590	0.671
Mega Drought	0.656	0.0300	1150	0.597	0.715
Hyper Drought	0.279	0.0159	1150	0.248	0.310
High Fire Severity					
No Drought	0.597	0.0339	1150	0.530	0.664
Mega Drought	0.600	0.1182	1150	0.368	0.832
Hyper Drought	0.211	0.0169	1150	0.178	0.245

C. alba & P. boldus

High Fire Severity					
Drought Level	Mean	SE	df	Lower	Upper
No Drought	0.998	0.0158	1234	0.583	1.29
Mega Drought	0.558	0.0235	1234	0.393	0.604
Hyper Drought	0.390	0.0163	1234	0.252	0.422
Medium Fire Severity					
No Drought	0.653	0.0355	1234	0.583	0.723
Mega Drought	0.453	0.0304	1234	0.393	0.512
Hyper Drought	0.303	0.0262	1234	0.252	0.355

Table III.S7. Report of post-fire recovery observed in previous studies using satellite indices (adapted from Bright 2019).

Location	Vegetation type	Authors	Year	Spectral index	Mean recovery time (year)
Spain	Mediterranean forest	Viedma et al.	1997	NDVI	1 to 18
California, USA	Chaparral	Hope et al.	2007	NDVI	10
Israel	Mediterranean forest	Wittenberg et al.	2007	EVI	3
Spain	Semi-arid	Vicente-Serrano et al.	2011	NDVI	24
SE Australia	Sclerophyll forest	Hislop et al.	2018	NBR	8 to 10
Western, USA	Temperate forest	Meng et al.	2015	NDVI	
Western, USA	Temperate forest	Bright et al.	2019	NBR	9 to 13
Spain	Mediterranean forest	Rodríguez-Blanco et al.	2023	TCTB	> 5

Abbreviations: *NDVI* Normalize Difference Vegetation Index, *EVI* Enhanced Vegetation Index, *NBR* Normalized Burn Ratio, *TCTB* Tasseled Cap Transformation Brightness.

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Capítulo IV. Drivers of Post-Fire Vegetation Recovery of Mediterranean Forest in Chile

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Resumen

La recuperación forestal post-incendio en los ecosistemas mediterráneos es fundamental para comprender la resiliencia de los bosques, con implicaciones significativas para los esfuerzos de conservación y la captura de carbono. Sin embargo, los efectos combinados del cambio climático y las condiciones más cálidas y secas pueden dificultar la recuperación de la productividad de la vegetación en bosques naturales relativamente poco estudiados en el centro de Chile. Identificar los factores clave que facilitan el retorno a los niveles de productividad previos al incendio sigue siendo crítico. En este estudio, aplicamos modelos de Random Forest y series temporales de NDVI derivadas de imágenes Landsat para evaluar la recuperación de tres subtipos de bosques esclerófilos siempre verdes en el centro de Chile, analizando 42 incendios ocurridos entre 1992 y 2017. Incorporamos variables clave como el verdor previo al incendio, la severidad del fuego, la severidad de la sequía y factores topográficos para predecir los resultados de recuperación. Nuestros modelos mostraron valores de R-cuadrado que oscilaron entre 0.70 y 0.89, indicando diferencias en la recuperación entre los subtipos de bosque y variaciones en la importancia de los factores clave. La severidad de la sequía post-incendio y el NDVI previo al fuego surgieron como los factores más influyentes en la recuperación, mientras que las características topográficas y la severidad del incendio desempeñaron un papel menos relevante, pero con un efecto diferenciado según el tipo de bosque. Estos hallazgos subrayan la importancia de integrar condiciones ambientales previas al incendio como factores climáticos post-incendio al evaluar la dinámica de recuperación forestal. Este estudio proporciona información valiosa que puede servir como base para estrategias de manejo forestal y conservación, particularmente en el contexto del cambio climático.

Palabras clave: Interacción de perturbaciones, sequía, incendio, recuperación forestal, teledetección, Mediterráneo, Random Forest.

Abstract

Post-fire forest recovery in Mediterranean ecosystems is essential for understanding forest resilience, with significant implications for conservation efforts and carbon sequestration. However, the combined effects of climate change and drier and warmer conditions may hinder the recovery of vegetation productivity in relatively underexplored natural forests in central Chile. Identifying the key factors facilitating the return to pre-fire productivity levels remains critical. In this study, we applied Random Forest models and NDVI time series derived from Landsat imagery to assess the recovery of three evergreen sclerophyllous forest subtypes in central Chile, analyzing 42 wildfires between 1992 and 2017. We incorporated key variables such as pre-fire greenness, fire severity, drought severity, and topographic factors to predict recovery outcomes. Our models showed R-squared values ranging from 0.70 to 0.89, indicating differences in recovery across forest subtypes and variations in the importance of key factors. Post-fire drought severity and pre-fire NDVI emerged as the most influential factors for recovery, while topographic features and fire severity played a less dominant but differentiated role across forest subtypes. These findings underscore the importance of integrating both pre-fire environmental conditions and post-fire climatic factors when assessing forest recovery dynamics. This study offers valuable insights that can serve as a foundation for forest management and conservation strategies, particularly in the context of climate change. Future research should focus on utilizing higher-resolution climate data and conducting localized field studies to improve recovery predictions and strengthen resilience models for these vulnerable forest ecosystems.

Keywords: Disturbance interaction, drought, wildfire, forest recovery, remote sensing, Mediterranean, Random Forest.

Introduction

Wildfires frequently alter vegetation structures worldwide, hindering ecosystem productivity and affecting the carbon budget due to the slow and variable regrowth of vegetation (Zheng et al., 2023). In Mediterranean ecosystems, fires have historically shaped dynamic patterns, leading to the evolution of species adapted to regenerate after disturbances (Keeley, Pausas, et al., 2011; Naveh, 2007). However, climate change has increased wildfire frequency and severity through warmer, drier conditions alongside longer and more intense droughts, threatening the resilience of these ecosystems and challenging post-fire recovery efforts (Abatzoglou & Williams, 2016; Seidl et al., 2017).

In Central Chile, a critical Mediterranean region, natural fire ignitions are rare compared to other Mediterranean areas. However, human activities have intensified fire frequency over the last three centuries, exacerbated by a notable decline in rainfall (Fuentes & Muñoz, 1995; González, 2020). This region has been experiencing a significant dry period since 2010, known as the 'Mega Drought,' culminating in a 'Hyper Drought' in 2019, with rainfall dropping below 30% of the historical average (Garreaud et al., 2020; Miranda et al., 2023). These conditions, combined with increased wildfires, pose substantial risks to the survival of native vegetation, which, while adapted to low soil water potential and resprouting after fires, faces challenges under the intensified drought and fire regimes (Armesto et al., 2009; Becerra et al., 2018).

We recognized that climatic conditions critically affect post-fire vegetation recovery, with recent studies highlighting the impact of post-fire climate on regeneration processes (Blanco-Rodríguez et al., 2023; Xu et al., 2024). The expected increase in drought frequency and severity could severely restrict vegetation re-establishment (Bendall et al., 2022; Stevens-Rumann et al., 2018). Other factors influencing recovery include vegetation type, pre-fire greenness, fire severity, topography, and soil properties (Fernandez-Manso et al., 2016). Despite the ecological significance, studies have shown that Mediterranean ecosystems

in the Southern Hemisphere remain underrepresented. We emphasized the necessity for comprehensive assessments at regional and local scales to improve understanding of vegetation recovery after fire events. These evaluations are crucial for identifying areas requiring targeted management interventions and for developing accurate models to analyze the impacts of disturbances on ecological functions (Bright et al., 2019; Meng et al., 2015).

Since 1984, the Landsat program has provided high-resolution imagery, enabling advanced studies of vegetation changes post-disturbance using methodologies like LandTrendr and indices like NDVI, which effectively assess vegetation productivity recovery (Kennedy et al., 2010; Veraverbeke et al., 2012). Integrating precise remote sensing techniques with analytical models enhances our ability to monitor and predict ecosystem responses to fire, informing conservation and recovery strategies. However, gaps persist in understanding the combined effects of climatic factors and fire on vegetation recovery in Southern Hemisphere Mediterranean regions (Castillo et al., 2020). As climate patterns and disturbance regimes evolve, we face uncertainty in achieving desired management outcomes. These challenges highlight the need for adaptive management strategies that respond to shifting conditions and ensure ecosystem resilience (Daniel et al., 2017; Turner, 2010). Our study aims to address these gaps by providing a comprehensive assessment of post-fire vegetation recovery in Central Chile, contributing valuable insights into the broader understanding of Mediterranean ecosystem responses under changing climatic conditions.

In this study, we evaluated short-term vegetation productivity recovery (5 years) following wildfires at a regional scale. We quantified recovery by analyzing NDVI time series from Landsat images using the LandTrendr algorithm (Kennedy et al., 2018). This approach allowed us to assess post-fire spectral forest recovery across 42 wildfires over 25 years (1992–2017) in three Mediterranean sclerophyllous forest subtypes within central Chile. To gain deeper insights into the factors driving recovery, we utilized random forest models based on two indicators: NDVI recovery (NDVIrec) and absolute NDVI values. These models

allowed us to identify the key controls affecting recovery, including the importance and effects of variables related to the fire, post-fire climatic conditions, and environmental factors.

Material and Methods

Study Area

Located in central Chile, the study area extends from the Pacific coast to the Andean foothills, between longitudes 71.5°W and 70.0°W and latitudes 32.0°S and 36.0°S, covering an approximate area of 50,000 km² (Figure IV.1). The region experiences a Mediterranean climate with winter rains and dry summers, heavily influenced by the El Niño-Southern Oscillation (ENSO) (Garreaud et al., 2020). Precipitation varies annually from about 220 mm in the central valley to around 700 mm along the coastal regions, while average temperatures range from 12°C to 15.1°C (data sourced from <http://explorador.cr2.cl/>). Our research focused on wildfires from 1992 to 2017, impacting remnants of native sclerophyllous forests. These forests are predominantly located in mesic, south-facing slopes and are classified into three main subtypes: degraded thorny shrublands dominated by *Vachellia caven* and *Maytenus boaria*; coastal evergreen Mediterranean Forests primarily comprising *Cryptocarya alba* and *Peumus boldus*; and Andean evergreen Mediterranean Forests characterized by *Quillaja saponaria* and *Lithrea caustica* (Donoso, 1982; Luebert & Plischoff, 2017). Typically, this region experiences one to two years of drought. However, between 2010 and 2020, the area underwent an unprecedented drought, including 2019 with record high temperatures and decreased vegetation greenness compared to 2000–2010 (Arroyo et al., 2020; Miranda et al., 2023).

Selection of burned forest areas

Figure IV.2 outlines the detailed workflow for selecting burned forest areas and an overall research methodology. We gathered fire data from Miranda et al. (2022a), which included scar polygons and fire severity ratings from the local forest service (Corporación Nacional Forestal, CONAF) records. This information was cross-referenced with official vegetation maps (CIREN-CONAF, 2013, 2016; CONAF, 2022). Using a multi-criteria approach, we filtered the data to focus on native forests and specific Mediterranean sclerophyllous forest subtypes: Q.

saponaria & *L. caustica*, *V. caven* & *M. boaria*, and *C. alba* & *P. boldus*. This selection prioritized areas with dense canopy coverage to ensure clear spectral responses. Overlap with previously burned areas was avoided. To ensure no changes in land cover, we analyzed the areas using the LandTrendr algorithm (Kennedy et al., 2018), assessing changes five years before and after each fire and corroborating these findings with visual verifications via Google Earth imagery. This rigorous selection process identified 44,108 pixels affected by 42 wildfires between 1992 and 2017, as detailed in Figure IV.1, Figure IV.2, Table IV.1, and Table IV.S1. 2017 saw a peak in qualifying pixels, reflecting the scale of that year's mega-fire season (Bowman et al., 2019).

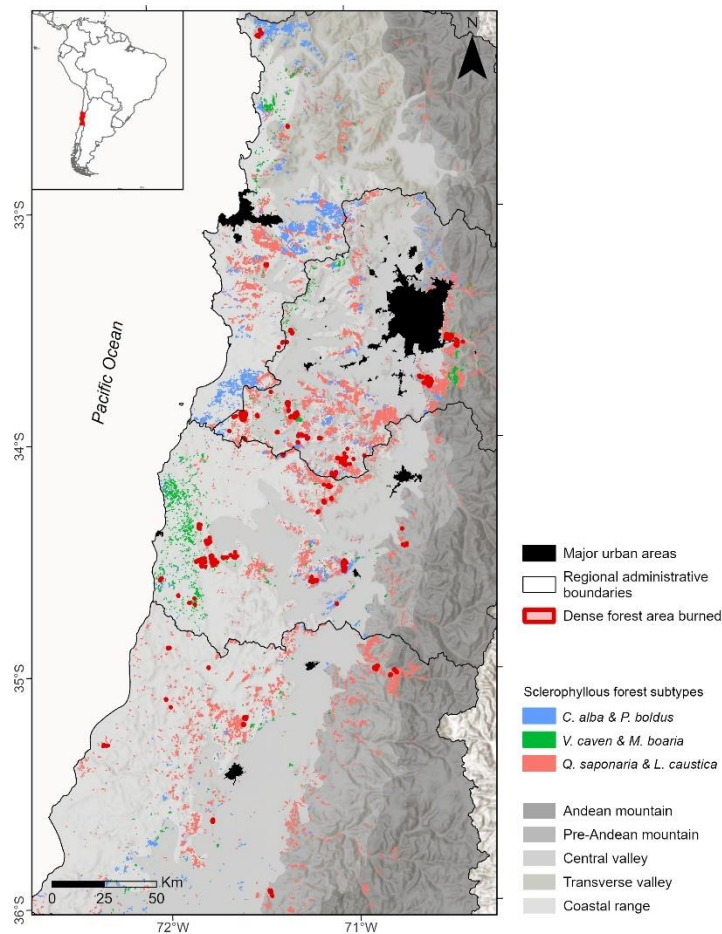


Figure IV.1. Study area. The location of the burned areas analyzed in central Chile, which occurred between 1992 and 2017, based on data from Miranda et al. (2022a).

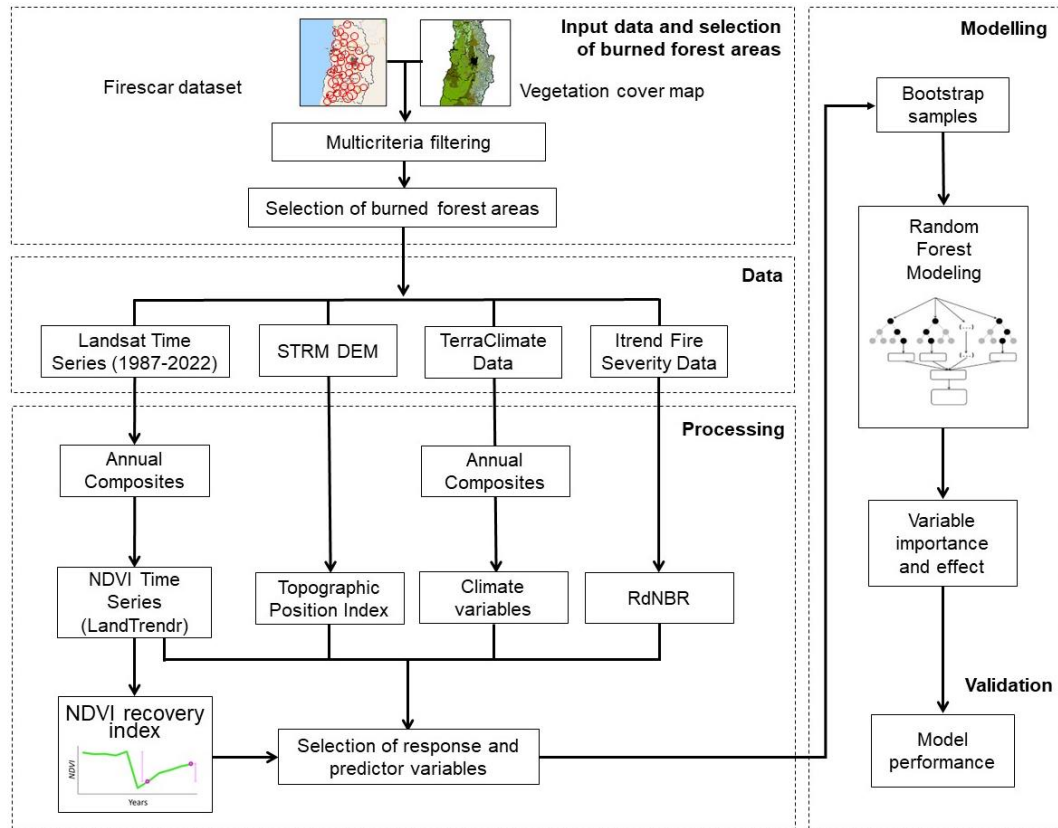


Figure IV.2. Overall research methodology flowchart. The study involved selecting burned forest areas and processing response and explanatory variables. Subsequently, we modeled post-fire vegetation recovery using Random Forest regression, implementing two distinct model types tailored to the response variables specific to each forest subtype. These models facilitated the evaluation of the relative importance and effects of several factors influencing post-fire vegetation recovery across central Chile.

Table IV.1. Characteristics of selected burned areas in the study area.

Forest wildfire season	Number of wildfires selected	Fire ID	Forest subtypes	Burn area (ha)	Chilean Administrative region
1992	1	11	<i>V. caven</i> & <i>M. boaria</i> ; <i>Q. saponaria</i> & <i>L. caustica</i>	2.7	Metropolitana
1997	2	29, 30	<i>V. caven</i> & <i>M. boaria</i> ; <i>C. alba</i> & <i>P. boldus</i> ; <i>Q. saponaria</i> & <i>L. caustica</i>	124.38	O'Higgins
1998	1	36	<i>Q. saponaria</i> & <i>L. caustica</i>	4.41	Maule
2004	1	11	<i>V. caven</i> & <i>M. boaria</i> ; <i>Q. saponaria</i> & <i>L. caustica</i> ; <i>C. alba</i> & <i>P. boldus</i>	115.02	Metropolitana
2005	3	13,16,41	<i>Q. saponaria</i> & <i>L. caustica</i> ; <i>V. caven</i> & <i>M. boaria</i>	217.44	Metropolitana Maule

Forest wildfire season	Number of wildfires selected	Fire ID	Forest subtypes	Burn area (ha)	Chilean Administrative region
2008	2	24,31	<i>Q. saponaria</i> & <i>L. caustica</i> ; <i>V. caven</i> & <i>M. boaria</i> ; <i>C. alba</i> & <i>P. boldus</i>	355.41	O'Higgins
2009	1	37	<i>Q. saponaria</i> & <i>L. caustica</i>	68.49	Maule
2010	2	19,32	<i>V. caven</i> & <i>M. boaria</i> ; <i>Q. saponaria</i> & <i>L. caustica</i>	46.08	Metropolitana, O'Higgins
2011	3	17,22,38	<i>Q. saponaria</i> & <i>L. caustica</i> ; <i>C. alba</i> & <i>P. boldus</i>	146.61	O'Higgins, Maule
2012	2	25,26	<i>Q. saponaria</i> & <i>L. caustica</i>	52.29	O'Higgins
2013	3	6,21	<i>Q. saponaria</i> & <i>L. caustica</i> ; <i>C. alba</i> & <i>P. boldus</i>	143.46	Metropolitana, O'Higgins
2014	4	4,7,14,18, 40	<i>C. alba</i> & <i>P. boldus</i> ; <i>Q. saponaria</i> & <i>L. caustica</i> ; <i>V. caven</i> & <i>M. boaria</i>	222.93	Metropolitana, Maule
2015	3	23,27,34	<i>C. alba</i> & <i>P. boldus</i> ; <i>Q. saponaria</i> & <i>L. caustica</i>	104.67	O'Higgins
2016	3	2,12,33	<i>Q. saponaria</i> & <i>L. caustica</i> ; <i>V. caven</i> & <i>M. boaria</i> ; <i>C. alba</i> & <i>P. boldus</i>	31.23	Valparaíso, Metropolitana, O'Higgins
2017	11	1,3,5,8,9,15,20,28, 35,39,42	<i>V. caven</i> & <i>M. boaria</i> ; <i>Q. saponaria</i> & <i>L. caustica</i> ; <i>C. alba</i> & <i>P. boldus</i>	2334.6	Valparaíso, Metropolitana, O'Higgins, Maule

NDVI from Landsat time series

We employed the NDVI, as defined by Rouse et al. (1974), to trace and analyze forest productivity recovery following wildfires for the areas previously selected. Utilizing the LandTrendr-GEE algorithm (Kennedy et al., 2018), a spectral-temporal segmentation tool, we isolated significant changes within pixel spectral histories to map continuous or abrupt vegetative changes over time. This approach, aligned with Kennedy et al. (2010) techniques enabled a detailed assessment of spectral forest dynamics in central Chile before, during, and after wildfires from 1992 to 2017. In our study, LandTrendr served two critical

methodological roles: initially identifying changes to select burned areas and subsequently generating a noise-free NDVI time series to evaluate forest recovery post-fire.

To build a robust NDVI time series, we utilized high-resolution, 30-meter Landsat imagery from the United States Geological Survey (USGS), accessed through Google Earth Engine (GEE), an open cloud-computing platform designed for geospatial analysis (Gorelick et al., 2017). We processed all available TM/ETM+/OLI/OLI2 Level-2, Collection 2, Surface Reflectance images (<https://developers.google.com/earth-engine/datasets/catalog/landsat>) from Landsat 5, 7, 8, and 9 spanning from 1987 to 2022 during the local summer season (December 21 - March 31). We extended the observation period during limited cloud-free visibility to ensure a clear and accurate dataset. We employed medoid compositing annually, incorporating images from any sensor relevant to each summer season across the years analyzed. This period was selected to exclude the presence of herbaceous vegetation typical of the wet season, focusing exclusively on the regeneration of trees and shrubs. The resultant NDVI series provided a fitted, annual, cloud-free view of vegetation, summarized by the median values of the summer season.

Post-fire Recovery Metric

To assess forest recovery, we measured the relative change in NDVI from pre-fire levels to the years following the wildfire (Figure IV.3), utilizing the LandTrendr time series. We defined NDVI recovery as the ratio of NDVI recovery at year five to the magnitude of NDVI reduction to the wildfire, following the methodology outlined by Bright et al. (2019). This approach provides a measure of recovery proportional to the initial damage caused by the wildfire. We chose the NDVI value from the first year after the wildfire as a proxy for post-fire vegetation conditions. This choice reflects the emergence of open growing conditions and the survival of any remnant tree overstory (Collins & Roller, 2013; Donato et al., 2009). We preferred the NDVI of year one over the immediate post-fire NDVI to account for possible continued declines in NDVI within the year following the disturbance,

which could indicate ongoing ecological shifts (Rossetti et al., 2022; Serra-Burriel et al., 2021; Solans Vila & Barbosa, 2010). Furthermore, changes in surface reflectance, resulting from the leaching remains of burned material, can also affect NDVI readings post-fire (Meng et al., 2015; Miller et al., 2013; White et al., 1996).

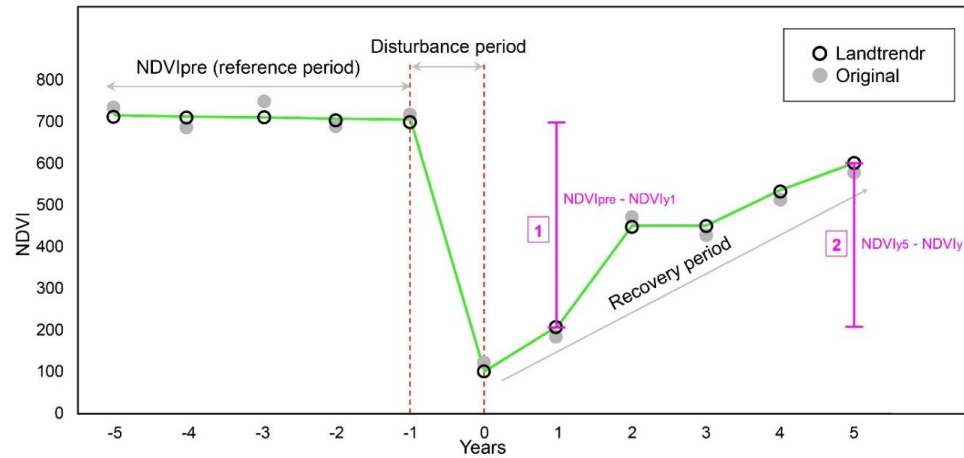


Figure IV.3. This conceptual diagram illustrates how LandTrendr fits the normalized difference vegetation index (NDVI) values for a fire-affected pixel, fitting these values to spectral-temporal segments. Solid gray circles represent the original NDVI time series for the pixel, while the corresponding LandTrendr-adjusted values are shown as open black circles. NDVI recovery is quantified by the ratio of distance 2 ($NDVI_{y5} - NDVI_{y1}$) to distance 1 ($NDVI_{pre} - NDVI_{y1}$). Here, $NDVI_{y5}$ represents the NDVI value five years after the wildfire, $NDVI_{y1}$ is the NDVI value in the first-year post-disturbance, and $NDVI_{pre}$ is the NDVI value for the five years preceding the wildfire. In the $NDVI_{rec}$ metric, values closer to 1 indicate greater recovery (with 1 representing full recovery), while values near zero suggest no recovery and negative values indicate further decline beyond post-fire conditions.

Predictor variables

We selected a set of predictor variables influencing forest recovery after wildfires, guided by previous studies in Mediterranean regions (Blanco-Rodríguez et al., 2023; Martín-Alcón & Coll, 2016), which demonstrated significant correlations with post-fire recovery. The input data for these predictors were primarily sourced from the Google Earth Engine (GEE) catalog, except for fire severity data, which we imported and processed within GEE.

To capture pre-disturbance forest behavior, we used the NDVI value before the wildfire ($NDVI_{pre}$). This was calculated over the five years preceding the wildfire, with a weighted emphasis on the year closest to the disturbance. By assigning greater weight to more recent years, we minimized the influence of earlier years

and better captured the negative trends leading up to the wildfire. This approach was particularly crucial for fires occurring during prolonged droughts, as it prevented an underestimation of recovery. NDVI_{drop} is the difference between the NDVI of the year before the fire and the first year after the fire. This was used to evaluate the immediate impact of the forest fire and the initial recovery status of the forest (Collins & Roller, 2013; Meng et al., 2015). Fire severity was indicated by the Relative Differenced Normalized Burn Ratio (RdNBR) values (Miller & Thode, 2007), which we obtained at a 30-meter resolution from (Miranda et al., 2022a) via the Open Data Platform Itrend (<https://www.plataformadedatos.cl/datasets/en/492F65B350AAF9D4>).

For topographic variables, we used a 30-meter resolution Digital Elevation Model (DEM) from the Shuttle Radar Topography Mission (SRTM) (Farr et al., 2007). We derived elevation, northness, eastness, and the Topographic Position Index (TPI) from the DEM. Northness and eastness were continuous values calculated using the cosine and sine of the aspect, respectively, with values near 1 indicating a north-facing orientation and values near -1 indicating a south-facing orientation. Eastness followed a similar pattern. TPI provided a numerical measure of slope position, with higher values indicating ridges and lower values indicating valley bottoms, while values near zero could indicate flat areas or mid-slopes (Wilson & Gallant, 2000). TPI values are closely related to water flow and surface fluid accumulation.

To describe post-fire climatic conditions, we concentrated on drought severity and we utilized the TerraClimate dataset from the University of Idaho (Abatzoglou et al., 2018), offers monthly climate and water balance data for global terrestrial surfaces. We calculated the Palmer Drought Severity Index (PDSI) annually. Climate anomalies (z-scores) were calculated for each pixel based on the ~60-year climate record (1958-2022) using the following equation:

$$z = \frac{X - \mu}{\sigma} \quad (\text{Eq. 1})$$

Where X is the raw value for the year of interest, μ is the climate normal (1958-2022) mean, and σ is the standard deviation. These standardized values allowed us to compare wildfires across different years and locations and highlight extreme conditions (Arnold et al., 2014). Since TerraClimate data has a spatial resolution of ~4 kilometers, one TerraClimate pixel spanned multiple 30-meter time-series pixels, assigning the same climate value to those 30-meter pixels. We used post-fire climatic anomalies for year 0 (PDSI_{y0}) and the average anomalies from year 0 to year 4 (PDSI_{lav}) as predictor variables. Every variable was chosen to explore the impact of post-fire climate on forest recovery and to facilitate comparisons across different Mediterranean regions (Blanco-Rodríguez et al., 2023; Bright et al., 2019; Viedma et al., 1997). After performing preliminary correlation analyses, we selected NDVI_{pre}, NDVI_{y1}, PDSI_{y0}, PDSI_{lav}, elevation, northness, eastness, and TPI (Table IV.2) as the final predictor variables, as these showed the strongest correlations with post-fire recovery.

Table IV. 2. Response and predictor variables are considered in the models.

Type of the variable	Variables	Unit	Range	Description
Pre-fire effect	NDVI _{pre}	Normalized Value	0-100	A proxy for the pre-fire status of greenness. Consider the value of NDVI between year -1 to year -5.
Post-fire immediate effect	NDVI _{drop}	Normalized Value	0-100	Post-fire legacy at year 1, as measured by the decline in pre-fire NDVI relative to one year after the wildfire. A proxy for the fire impact and the early status of forest photosynthetic activity post-fire.
	RdNBR	Normalized Value	0-100	A proxy for fire severity was calculated for year 0.
Post-fire climatic conditions	Drought Severity at wildfire year (PDSI _{y0}) Drought Severity average year 0 to year 4 (PDSI _{lav})	Z-score	-3 to 3	Annual drought severity index anomalies (z-score). Considers the anomaly of the year 0 average an year 0 to year 4 average. Based on the record of more than 60 years (1958-2022).
Topography	Elevation	m	0-1250	Elevation. Height of terrain above sea level (m).

Type of the variable	Variables	Unit	Range	Description
	Nness	Standardized value	-1 to 1	Degree of orientation to the north.
	Eness	Normalized Value	-1 to 1	Degree of orientation to East.
	Topographic Position Index	Standardized value	-1 to 1	A numerical measure of slope position. Higher values indicate locations closer to ridgetops, and lower values indicate valley bottoms.

Modeling of post-fire recovery

We applied Random Forest (RF) models to evaluate the influence of selected environmental and climatic factors on forest recovery five years after wildfires. Random forest, a non-parametric machine learning ensemble based on decision trees, is well-suited for handling large datasets and is known for its ability to reduce overfitting (Breiman, 2001; Hastie et al., 2009). Additionally, random forest has been demonstrated to effectively capture interactions between variables (Strobl et al., 2007) and to be more robust against outliers compared to other regression methods (Robnik-Šikonja & Kononenko, 2008). We implemented the random forest regression models in R using the *ranger* package (Liaw & Wiener, 2002; Team, 2020). The overall modeling strategy is outlined in Figure IV.2 and detailed further in Figure IV.S3.

We developed models for two distinct response variables, NDVIrec, and the absolute NDVI values. To evaluate model performance, we combined bootstrapping with cross-validation as resampling techniques. Bootstrapping is used in random forest to enhance model robustness and generalizability (White et al., 2014). By introducing variability into the training datasets, bootstrapping contributes to the diversity of the decision trees within the ensemble.

For each response variable, we developed three models—one for each forest subtype—resulting in a total of six final model types. From 44,108 pixels, we generated 500 bootstrap resamples for each forest subtype, with data in each

resample proportional to the subtype's representation. We used partial stratified random sampling to reduce bias from years with high wildfire occurrence (Table IV.1) and avoid spatial autocorrelation. We verified spatial independence by examining the spatial autocorrelation of residuals using a variogram and Global Moran's I (p -value < 0.05) (Moran, 1950). Pixels were grouped by drought level and fire severity, and an equal number of pixels was drawn from each group to prevent over or under representation. Within each group, we employed stratified random sampling, ensuring the samples were proportional to fire year and fire ID, with a minimum distance of 60 meters between pixels to prevent spatial autocorrelation based on the variogram results (details in Table IV.S2).

From the 500 randomly selected samples, we paired 40 into 20 training/validation sets to assess variable importance, excluding predictor variables with multicollinearity (Figure IV.S1). We measured the drop in model performance using the mean R-square when each variable was excluded (Figure IV.S3). For the final model, we selected variables that improved R-square performance by more than 0.01 or represented key metrics like fire severity (RdNBR), as these were our primary variables of interest. This approach provided a baseline model with top four predictor variables for each response type. We assessed the accuracy for each selected model by training 500 independent models using the full bootstrap resamples. We evaluated each model with five randomly selected resamples and repeated this process with 500 bootstrap samples, validating the models through a 5-fold out-of-bag (OOB) cross-validation.

To compare variable importance across forest subtypes, we calculated the Model Improvement Ratio (MIR) (Murphy et al., 2010). MIR is determined by dividing the importance of a specific metric (I_n) by the maximum model improvement score (I_{max}), which always has a value of 1. Critical variables exhibit values close to 1, indicating high importance. Finally, we used random forest models to examine the marginal effects of predictor variables on short-term vegetation recovery following wildfires, using partial dependence plots to illustrate these effects.

Result

We developed models for two response variables, NDVI_{rec} and NDVI, for each forest subtype. Tables IV.3 and IV.4 present the top four predictor variables identified for each response variable and forest subtype. For NDVI_{rec}, the most influential predictor across all subtypes was the average post-fire drought severity. The average recovery index ranged from negative values to 1.2, depending on drought severity and forest subtype (Figure IV.4). *Q. saponaria* & *L. caustica* showed an average NDVI recovery of 0.60, *V. caven* & *M. boaria* had 0.49, and *C. alba* & *P. boldus* exhibited 0.56. The second most important variable was the NDVI drop in year 1 for *Q. saponaria* & *L. caustica* and *V. caven* & *M. boaria*, while elevation was the second most important for *C. alba* & *P. boldus*. NDVI_{pre} ranked third for *Q. saponaria* & *L. caustica* and *C. alba* & *P. boldus*, while elevation was third for *V. caven* & *M. boaria*. Fire severity (RdNBR) was the least important predictor for *V. caven* & *M. boaria* and *C. alba* & *P. boldus*, whereas elevation had the lower impact on *Q. saponaria* & *L. caustica* (Table IV.3, Figure IV.S3).

In the NDVI models, the state previous of the wildfire (NDVI_{pre}) was the strongest predictor across all subtypes, followed by the average post-fire drought severity (PDSI_{av}). The TPI ranked third for *Q. saponaria* & *L. caustica* and *V. caven* & *M. boaria*, while elevation held this position for *C. alba* & *P. boldus*. Fire severity (RdNBR) had the lowest importance for *Q. saponaria* & *L. caustica* and *C. alba* & *P. boldus*, while northness was the least significant for *V. caven* & *M. boaria* (Table IV.4, Figure IV.S3).

We ran 500 Random Forest models with 5-fold out-of-bag cross-validation for each forest subtype, incorporating the four most significant predictor variables. The NDVI_{rec} models showed mean R-square values ranging from 0.70 to 0.80 across subtypes, while the NDVI models demonstrated R-square values between 0.75 and 0.89. In both sets of models, *C. alba* & *P. boldus* achieved the highest

R-square values, while *V. caven* & *M. boaria* had the lowest (Table IV.5, Figure IV.S4).

Table IV.3. Model Improvement Ratio (MIR) scores for Random Forest models predicting NDVI_{rec} in year five across three forest subtypes in the Mediterranean landscape of central Chile. Variable importance scores range from 0 (least important) to 1 (most important).

Variable	Model Improvement Ratio scores		
	<i>Q. saponaria</i> & <i>L. caustica</i>	<i>V. caven</i> & <i>M. boaria</i>	<i>C. alba</i> & <i>P. boldus</i>
Drought severity average post-fire (PDSI)	1.00	1.00	1.00
NDVI drop (NDVI _{y1})	0.14	0.77	-
Pre-fire NDVI	0.08	-	0.11
Fire Severity (RdNBR)	-	0.25	0.08
Elevation	0.06	0.48	0.14

Table IV.4. Model Improvement Ratio (MIR) scores for Random Forest models predicting NDVI in year five across the same forest subtypes.

Variable	Model Improvement Ratio scores		
	<i>Q. saponaria</i> & <i>L. caustica</i>	<i>V. caven</i> & <i>M. boaria</i>	<i>C. alba</i> & <i>P. boldus</i>
Pre-fire NDVI	1.00	1.00	1.00
Drought severity average post-fire (PDSI)	0.58	0.45	0.78
Topographic Position Index (TPI)	0.09	0.18	-
Fire Severity (RdNBR)	0.09	-	0.06
Elevation	-	-	0.14
Northness index	-	0.16	-

The Random Forest models helped quantify the marginal effects of the predictor variables on post-fire recovery. For NDVI_{rec} (Figure IV.3), recovery consistently decreased as the post-fire drought severity anomaly worsened across all subtypes, but the effect is not as clear (with slight differences among forest subtypes). Higher pre-fire NDVI values correlated with lower recovery in *Q. saponaria* & *L. caustica* and *C. alba* & *P. boldus*. Elevation, NDVI_{y1}, and fire

severity positively correlated with recovery, although these were less pronounced for *V. caven* & *M. boaria*.

In the NDVI models (Figure IV.4), post-fire drought severity anomaly negatively impacted NDVI values, though these effects were weaker in *V. caven* & *M. boaria* and *C. alba* & *P. boldus* compared to *Q. saponaria* & *L. caustica*. Pre-fire NDVI and elevation positively influenced NDVI, while higher fire severity and north-facing orientation were associated with lower NDVI values. The Topographic Position Index (TPI) showed different effects depending on the subtype. Valley locations (negative TPI values) corresponded to higher NDVI, except in *Q. saponaria* & *L. caustica*, where no clear pattern emerged.

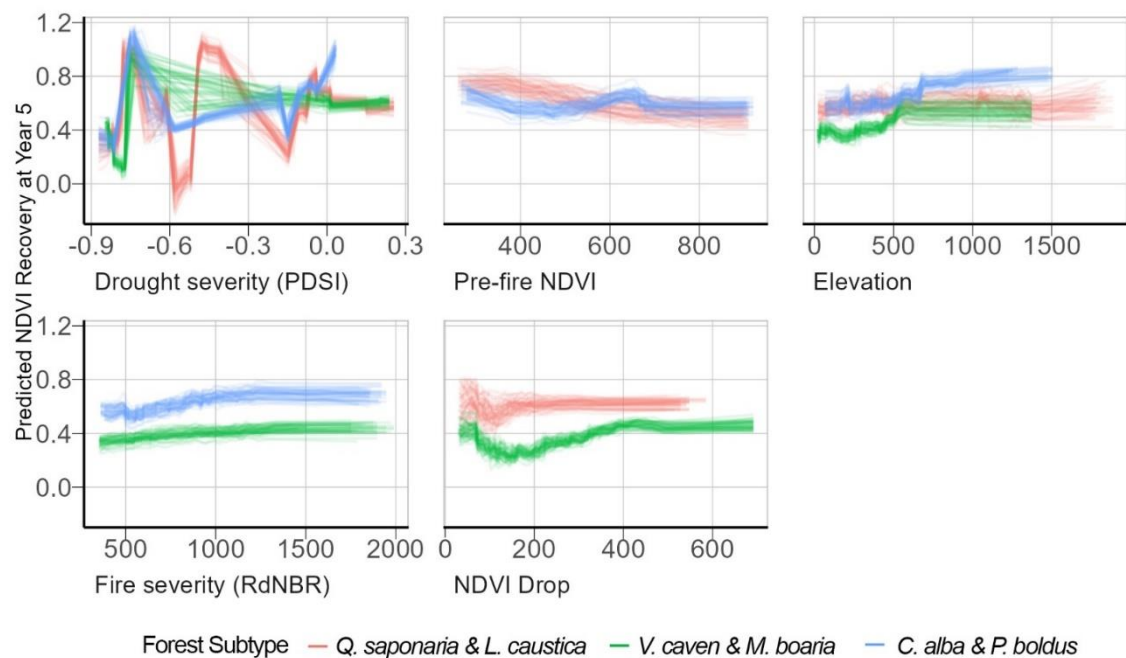


Figure IV.4. Partial dependence plots showing the marginal effect of explanatory variables (x-axis) on post-fire NDVI recovery (y-axis) based on Random Forest models for three forest subtypes in the Mediterranean landscape of central Chile.

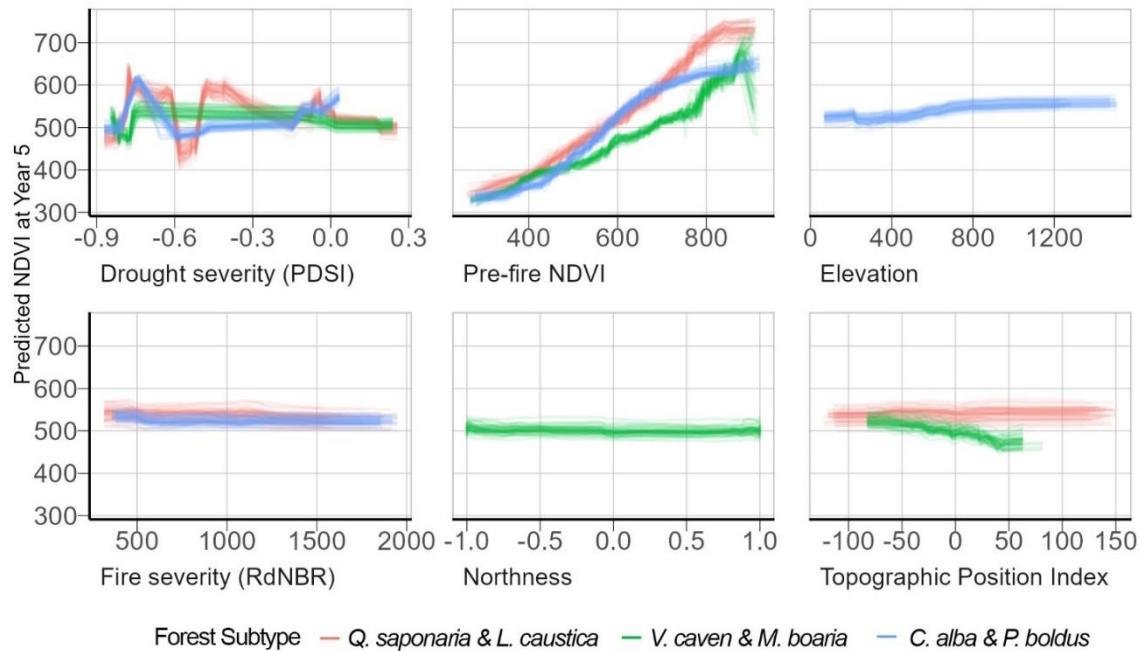


Figure IV.5. Partial dependence plots illustrating the marginal effect of explanatory variables (x-axis) on post-fire NDVI (y-axis) based on Random Forest models for three forest subtypes in the Mediterranean landscape of central Chile.

Table IV.5. Summary of 500 Random Forest models with five-fold out-of-bag cross-validation.

Response variable	Models forest subtype	Mean R-square (SD)	Mean RMSE square (SD)	Mean MAE (SD)
NDVIrec	<i>Q. saponaria & L. caustica</i>	0.74(0.009)	0.29(0.005)	0.19(0.002)
	<i>V. caven & M. boaria</i>	0.70(0.009)	0.20(0.003)	0.15(0.002)
	<i>C. alba & P. boldus</i>	0.80(0.007)	0.19(0.003)	0.13(0.002)
NDVI	<i>Q. saponaria & L. caustica</i>	0.88(0.004)	37.14(0.552)	26.89(0.327)
	<i>V. caven & M. boaria</i>	0.76(0.009)	56.02(1.028)	39.39(0.563)
	<i>C. alba & P. boldus</i>	0.89(0.004)	35.45(0.570)	25.78(0.346)

Discussion

Drought Severity and Post-Fire Recovery

Our study demonstrated that drought severity is a key factor influencing short-term vegetation recovery after wildfires in the Mediterranean forests of central Chile. NDVIrec and NDVI models ranked drought severity among the most important variables (Tables IV.3 and IV.4). The average recovery index ranged from negative values to 1.2, depending on drought severity and forest subtype (Figure IV.4). However, interpreting the effects of drought severity in the partial dependence plot (Figures IV.4 and IV.5) is challenging due to the feature independence assumption. This assumption complicates the interpretation, as partial dependence plots assume that the variable of interest is independent of other variables, potentially confounding the complex interactions captured more accurately by the random forest model. These findings emphasize the crucial role and the complexity of drought in restricting post-fire vegetation regrowth, particularly as climate change is projected to increase the frequency and intensity of droughts in this region (Bozkurt et al., 2018; Miranda et al., 2023; Rodman et al., 2020).

Our study is one of the few quantitative assessments of post-fire recovery in central Chile that considers drought conditions. Similar studies in other Mediterranean regions have shown that prolonged post-fire droughts can significantly reduce soil moisture, hindering seed germination and seedling establishment (Blanco-Rodríguez et al., 2023; Dong et al., 2019; Vidal-Macua et al., 2017). Drought conditions disrupt key ecological processes needed for vegetation regrowth (Broncano & Retana, 2004; Sánchez-Gómez et al., 2006), and reduced water availability delays the initiation of recovery after wildfires (Rossetti et al., 2022). These findings are consistent with our observations that drought severity was a dominant factor influencing recovery across all subtypes. Blanco-Rodríguez et al. (2023) emphasized that the duration of drought impacts post-fire recovery differently depending on aridity levels. In semi-arid and humid regions of the western Mediterranean, drought effects were more pronounced,

aligning with studies suggesting that species adapted to extreme drought conditions may face antagonistic effects during recovery. For example, traits like embolism resistance that improve drought survival could simultaneously hinder regrowth potential (Resco de Dios et al., 2018). This antagonism underscores the complexity of interactions between fire, climate, and vegetation response in Mediterranean ecosystems.

In addition, the Palmer Drought Severity Index (PDSI) was a significant predictor of post-fire recovery in other studies (Storey et al., 2021; Zhang et al., 2021), further validating its importance in determining recovery trajectories. As our models demonstrate, increased drought severity directly correlates with slower or incomplete recovery in short terms, particularly for forest subtype such as *V. caven* & *M. boaria*, which were more vulnerable to severe drought impacts.

Relationships of Fire, Environmental Factors, and Vegetation Recovery

Pre-fire vegetation greenness was another important factor influencing post-fire recovery, consistent with findings from Bright et al. (2019). For *Q. saponaria* & *L. caustica*, higher pre-fire NDVI values were associated with slower recovery (NDVIrec). This trend suggests that denser, healthier vegetation before the fire may be more susceptible to intense burning, leading to more significant structural damage and prolonged recovery. However, *C. alba* & *P. boldus* exhibited no clear pattern in response to pre-fire NDVI, highlighting the complexity of the relationship between initial vegetation conditions and post-fire recovery. In the case of the NDVI models, the positive relationship for all subtypes, being less marked for *V. caven* & *M. boaria*, was expected given the structure and composition of the thorny trees as opposed to the evergreen forest.

Topographic factors also played a role in post-fire recovery. Elevation had a positive effect on recovery for *C. alba* & *P. boldus* and *V. caven* & *M. boaria*, where higher altitudes provided more favorable conditions for regrowth. Cooler temperatures and increased moisture availability at higher elevations likely contributed to this trend. However, *Q. saponaria* & *L. caustica* showed minimal

sensitivity to elevation, suggesting that factors such as soil conditions and fire severity might be more critical in determining recovery outcomes for this subtype.

Our findings are supported by previous studies reporting that dense forest cover was more prevalent on gentler slopes at higher altitudes before wildfires (Smith-Ramírez et al., 2022). Valleys and ravine bottoms (negative TPI values) had higher vegetation productivity, likely due to more humid conditions and reduced solar radiation compared to north-facing slopes. This suggests that topographic moisture can mitigate the effects of drought on recovery, though only up to a certain threshold of drought severity. Our analysis showed that other topographic variables, although elevation, had a marginally weak effect on the post-fire response, observed for *Q. saponaria* & *L. caustica* and *V. caven* & *M. boaria* for NDVI models. Nevertheless, micro-climate and topography frequently exhibit correlations, indicating that the localized impacts of topography may be more pronounced than our analyses indicate (Bright et al., 2019).

The NDVIDrop variable proved to be a significant predictor for *Q. saponaria* & *L. caustica* and *V. caven* & *M. boaria*, serving as a proxy for fire resistance for these forest subtypes or the impact of the fire severity. *V. caven* & *M. boaria* displayed lower resilience as NDVIDrop increased, suggesting that this subtype is less capable of recovering from high-severity fires. This diminished recovery may be due to the combined effects of reduced water availability, elevated temperatures, and post-fire herbivory (Montoya-Tangarife et al., 2017; Vita et al., 1997). Herbivory has been shown to further impair regrowth in Mediterranean ecosystems (Bugalho et al., 2011), compounding the challenges faced by this forest subtype. Fire severity also influenced post-fire vegetation recovery, although the model did not show a marked relationship to that reported by Smith-Ramírez et al. (2022), we decided to include it in the models to evaluate its effect. For *C. alba* & *P. boldus*, fire severity (as measured by RdNBR) has a positive relationship with NDVI recovery, where higher RdNBR values correspond to higher predicted NDVI at Year 5. This trend indicates potential resilience or adaptability to fire disturbances. *V. caven* & *M. boaria*, however, exhibit a minimal

response to increasing fire severity (Figure IV.4) and the same for *Q. saponaria* & *L. caustica* for NDVI models (Figure IV.5).

Limitations and Future Directions

We recognized that the coarser resolution of our climate data compared to the response and predictor variables might have reduced our models' explanatory power and increased uncertainty (de Knegt et al., 2010). Nonetheless, we used globally accessible climate data to establish a framework applicable to other understudied regions with similar ecological conditions. Future research should employ finer-scale climate data or stratified field sampling to enhance precision and better capture post-fire drought effects across broader spatial and temporal scales (Hansen et al., 2013). Incorporating localized datasets would improve our understanding of microclimatic variability, which is crucial for plant regeneration and ecosystem resilience (Franklin et al., 2016), and refine predictions of post-fire recovery dynamics in regions where fire regimes are intensifying due to climate change.

We noted that spectral indices from satellite sensors are increasingly significant in evaluating post-fire recovery, especially where resources limit comprehensive field studies (Fernandez-Manso et al., 2016; Garreaud et al., 2017; Meng et al., 2015). While various indices like NBR, EVI, and TCTB have been used, we employed NDVI due to its effectiveness in Mediterranean regions and its ability to detect disturbances like drought (Hope et al., 2007; Miranda et al., 2020; Miranda et al., 2023; Vicente-Serrano et al., 2011). However, NDVI primarily reflects changes in vegetation density and health through photosynthetic activity and lacks detailed information on vegetation type and structure, making it challenging to distinguish vertical layers or accurately identify species composition (Blanco-Rodríguez et al., 2023; Meng et al., 2018). Combining field data with remote sensing is essential for a comprehensive understanding but remains difficult in understudied regions (Hudak et al., 2007; Senf, 2022; Skidmore et al., 2021).

Our analysis did not detect post-fire changes in forest structure or composition. Studies focusing on photosynthetic activity and productivity often omit field-based validations due to high costs, which can lead to misinterpretations given the variability in plant community compositions (Barbosa & Asner, 2017). This issue is particularly relevant in semi-arid or drought-prone Mediterranean ecosystems, where species composition varies significantly. In our study, drought-adapted forest subtypes like *Q. saponaria* & *L. caustica* showed stronger post-fire recovery under drought conditions compared to *C. alba* & *P. boldus*, which are more sensitive to drought.

Our focus on NDVI aimed to provide a broad overview of forest recovery in a relatively understudied landscape, laying the groundwork for future studies that could investigate specific vegetation characteristics using time-series multispectral imagery. Such efforts would deepen our understanding of the resilience and resistance of Mediterranean ecosystems to disturbances, especially under anticipated warmer and drier conditions. We faced challenges due to the fragmented nature of native forests in central Chile, which limited the spatial scale of analysis and reduced the number of pixels in areas with dense forest coverage (Armesto, 2007; Miranda et al., 2020; Schulz et al., 2010). The accuracy of our results was also affected by the limitations of official vegetation maps, although these maps had an overall accuracy of 75.1% to 82.7% (CONAF, 2022).

Despite these limitations, advancements in next-generation remote-sensing technologies promise to improve the quality and effectiveness of post-fire recovery studies, leading to more refined and reliable assessments in the future (Cavender-Bares et al., 2022; Gao et al., 2020).

Implications for Forest Management and Conservation

The integration of NDVI and NDVI recovery models provides a comprehensive framework for forest management. NDVI models are helpful and can contribute to estimates of aboveground biomass and carbon storage in forest ecosystems (Xu

et al., 2024). As climate change intensifies water stress, the sensitivity of ecosystems to drought is expected to increase, resulting in reduced terrestrial carbon uptake (Liu et al., 2024). These models are invaluable for assessing forests' roles in global carbon cycles and projecting ecosystem services, such as carbon sequestration, under varying environmental conditions (Roche et al., 2024; Running et al., 2004).

On the other hand, NDVI recovery models (NDVIrec) are more nuanced and are particularly relevant for conservation planning and management. These models can identify areas where forest subtypes are most vulnerable to new disturbance regimes, such as increased fire frequency and more arid conditions. Understanding this vulnerability is crucial for prioritizing conservation efforts and reinforcing strategies to enhance the resilience of at-risk forest subtypes (Johnstone et al., 2016; Turner et al., 2020). By integrating these two modeling approaches, forest managers can balance ecosystem productivity with resilience, which is increasingly important as environmental pressures escalate (Millar et al., 2007). This dual approach allows for a more informed strategy to optimize forest ecosystem services while improving the capacity of forests to recover from disturbances in the face of global climate change.

Conclusions

We investigated the short-term post-fire recovery of Mediterranean forests in central Chile, focusing on the influence of drought severity, fire severity, and topographic factors. By applying Random Forest models to predict NDVI and NDVI recovery metrics, we identified the most significant environmental and climatic variables that influence the regeneration process. Our analysis spanned 42 wildfires, utilizing NDVI from Landsat imagery to assess forest greenness five years after the fire events.

The findings confirmed that post-fire drought severity was the most influential variable affecting vegetation recovery across all forest subtypes. Pre-fire vegetation greenness, represented by NDVI values, also played a key role, particularly in *Q. saponaria* & *L. caustica*, where higher pre-fire NDVI values were associated with slower recovery rates. In contrast, the recovery of *V. caven* & *M. boaria* was more sensitive to the initial NDVI drop, indicating its vulnerability to more intense fire disturbances. Elevation and topographic features, such as the Topographic Position Index, showed varied effects across subtypes, with higher altitudes favoring recovery in *C. alba* & *P. boldus* and *V. caven* & *M. boaria*.

Our study highlights the complex interplay between fire severity, drought intensity, and landscape factors, all shaping post-fire recovery dynamics in Mediterranean forests. These results underscore the critical need for adaptive management strategies, particularly in the context of increasing droughts due to climate change. Integrating both NDVI and NDVI recovery models provides a comprehensive tool for forest management, enabling the prediction of carbon sequestration potential and identifying areas most vulnerable to future disturbances. Furthermore, this research contributes to the broader discourse on forest resilience and ecological responses to climate-induced disturbances. By employing remote sensing techniques to quantify recovery metrics, we provide a robust framework for evaluating forest dynamics that can be applied to similar ecosystems globally. The insights gained from this study not only enhance our

understanding of Mediterranean forest recovery but also serve as a valuable resource for policymakers and land managers aiming to mitigate the impacts of climate change on these ecosystems. Future research should refine these models by incorporating additional variables, such as soil moisture and species diversity, to enhance their predictive capabilities. Understanding these dynamics is essential for forecasting future forest resilience in the face of climate change, particularly as drought frequency and intensity are expected to increase.

Supplementary Materials

Figures

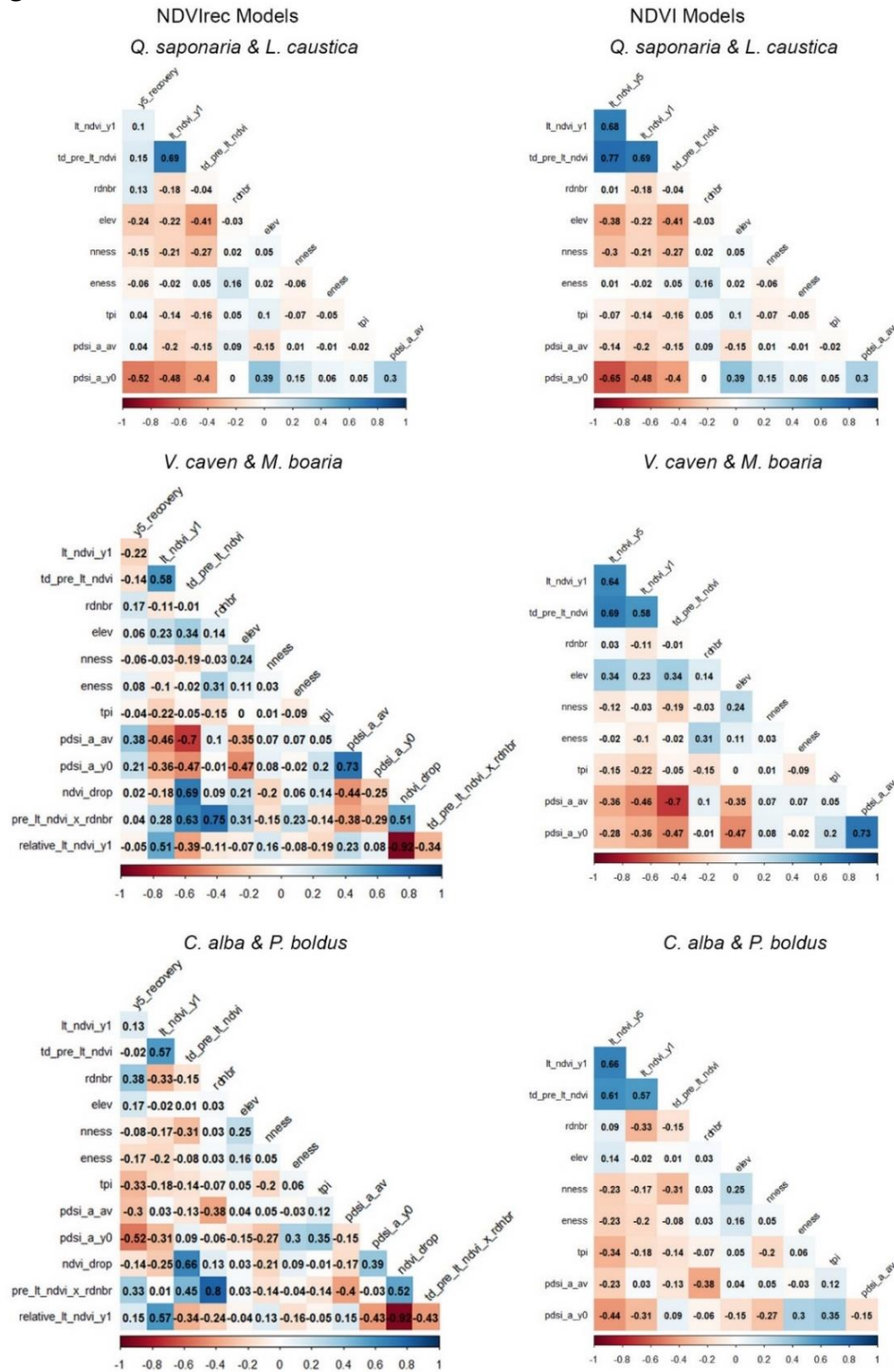


Figure IV.S1. The correlation matrix includes all predictor variables and recovery proxy for NDVIrec and NDVI models. Correlation coefficients for each variable are shown in bold.

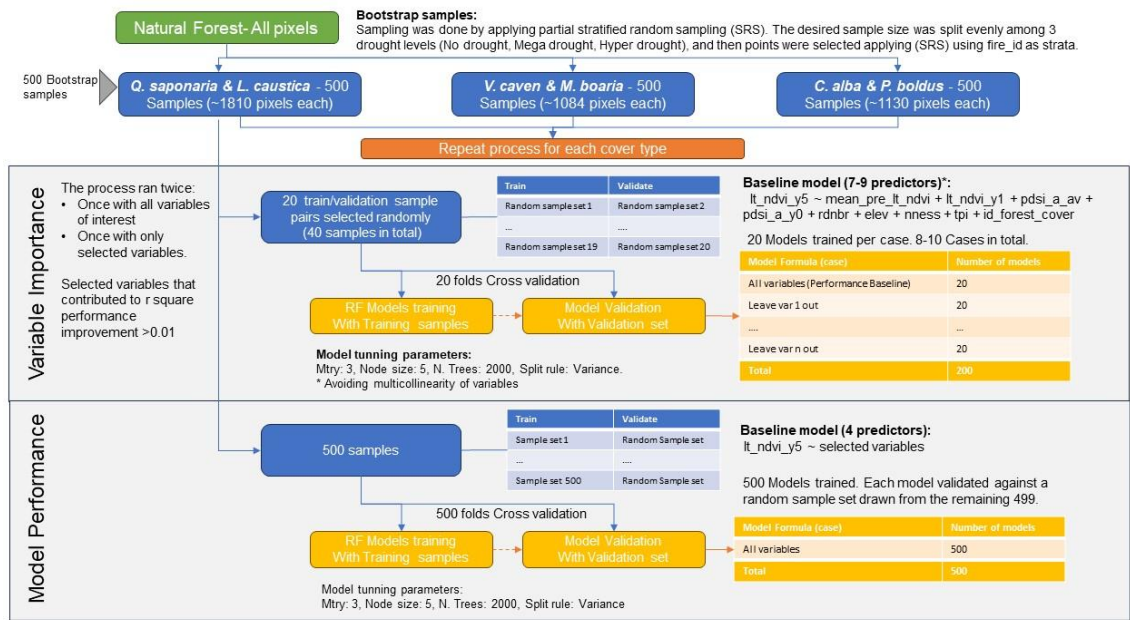


Figure IV.S2. Strategy of Model. Process diagram of sampling, selection of predictor variables, and performance for the Random Forest Modeling to examine factors of post-fire vegetation recovery in central Chile.

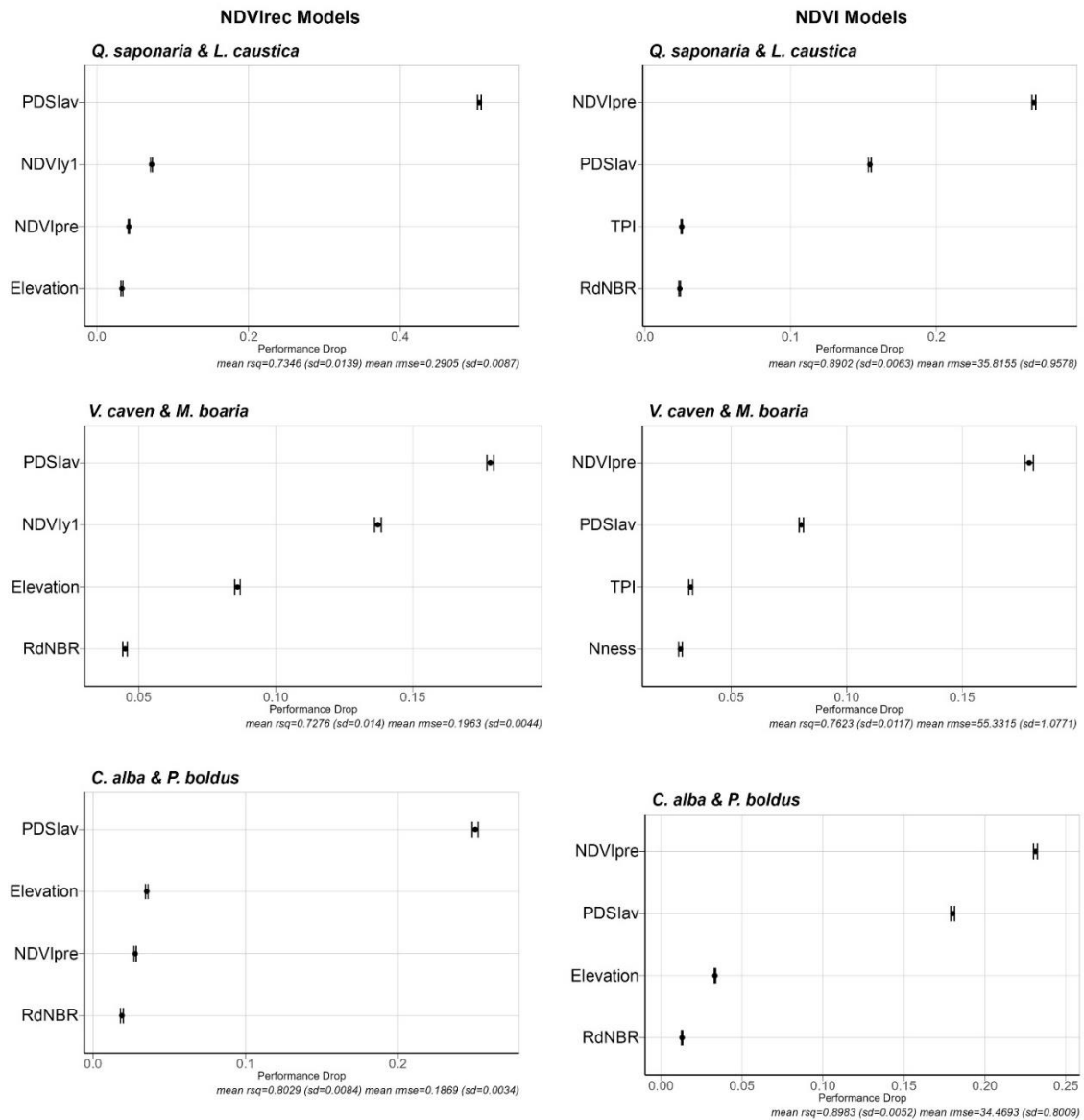


Figure IV.S3. Importance values by performance drop of predictor variables for the vegetation recovery five years after a fire in the Mediterranean forest of Central Chile. The point represents the median importance value derived from the samples of random forest models for all forest subtypes. Note the different finish locations for the data.

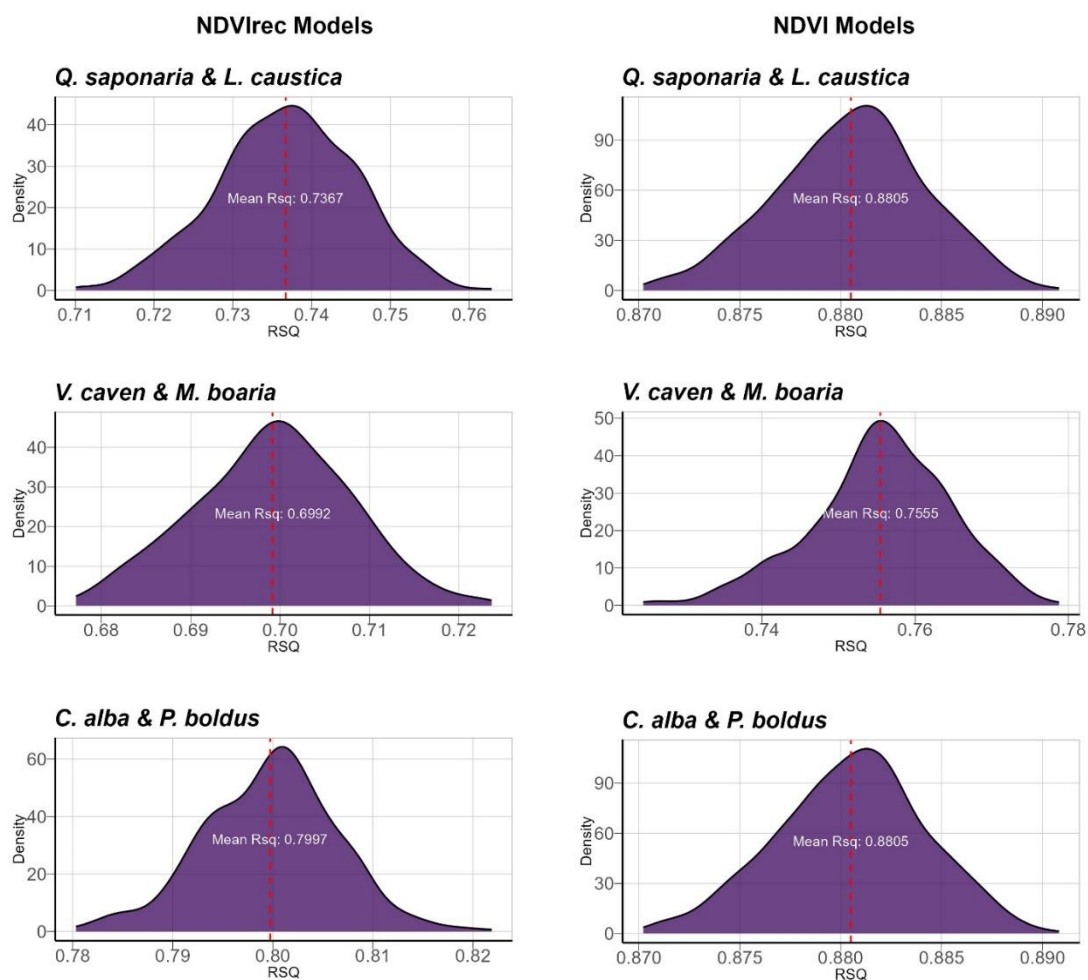


Figure IV.S4. Results from 500 Random Forest models with 5-fold OOB cross-validation.

Tables

Table IV.S1. Wildfires selected in the study area and their characteristics.

ID	ID CONAF	Fire Name	Fire year	Chilean Region	Forest subtype	Wildfire area (ha)	Lat	Lon
1	ID189237	Santa Maria - Los Molles	2017	Valparaíso	<i>Qs & Lc, Vc & Mb, Ca & Pb</i>	1,190.30	-32.24	-71.49
2	ID189192	Madre del Agua	2016	Valparaíso	<i>Qs & Lc</i>	417.2	-32.65	-71.32
3	ID189119	Lo Orozco	2017	Valparaíso	<i>Qs & Lc, Vc & Mb</i>	169.9	-33.24	-71.42
4	ID169148	El Penon	2014	Metropolitana	<i>Qs & Lc</i>	606,3	-33.57	-70.51
5	ID189223	El Toyo	2017	Metropolitana	<i>Qs & Lc</i>	891,8	-33.58	-70.44
6	ID169133	El Manzano	2013	Metropolitana	<i>Qs & Lc</i>	445.4	-33.59	-70.41
7	ID169171	El Carrizo	2014	Metropolitana	<i>Vc & Mb, Ca & Pb</i>	14,173,5	-33.64	-71.37
8	ID189257	Rinconada de Pirque	2017	Metropolitana	<i>Qs & Lc, Ca & Pb</i>	3,228.20	-33.73	-70.58
9	ID189124	San Rafael De Puro	2017	Metropolitana	<i>Qs & Lc</i>	130	-33.79	-71.41
10	ID39037	Los Maitenes	1992	Metropolitana	<i>Qs & Lc, Vc & Mb, Ca & Pb</i>	497.2	-33.82	-71.34
11	ID112326	Cruce Las Aranas	2004	Metropolitana	<i>Qs & Lc, Vc & Mb, Ca & Pb</i>	1,911.40	-33.87	-71.33
12	ID189195	Quilamuta	2016	Metropolitana	<i>Qs & Lc, Vc & Mb</i>	511.2	-33.89	-71.50
13	ID118979	La Manga	2005	Metropolitana	<i>Qs & Lc, Vc & Mb</i>	2,057.20	-33.89	-71.61
14	ID169040	Corneche	2014	Metropolitana	<i>Qs & Lc, Ca & Pb</i>	255.8	-33.95	-71.63
15	ID189264	Lo Chacon	2017	Metropolitana	<i>Ca & Pb</i>	6,035.80	-33.96	-71.28
16	ID118915	Longovilo	2005	Metropolitana	<i>Qs & Lc</i>	344.8	-33.97	-71.40
17	ID151627	Quelentaro	2011	O'Higgins	<i>Qs & Lc</i>	94.2	-33.99	-71.56
18	ID169139	El Membrillo	2014	Metropolitana	<i>Qs & Lc, Vc & Mb, Ca & Pb</i>	1252.52	-34.00	-71.28
19	ID146674	Cuesta Alhue	2010	Metropolitana	<i>Qs & Lc</i>	1,020.00	-34.02	-71.20
20	ID189263	Talami	2017	Metropolitana	<i>Qs & Lc, Ca & Pb</i>	7,747.70	-34.05	-70.99
21	ID169120	Cruce Santa Ines	2013	O'Higgins	<i>Qs & Lc</i>	217.1	-34.08	-71.37
22	ID151674	La Palmeria	2011	O'Higgins	<i>Qs & Lc, Ca & Pb</i>	1,490.40	-34.18	-71.12
23	ID177153	La Palmeria 4	2015	O'Higgins	<i>Qs & Lc</i>	576,2	-34.19	-71.12
24	ID136426	Quebrada Quillyquen	2008	O'Higgins	<i>Qs & Lc</i>	126.4	-34.26	-71.61
25	ID157096	Rinconada de Idahue	2012	O'Higgins	<i>Qs & Lc</i>	71.1	-34.29	-71.15

ID	ID CONAF	Fire Name	Fire year	Chilean Region	Forest subtype	Wildfire area (ha)	Lat	Lon
26	ID157061	Pampa Idahue	2012	O'Higgins	<i>Qs & Lc</i>	52	-34.31	-71.17
27	ID177202	Las Nieves 4	2015	O'Higgins	<i>Ca & Pb</i>	688,9	-34.47	-70.75
28	ID189265	Rincon de Yaquil 4	2017	O'Higgins	<i>Qs & Lc, Vc & Mb, Ca & Pb</i>	40,366.70	-34.56	-71.28
29	ID68831	El Calabozo	1997	O'Higgins	<i>Qs & Lc</i>	1,636.10	-34.57	-71.04
30	ID68630	Las Cruces	1997	O'Higgins	<i>Vc & Mb</i>	66.4	-34.58	-71.98
31	ID136494	San Jose De Apalta	2008	O'Higgins	<i>Qs & Lc</i>	2,221.90	-34.62	-71.23
32	ID146656	Paredones	2010	O'Higgins	<i>Vc & Mb</i>	150.6	-34.64	-71.90
33	ID189226	Alto Nilahue	2016	O'Higgins	<i>Vc & Mb</i>	5,463.40	-34.67	-71.81
34	ID176579	Lo Orozco	2015	O'Higgins	<i>Qs & Lc</i>	19.1	-34.70	-71.07
35	ID189275	Las Cardillas	2017	Maule	<i>Qs & Lc, Ca & Pb</i>	52,908.60	-34.90	-71.99
36	ID73968	Los Maquis	1998	Maule	<i>Ca & Pb</i>	32.6	-34.98	-70.89
37	ID142593	La Aguadilla	2009	Maule	<i>Qs & Lc, Vc & Mb, Ca & Pb</i>	174.6	-34.98	-70.91
38	ID151664	Los Quenes	2011	Maule	<i>Ca & Pb</i>	424.5	-35.02	-70.81
39	ID189254	Tabunco- El Aguila Convenio	2017	Maule	<i>Qs & Lc</i>	3,215.10	-35.18	-71.99
40	ID169169	Quivolgo 1	2014	Maule	<i>Ca & Pb</i>	2,670,9	-35.32	-72.39
41	ID118965	Loncomilla	2005	Maule	<i>Qs & Lc</i>	742.2	-35.66	-71.76
42	ID189243	Llepo	2017	Maule	<i>Qs & Lc</i>	1,839.90	-35.95	-71.48

*CONAF: Corporación Nacional Forestal. Abbreviation: Lat: latitude, Lon: longitude.

Table IV.S2. Sampling by forest subtype after the Partial Stratified Random Sampling (SRS).

Forest subtype	Min	1stQ	Median	Mean	3rdQ	Max
<i>Q. saponaria & L. caustica</i>	1804	1809	1811	1811	1812	1818
<i>V. caven & M. boaria</i>	1060	1080	1085	1084	1088	1099
<i>C. alba & P. boldus</i>	1112	1130	1135	1135	1140	1161

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Capítulo V. Discusión General de la Investigación

Discusión General de la Investigación

Esta investigación ha proporcionado un avance significativo en la comprensión de cómo diversos factores ambientales influyen en la recuperación de los bosques mediterráneos de Chile central tras incendios forestales. La combinación de las condiciones climáticas, el estado previo de la vegetación, las condiciones topográficas y las características del incendio desempeñan un papel crucial en la recuperación post-incendio de estos ecosistemas, cuya resiliencia es de vital importancia en el contexto del cambio climático global. A través del uso de series temporales de NDVI y modelos de bosque aleatorio, este estudio permite una caracterización detallada de los patrones de recuperación a corto plazo (5 años) de tres subtipos forestales, lo que representa una contribución relevante a la ecología de disturbios en ecosistemas mediterráneos.

Los resultados de esta investigación muestran que la recuperación forestal no es homogénea entre los subtipos de bosque ni entre las diferentes condiciones climáticas. *Quillaja saponaria* & *Lithrea caustica* (bosque andino mediterráneo), demostró una capacidad de recuperación notablemente mayor en comparación con *Cryptocarya alba* & *Peumus boldus*, subtipo característico de los bosques costeros durante la Mega Sequía. Estas diferencias reflejan cómo la adaptación biológica de estas especies a las condiciones climáticas y la topografía influye en su respuesta a las perturbaciones, sin embargo al sobrepasar ciertos umbrales climáticos en condiciones más extremas, como en una condición de Hiper Sequía *Cryptocarya alba* & *Peumus boldus* responde de mejor manera en la recuperación. Esto concuerda con estudios previos que subrayan la importancia de las características específicas de las especies en la respuesta a disturbios (Bright et al., 2019; Pausas, 1999).

En términos de los factores climáticos, la severidad de la sequía posterior al incendio se observó como uno de los factores más influyentes en la capacidad de recuperación de los bosques mediterráneos. Durante el período de sequía extrema, particularmente durante la llamada Mega Sequía y la Hiper Sequía, la

recuperación de los subtipos forestales mostró una disminución marcada. Este hallazgo es consistente con investigaciones previas que documentan la dificultad de los ecosistemas mediterráneos para regenerarse en contextos de estrés hídrico prolongado (Seidl et al., 2017; Thom et al., 2017). De hecho, las tasas de recuperación del subtipo de bosque dominado por *Vachellia caven* & *Maytenus boaria* fueron particularmente bajas bajo estas condiciones de sequía severa, lo que indica su mayor sensibilidad a los efectos combinados del fuego y la sequía en la recuperación a corto plazo.

Un hallazgo clave de este estudio es la importancia del verdor previo al incendio, medido a través del NDVI, como un predictor importante de la recuperación post-incendio. Las áreas con mayores niveles de NDVI antes del incendio tendieron a mostrar una menor capacidad de recuperación. Este resultado puede estar relacionado con la mayor densidad de biomasa en estas áreas, lo que genera incendios de mayor severidad y, por tanto, mayores daños a la vegetación. Este hallazgo subraya la compleja relación entre la estructura de la vegetación, la severidad del incendio y la capacidad de recuperación. De hecho, investigaciones previas han sugerido que los ecosistemas con mayor biomasa pueden experimentar un mayor impacto negativo en términos de regeneración debido a la mayor intensidad de los incendios (Meng et al., 2015; Wittenberg et al., 2007). Por otro lado, las condiciones topográficas también jugaron un papel relevante en la dinámica de recuperación. Las áreas situadas en posiciones topográficas más bajas y con mayor acceso a la humedad mostraron tasas de recuperación más rápidas, mientras que las áreas expuestas y más secas, como las orientadas hacia el norte, experimentaron una regeneración más lenta. Este patrón coincide con lo observado en estudios sobre el efecto de la topografía en la regeneración post-incendio, donde factores como la disponibilidad de agua y la exposición al sol modulan la capacidad de las especies para regenerarse (Broncano & Retana, 2004; Meng et al., 2015).

Desde una perspectiva de gestión, los resultados de esta investigación tienen importantes implicaciones. El manejo forestal en áreas mediterráneas, especialmente en regiones propensas a la sequía como Chile central, debe

incorporar tanto los factores climáticos como los ambientales al planificar estrategias de restauración post-incendio. Esto implica priorizar las áreas más vulnerables y reconocer las diferencias en la resiliencia de las especies o formaciones vegetacionales ante las perturbaciones naturales. Asimismo, es crucial desarrollar modelos de predicción más detallados que integren datos climáticos de mayor resolución y estudios de campo localizados. Estos esfuerzos permitirían mejorar la precisión en la predicción de la recuperación de los ecosistemas y, por tanto, ayudarían a fortalecer la capacidad de los bosques mediterráneos para resistir perturbaciones futuras exacerbadas por el cambio climático.

Este estudio destaca la necesidad de realizar investigaciones más exhaustivas que evalúen cómo los ecosistemas mediterráneos, y en particular los del hemisferio sur, responden a las interacciones entre incendios forestales, sequías y otros forzantes climáticos. La evidencia sugiere que la frecuencia e intensidad de estos disturbios aumentará en las próximas décadas, lo que incrementa la urgencia de desarrollar estrategias de manejo adaptativo que mejoren la resiliencia de los ecosistemas. A futuro, la investigación debe centrarse en explorar en mayor profundidad las relaciones entre la sequía, la regeneración forestal y el cambio climático, con el objetivo de proteger y conservar estos importantes ecosistemas frente a las crecientes amenazas ambientales.

Capítulo VI. Conclusión General de la Investigación

Conclusión General de la Investigación

A partir de los resultados obtenidos en esta investigación, se puede concluir que la recuperación forestal post-incendio en los ecosistemas mediterráneos de Chile central está fuertemente influenciada por factores climáticos y ambientales. En particular, se identificó que la severidad de la sequía posterior al incendio y la intensidad de los incendios son las principales limitantes para la recuperación de la productividad de los bosques, medida a través de índices espectrales como el NDVI. Estos hallazgos sugieren que, en escenarios de cambio climático, donde se espera un incremento en la frecuencia y duración de las sequías, la capacidad de recuperación de los ecosistemas forestales se verá comprometida, especialmente en formaciones vegetacionales menos adaptadas a condiciones de estrés hídrico y con menos mecanismos para su resistencia y resiliencia.

Los resultados muestran que los subtipos de bosque mediterráneo analizados, como *Cryptocarya alba* & *Peumus boldus*, exhibieron una mayor recuperación frente a las condiciones de sequía extrema, en la Hiper Sequía en comparación con otros subtipos. Esta capacidad diferencial de recuperación destaca la importancia de considerar las particularidades de cada subtipo forestal al diseñar estrategias de manejo y restauración. Asimismo, la variabilidad en la respuesta a las perturbaciones sugiere que ciertas especies pueden desempeñar un papel clave en la estabilidad a largo plazo de estos ecosistemas, actuando como "especies refugio" en un contexto de cambio climático.

Por otro lado, esta investigación resalta la relevancia de emplear modelos predictivos, como los modelos de bosques aleatorios, que permitieron identificar y cuantificar la influencia relativa de distintos factores en la recuperación post-incendio. La integración de estos modelos con series temporales de datos satelitales, como las imágenes Landsat, ha demostrado ser una herramienta eficaz para el monitoreo continuo de la dinámica de recuperación forestal. Esta metodología proporciona un enfoque robusto para predecir las áreas más

vulnerables a futuros eventos de sequía e incendios, lo cual es crucial para la planificación de intervenciones de manejo preventivo.

A nivel general, este estudio subraya la necesidad urgente de adaptar las estrategias de manejo forestal a las nuevas condiciones impuestas por el cambio climático. La interacción entre las perturbaciones naturales, como los incendios y las sequías prolongadas, está creando nuevos desafíos para la conservación y restauración de los ecosistemas mediterráneos. En este sentido, se recomienda incorporar datos climáticos de mayor resolución y estudios de campo localizados para refinar las predicciones y mejorar la capacidad de los modelos actuales. Solo mediante un enfoque multidimensional que considere tanto los factores climáticos como las particularidades ecológicas de cada especie, será posible desarrollar estrategias efectivas para fortalecer la resiliencia de estos ecosistemas vulnerables.

Capítulo VII. Productividad Científica y Difusión

Participación en Congresos Internacionales y Nacionales

- Póster: **Hernández-Duarte A.**, Saavedra (2024). Insights into Post-Fire Dynamics: Evaluating Short-Term Vegetation Recovery During Mega Drought in Central Chilean Mediterranean Forests. General Assembly 2024 of the European Geosciences Union (EGU), Vienna 2024.
<https://meetingorganizer.copernicus.org/EGU24/EGU24-13580.html>
- Póster: **Hernández-Duarte A.**, Saavedra F., Sibold J. (2022) Fire-drought disturbance created compound effects in Mediterranean Forest Landscape. American Geophysical Union (AGU) Fall Meeting, Chicago, United States.
<https://agu.confex.com/agu/fm22/meetingapp.cgi/Paper/1093270>.
- Presentación Oral: **Hernández-Duarte A.**, Saavedra F. (2022) Análisis espacial y temporal de la interacción de perturbaciones ecológicas utilizando series temporales de Landsat en un paisaje forestal mediterráneo. Congreso Nacional e Internacional de la Sociedad Chilena de Geografía (SOCHIGEO), Santiago 2022.
- Presentación Oral: **Hernández-Duarte A.**, Saavedra F. (2022) Interaction between fires and drought and their effects on the recovery of a heterogeneous Mediterranean landscape in South America. Extraordinary IGU Centennial Congress International Geographical Union (IGU-UGI), Paris 2022.
- Presentación Oral: **Hernández-Duarte A.**, Saavedra F. (2022) Interaction between disturbances and their effects on the recovery of a heterogeneous Mediterranean landscape in South America. General Assembly 2022 of the European Geosciences Union (EGU), Vienna 2022.
<https://doi.org/10.5194/egusphere-egu22-10480>

- Presentación Oral: **Hernández-Duarte, A.**, Saavedra, F., Moscoso, C. (2021). Interaction between disturbances and their effects on the recovery of a heterogeneous Mediterranean landscape in South America, Reunión de Otoño de American Geophysical Union (AGU), Estados Unidos, New Orleans, 2021.
- Presentación Oral: **Hernández-Duarte, A.**, Saavedra, F., Moscoso, C. (2021). Interacción entre perturbaciones y sus efectos en la recuperación del bosque esclerófilo mediterráneo de América del Sur, Congreso Nacional e Internacional de Geografía (SOCHIGEO), Chile, Valparaíso, 2021.
- Presentación Oral: **Hernández-Duarte A.**, Saavedra F. (2021). Interacción entre perturbaciones y sus efectos en la recuperación de un paisaje mediterráneo heterogéneo de América del Sur, Reunión Bienal International Association Of Landscape Ecology (IALE-Chile), Chile, Temuco, 2021.

Dirección de Tesis de Pregrado

- Directora de tesis de Pregrado título: “Análisis sobre la recuperación del bosque esclerófilo en áreas incendiadas y expuestas a sequía meteorológica utilizando índices espectrales de vegetación y datos en terreno”. Tesis que adjudicó el concurso Financiamiento de tesis de Pregrado 2021, INNES 19101. DGI Universidad de Playa Ancha.
- Directora de tesis de Pregrado título: “Propuesta de Regeneración de la Vegetación Nativa del Jardín Botánico Afectada por el Incendio Forestal de la Región Valparaíso de Febrero del 2024” (Tesis en desarrollo).

Pasantías de investigación

- Misión científica a IGE's en el marco del proyecto Andesnow. Institut des Géosciences de l'Environnement (IGE) de la Université Grenoble Alpes, Grenoble, Francia. 2022.
- Geography 592 Special Topics: Forests in a Warming World. Colorado State University, Dept. of Anthropology & Geography, Geography, Biogeography Lab. Fort Collins, Estados Unidos (online). Profesor/Investigador responsable: Jason Sibold. Financiado por Proyecto FOVI210026. 2022.

Adjudicación de Proyectos de Investigación de Financiamiento Externo

- Investigadora Principal del Proyecto FONDEF IDeA ID22I10210 "Plataforma de Monitoreo Satelital para la Gestión y Planificación de las Ciudades". 2022-2024.
- Tesista Doctorado del Proyecto FOVI210026 "Fortalecimiento del intercambio y vinculación internacional de investigación y formación de recursos humanos para el estudio de cambios en el paisaje y sus efectos en ambientes de montaña", concurso de fomento a la vinculación internacional para instituciones de investigación regionales 2021, de la Agencia Nacional de Investigación y Desarrollo. 2023.
- Investigadora del Proyecto del Proyecto "Quantification of the spatiotemporal variability of the snow cover along the South American Andes, ANDESNOW" Código CLI2020006 de la Agencia Nacional de Investigación y Desarrollo. 2020-2022.
- Tesista Doctorado FONDEF IDeA I+D 2020 ID20i10058 "Observatorio Satelital de Nieves" de la Agencia Nacional de Investigación y Desarrollo.

Colaboración en Proyectos de Investigación de Financiamiento Externo

- Tesista Doctorado Proyecto ANILLO ACT210080 "Cold-Blooded: Drivers of Climate Change Refugia for Glaciers and Streamflow Responses", adjudicado por la Universidad de Concepción. 2023-2024
- Colaboradora Proyecto FSEQ210022 "A multi-scale drought Observatory for Chile: an early warning system to mitigate agricultural And ecological impacts", concurso Fondo de Investigación Estratégica en Sequía año 2021, de la Agencia Nacional de Investigación y Desarrollo. 2022-2023

Proyectos de Investigación de Financiamiento Interno

- Tesista Doctorado Proyecto "Uso de tecnología satelital en el monitoreo de nieves en la cordillera de Los Andes", línea de Financiamiento Concurso Semilleros de Investigación de la Universidad de Playa Ancha.

Proyectos Vinculación con el Medio

- Tesista Doctorado Proyecto VcM "De lo análogo a lo digital, cambios medioambientales desde la perspectiva tecnológica y de la comunidad de Villa Alemana", línea de Financiamiento Concurso Fondo Social Crealab en el marco de la dirección general de vinculación con el medio y de los convenios de desempeño UPA 2095 y UPA 2193 Universidad de Playa Ancha. 2022.
- Colaboradora del Proyecto "Re-conociendo la Reserva de la Biosfera La Campana Peñuelas: Formación ambiental y territorial de las comunidades" Línea de Financiamiento Vinculación con el Medio de la Universidad de Playa Ancha. 2021.

Formulación de Proyectos con Financiamiento Externo e Interno

- Directora de la postulación FONDEF IDeA 2025: "Integrando Teledetección y Filogenética en el Desarrollo de Indicadores de Biodiversidad Vegetal para la Gestión de Sitios de Alto Valor Ecológico".
- Postulación de proyecto Semillero 2024 de Investigación a la Dirección de General de Investigación (UPLA), en apoyo a estudiantes de doctorado y de la carrera de Geografía. "Aproximación biogeográfica al estado de conservación post mega sequía del sitio RAMSAR "Humedal Las Salinas de Huentelauquén" para el manejo y puesta en valor desde su Comunidad Agrícola"

Representante de la Universidad

- Representante de la Universidad ante la Comisión de Prevención de Riesgo del Consejo de Rectores de Valparaíso (CRUV). Decreto Exento 1000/2024.

Publicaciones realizadas durante el Programa de Doctorado

- Hernández-Duarte, A., Francois Sepúlveda, J. P., Contreras Figueroa, V., Saud Valero, F. R., & Saavedra, F. (2021). Cambios en la cobertura de nieve y su relación con el caudal para la caracterización, monitoreo y gestión de las cuencas de montaña en los Andes extratropicales de Chile entre los 29° y 37°S utilizando teledetección. Boletín de Estudios Geográficos, (116), 123–155. <https://doi.org/10.48162/rev.40.010>

Otras publicaciones en preparación

- Assessing historical changes of the megadrought and their impacts on vegetation and water access in the climatic transition from Semiarid to Mediterranean basins of Chile (Applied Geography, WOS Q1). Autores:

Muñoz, A., Álvarez-Garretón, C., Duncan C., Chávez R., Saavedra, F., Schneider I., **Hernández-Duarte, A.**, González M., Madariaga M.

- A. Climate and fuel controls on wildfire risk in Mediterranean regions (AGU Advance, WOS Q1). Autores: Kampf S., Castro F., Nunes L., Stevens-Rumann, C., **Hernández-Duarte, A.**, Urretavizcaya M., Mosso C., Miranda, A.
- Analyzing Snowpack Variability in the Andes Mountains Using Remote Sensing and Cloud Reduction Techniques (Frontiers, WOS Q1). Autores: Saavedra, F., **Hernández-Duarte, A.**, González, D., Aguirre, Y., Contreras, V., Medina, J., Arancibia, P., Muñoz, G., Caro, A., Rabatel, A., Condom, T., Masiokas, M., Fassnacht, S., Kampf, S.
- Breaking The Ice: Contributions And Challenges For Andean Glaciological Research Led By Women (Annals of the American Association of Geographers, WOS Q1). Autores: Huaico Malhue, A., **Hernández-Duarte, A.**, Lizama, E., Herrera, M., San Juan, M., Calderón de la Barca, N.

Capítulo VIII. Referencias

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