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Facultad de Ciencias Ambientales
Programa de Doctorado en Ciencias Ambientales mención Sistemas Acuáticos Continentales

MODIFICACIONES CAUSADAS POR EL TERREMOTO 8,8 MW DEL 2010 SOBRE EL HUMEDAL COSTERO TUBUL RAQUI: UNA PROPUESTA EMERGÉTICA PARA LOGRAR UNA EVALUACIÓN AMBIENTAL HOLÍSTICA

TESIS PARA OPTAR AL GRADO DE

Doctor en Ciencias Ambientales con mención en Sistemas Acuáticos Continentales

NATALIA ESTRELLA SANDOVAL NOVA

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La Tesis de Doctorado en Ciencias Ambientales con mención en Sistemas Acuáticos Continentales: "*Modificaciones causadas por el terremoto 8,8 MW del 2010 sobre el humedal costero Tubul-Raqui: una propuesta emergética para lograr una evaluación ambiental holística*", de la Srta. Natalia Sandoval Nova, realizada en la Facultad de Ciencias Ambientales y Centro Eula-Chile, Universidad de Concepción, ha sido evaluada por la siguiente Comisión de Evaluación:

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Nada te turbe, nada te espante, todo se pasa, Dios no se muda, la paciencia todo lo alcanza; quien a Dios tiene nada le falta, sólo Dios basta.

Santa Teresa de Ávila

A mi hermano Nelson

por su valentía, coraje y amor a la vida,

1981-2018

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RESUMEN

Los humedales costeros, son ecosistemas que poseen una configuración que permite una interacción periódica entre el medio terrestre y marino, modelado por un régimen de inundación mareal. Esta característica entrega a estas zonas funciones ecológicas únicas, las que proporcionan variados servicios ecosistémicos a la sociedad, los que pueden disminuir a causa de perturbaciones antropogénicas y/o naturales. Entre estas últimas, las más frecuentes en Chile son las perturbaciones sismogénicas, las que modifican la morfología costera por alzamiento o subsidencia de la plataforma continental. Esto fue observado en el Humedal Tubul-Raqui, uno ecosistemas más importantes de Chile, en donde el terremoto 8,8 Richter del 2010 causó el alzamiento litoral de hasta 1,6 m.s.n.m, lo que disminuyó la zona de interacción río-mar presente en la marisma, causando importantes modificaciones en el ecosistema.

En este estudio se evaluaron los cambios generados por esta perturbación natural sobre las condiciones ambientales del ecosistema. Para ello se realizó un análisis cuali y cuantitativo con: i) estudio de campo y comparación con datos históricos del ecosistema, ii) evaluación mediante el uso de indicadores biológicos (mediante bioindicadores) y iii) análisis geomorfológico. Complementariamente, y con el objeto de implementar una nueva herramienta de evaluación ambiental, frente a perturbaciones naturales de gran magnitud que incorpore el impacto socio-ecológico del terremoto, se exploró el uso de la "síntesis emergética" por medio del índice de Intensidad del Desarrollo del Paisaje (LDI).

Los resultados muestran que los cambios más severos registrados casi inmediatamente después del evento perturbador y relacionado con los antecedentes históricos del lugar fueron: a) la desecación total de la red de canales internos que irrigan el humedal, y parcial de uno de los canales principales de los ríos Tubul y Raqui, b) disminución de la salinidad de las aguas al interior del humedal y c) la desaparición de las dos especies bentónicas más importantes para la pesca artesanal: el alga "Pelillo" (*Gracilaria* spp.), y el bivalvo "navajuela" (*Tagelus dombeii*). En el caso de la comunidad macrobentónica (>0,5 mm) evidenciaron cambios significativos entre los periodos pre y post con especies altamente resilientes a la perturbación (*Paracorophium hartmannorum* y *Prionospio* (*Minuspio*) *patagonica*) y otras altamente sensibles (*e.g Boccardia* sp. *Kingiella chilenica*, *Littoridina cumingii*), que no son registradas post-terremoto.

Para evaluar conjuntamente todos los cambios observados (ecológicos y sociales) se utilizó la “síntesis emergética”, definida como: “la energía disponible de un tipo previamente utilizada directa e indirectamente para hacer un servicio o producto” (Odum, 1996), y que fue incorporada a la evaluación mediante el indicador LDI (Landscape Development Intensity). Por medio de este, fue posible reconocer las principales fuentes de cambio en el sistema perturbado (fuentes renovables y no renovables). Se evaluaron los cambios en tres usos de la tierra: la recolección del "pelillo" (*Gracilaria* spp.), la ganadería y el área natural. Los cambios en el LDI total reflejaron un cambio repentino en el uso de la tierra, que disminuyó alrededor del 40,6% como consecuencia de la pérdida de servicios de aprovisionamiento en la zona y el cambio de la economía local a otras actividades tras la desaparición de Pelillo.

Las herramientas utilizadas en este estudio para evaluar el impacto del terremoto de 2010 en el humedal Tubul-Raqui fueron capaces de reflejar los importantes cambios sufridos por el ecosistema. Del mismo modo, la síntesis emergética y su índice Landscape Development Intensity Index (LDI) demostró ser un instrumento útil y que proporciona un enfoque global para evento de gran escala. Se sugiere su uso, junto con otros indicadores y perspectivas, en evaluaciones ambientales de ecosistemas perturbados naturalmente.

1 INTRODUCCIÓN

Los humedales costeros, como estuarios y marismas, son ecosistemas que responden a la geomorfología litoral, en donde la irregular línea que separa el continente del océano presenta una mínima elevación sobre el nivel del mar. Esto, junto con los procesos de erosión costera, permite la interacción entre las aguas dulces continentales y las salinas provenientes desde el mar, las cuales avanzan hacia zonas bajas producto del oleaje y/o un régimen de inundación mareal (Nichols y Bigs, 1985; Bird, 2007). La confluencia de las aguas, entrega a estas zonas funciones ecológicas únicas, las que proporcionan, de manera directa o indirecta, beneficios a la sociedad, vinculando al hombre con el ecosistema a través de lo que conocemos como Servicios Ecosistémicos (SE) (Ehrlich y Ehrlich, 1981; De Groot, 1987: Raffaelli y Hawkins, 1996: Daily, 1997: Constanza, 1997). En ecosistemas litorales, destacan los SE de abastecimiento (*i.e*. alimento, trabajo), regulación (*i.e.* biodiversidad, ciclo hidrológico, protección del suelo, perturbaciones naturales) y culturales (*i.e*. recreación, turismo, valor paisajístico) (Costanza et al. 1997; Potschin y Haines-Young, 2016).

No obstante, lo anterior no exime a los humedales costeros de conformar el grupo de los sistemas naturales más amenazados del mundo (Adam, 2002; Valiela y Sophia, 2008), lo que ocurre principalmente por desconocimiento de la comunidad, que considera a estos sistemas como territorios de inundación sin mayor utilidad que deben ser transformadas. Por este motivo, son intervenidos mayoritariamente a través del cambio en el uso del suelo o por impacto industrial, generalmente causado por derrames de distinto origen (Warwick, 1993; Liu et al. 2014). Estas alteraciones antropogénicas y sus impactos han sido ampliamente evaluados por la comunidad científica (Junk et al. 2013; Renzi et al. 2019). Sin embargo, existen además otro tipo de eventos que pueden modificar estos ecosistemas y que son escasamente abordados, como las alteraciones causadas por una perturbación natural (PN).

Se define perturbación a una modificación en un régimen de disturbios de mayor magnitud duración y/o intensidad, que puede causar cambios a patrones espaciales, temporales y estructurales en las especies, así como a la dinámica y funcionamiento de los ecosistemas (Bormann y Likens, 1979; Pickett y White,1985). Si entendemos que esto forma parte de los procesos de un sistema ecológico (Gunderson, 2000; Odum y Odum, 1995; Odum, 1985; Odum, 1969), ¿Por qué preocuparnos de una perturbación natural? La respuesta a ello se basa en un enfoque ambiental. Cuando un evento de la naturaleza tiene una implicancias ecológicas, económicas y sociales, entonces tenemos que avanzar en el conocimiento del comportamiento del sistema por diversos motivos. En el caso de las perturbaciones naturales de gran magnitud, que impactan los humedales costeros estos son las siguientes:

a) Las PN serán cada vez más frecuentes e intensas en un escenario de cambio climático global (Ibarrarán et al. 2009; Guevara et al. 2009).
b) Al igual que las de origen antrópico, pueden causar importantes daños estructurales y funcionales en los SE presentes en la zona costera. Esto involucra pérdidas de abastecimiento para las comunidades con menos recursos, que comúnmente se desarrollan en zonas cercanas al mar (Cardona et al. 2001; Kaplan et al. 2009; Ibarrarán et al. 2009).
c) Generalmente ocurren en zonas afectadas previamente por impactos antrópicos. Estos eventos consecutivos tienen un efecto sinérgico sobre el ecosistema causando alteraciones físicas, químicas y biológicas (Adger et al. 2005; Srinivas y Nakagawa, 2008).
d) Cuando la PN impacta un sistema poco intervenido, no se da tiempo suficiente al ecosistema de recuperarse en su ciclo natural (disturbio-perturbación-disturbio). Sino más bien, vuelven a ser alterados por un impacto antrópico pudiendo ocurrir el efecto anteriormente descrito.

En América del Sur, una de las perturbaciones naturales más frecuentes son las de origen sísmico, las que ocurren con mayor frecuencia y magnitud en Chile, por poseer alrededor de 3.500 km de costa que interactúan con la zona de subducción de la Placa de Nazca bajo Placa Sudamericana (Atwater et al. 1999; Lagos, 2000; Campos et al. 2002; Lagos y Cisternas, 2004; Quezada et al. 2012). En esta amplia extensión litoral, los humedales costeros, cobran gran importancia, ya que se ha demostrado que estos ecosistemas protegen las zonas costeras frente a perturbaciones naturales (Barbier, 2007; Chang et al. 2006; Hong et al. 2010), pero a su vez producto de ello, sufren importantes daños estructurales y funcionales que culminan en la pérdida de SE (Cardona et al. 2001; Kaplan et al. 2009; Ibarrarán et al. 2009).

Ejemplo de ello, fue el mega terremoto 8,8 Richter que impactó a Chile el 27 de febrero (27F) de 2010. En este evento, el impacto de un tsunami de olas de hasta 15 m y la elevación de la plataforma continental que alcanzó 2.5 m.s.n.m., se tradujo en importantes pérdidas (ecológicas, sociales y económicas) en la zona litoral y, en algunos casos, significó la reestructuración de los ecosistemas perturbados. En este sentido, posterior al evento quedó en evidencia la falta de herramientas que permitieran evaluar, de manera integral el alcance ambiental de la perturbación. El impacto fue abordado solo con métodos tradicionales (encuestas, cambios geomorfológicos, bioindicadores, entre otros), motivo por el cual, surge la necesidad de seguir avanzando en la implementación de nuevos métodos que nos permitan cuantificar estas variaciones mediante la incorporación de componentes de gran magnitud (mareas, viento, calor de la tierra etc.), además de los incluidos en evaluaciones tradiciones. De este modo se podrá interpretar de manera global, los cambios a gran escala, que pueden sufrir los ecosistemas perturbados, ya sea natural o antrópicamente.

Métodos de evaluación tradicional de ecosistemas perturbados

Bioindicadores

Una de las alternativas más usadas para las evaluaciones de las condiciones ecológicas de los humedales, es el uso de bioindicadores (Alba-tercedor, 1996; Rader et al. 2001), ya que estos permiten valorar respuestas biológicas frente a una perturbación en relación con la presencia y/o ausencia de especies y su estructura comunitaria (Gamboa et al. 2008). Entre los bioindicadores más usados destacan los macroinvertebrados bentónicos, que, dada su diversidad, corto ciclo de vida y alta sensibilidad reflejan de manera efectiva cambios en el tiempo (corto y largo plazo) (Marques et al. 2003; Pérez-Quintero, 2007; Lin et al. 2015). En los humedales costeros, el grupo de invertebrados utilizado es la meiofauna, dado que este grupo desempeña un papel insustituible en la transferencia de energía de los productores primarios a altos niveles tróficos en las redes alimenticias (Kurihara et al. 2007), por lo que son una buena herramienta en evaluaciones de impacto ambiental a diferente escala. Ejemplos de ello se pueden ver en el Capítulo 3, sección 5.3.

Índices bióticos y de integridad ecológica

Además del uso de bioindicadores, tradicionalmente las perturbaciones que afectan a los sistemas de humedal son evaluadas mediante diversos índices cualitativos y/o cuantitativos, que se caracterizan por ser signos, típicamente mesurable, que pueden reflejar las características del ecosistema, permitiendo hacer juicios sobre condiciones actuales, pasadas o hacia el futuro (Hilsenhoff, 1987; Karr y Chu, 1997). De ellos, destacan los *índices bióticos* cuya frecuencia de uso en investigaciones de ecosistemas perturbados antrópicamente, da luces de que esta es una efectiva forma de evaluación ambiental. Un índice biótico tiene como ventaja de que es una medida simple para evaluar un solo tipo de perturbación (por ej. contaminación orgánica), utilizando algún grupo biológico, como los macroinvertebrados acuáticos (e.g. Índice Biótico de Familias-Hilsenhoff, 1988). A medida que la comunidad biológica presente una alta diversidad, riqueza de especies y equidad, este presentará un estado de salud del ecosistema mejor que otro que no presente estas condiciones, comparativamente hablando (Angermeier y Karr, 1994).

Otro avance en la incorporación de factores en una evaluación ha sido el desarrollo de *Índices de Integridad Biótica* (IBI). *)*. Este índice propuesto por Karr en 1981, fue implementado inicialmente para evaluar la integridad ecológica de ríos de Norte América utilizando la comunidad de peces como indicador biológico. Posteriormente, numerosos estudios IBI se han publicado utilizando otros indicadores biológicos, como macroinvertebrados, aves, o macrófitas (Kerans y Karr, 1994). Este índice busca definir atributos o características de las poblaciones, comunidades y ecosistemas con los diferentes tipos de actividades humanas que se realizan en una zona o región, de manera tal que permiten evaluar el impacto de estas sobre el ambiente como una expresión numérica (Karr, 1991; Karr y Chu, 1999; Parrish et al. 2003). Entendiendo como integridad buena de un ecosistema, a un estado similar al natural, o a aquel en el cual el impacto de las actividades antrópicas (presentes o pasadas) no sea detectable (Burgos y Laurent, 2011).

A partir de índices como el IBI, que fue pensado para ser implementado en ambientes lóticos, se han desarrollados otros más específicos para humedales como el Index of Wetland Condition (IWC). Sin embargo, este finalmente fue propuesto como complemento a otros de integridad como el enfoque hydrogeomorphic (HGM) de clasificación de humedales y solo para humedales dulceacuícolas (Jakcob et al. 2010). Es decir, los índices de integridad finalmente no evitan la aglomeración de los mismo. No obstante, todos los problemas detectables en estas y otras evaluaciones ecológicas ocurren esencialmente por la complejidad de los ecosistemas (Müller et al. 2000).

En este contexto, se han propuesto muchos enfoques para el desarrollo de índices de integridad ecológica, (e.g. Ortega et al. 2004; Solimini et al. 2008; Borja et al. 2009; Tan et al. 2015), pero se aplican a áreas muy específicas de ecosistemas acuáticos o terrestres (Imam y Arif, 2001). Por otro lado, la reducción o incorporación de componentes abióticos está sujeto a innumerables supuestos y criterios, determinados por la experiencia del especialista (Selkone et al. 2008), lo que, en líneas generales, no representa mayor dificultad. Lo complejo de esto, surge al momento de elegir el modelo apropiado, dado que especialistas de diferentes áreas, han desarrollado índices para evaluar ecosistemas comunes (e.g. IBI[1]; AMBI[2], EEI[3]).

Por lo anterior, cuando se requiere utilizar uno de ellos para evaluar el impacto de una perturbación a gran escala como los de origen natural, nos enfrentamos a preguntas cuyas respuestas, nuevamente, están sujetas al criterio del especialista como: ¿qué componentes fisicoquímicos deben estar incluidos en el índice para ser aplicado?, ¿cuál es la comunidad biótica idónea en la evaluación?, entre otras. Todo ello, aumenta el sesgo de la evaluación y limita la inclusión de componentes bióticos y abióticos, ya que su incorporación se encuentra sujeto a lo que esté o no considerado en el índice previamente desarrollado.

Las limitaciones más frecuentes de estos índices son:

a) Agregan o sintetizan la información de los indicadores (Prescott-Allen, 2001; Sutton, 2003; Esty et al. 2005).
b) Requieren de decisiones arbitrarias en cuanto a su selección, ponderación y agregación (Morse y Fraser, 2005).
c) No consideran variaciones estructurales y/o funcionales del ecosistema, ni los alcance que estas pudieran tener en sus servicios ecosistémicos.

Conforme a lo anterior, existen teorías de los sistemas, basados en la cuantificación de la energía (Odum, 1968). Ellos proporcionan una base teórica para definir, medir e interpretar, de manera holísticas, los cambios en un ecosistema. Esto se presenta como una alternativa menos sesgada, al ser métodos basados en flujos de energía, expresados numéricamente y que muestran el funcionamiento de un ecosistema (Odum, 1996), a través de una delimitación conceptual, lo cual facilita la interpretación de los cambios, al incluir variables bióticas y abióticas, acorde a la pregunta que necesitamos responder.

[1] Índice de integridad biótica (IBI) para sistemas costeros (Nelson 1990).[2] AMBI (AZTI´ Marine Biotic Index) (Borja et al. 2000).[3] Índice de Evaluación Ecológica (EEI) Orfanidis et al. (2001).

Evaluación energética de los ecosistemas

Mediante el estudio de los flujos de energía de los ecosistemas desarrollados por H.T. Odum (Odum y Odum, 1955; Odum, 1956, 1957), es que comienzan a surgir en él las interrogantes respecto de la transferencia de la energía desde las fuentes principales (sol, los efectos de las fuerzas gravitacionales de la luna principalmente sobre los océanos, el calor disipado desde el núcleo de la Tierra) hacia la biota que las consume. Odum comenzó a diferenciar la energía inicial de la terminal en algunos procesos naturales. Por ejemplo, en el caso del sol, las plantas absorben su energía y queda disponible como alimento para un consumidor herbívoro, el cual es consumido con posterioridad por un carnívoro, entonces: ¿cuánto de la energía del sol finalmente recibió el carnívoro? Respecto de ello, la energía inicial del sol particularmente difusa no tendría el mismo "costo" que la energía que contiene el carnívoro, ya que ha tenido que pasar por diferentes procesos en el tiempo para quedar disponible para un consumidor terminal.

En este sentido, una parte de la energía es transferida concentrada y otra parte se "pierde". Por lo tanto, a medida que avanzamos en una cadena trófica tenemos menor energía, pero mayor valor de concentración de energía, por lo comienza una búsqueda de transformar la relación del tiempo y la concentración de la energía en una medida única.

Entre las medidas de la energía más utilizadas se encuentran la *energía incorporada* y la *exergía*. Esta última se define como la suma de las energías de todos los tipos que se encuentran disponibles dentro de un sistema (Dolan, 2007) o bien como la cantidad de trabajo que el sistema puede realizar al ser puesto en equilibrio con su medio ambiente (Jorgensen, 2006). La exergía ha sido utilizada para evaluar, mediante indicadores ecológicos de salud, ecosistemas terrestres y acuáticos, *i.e.*, Christensen (1995); Jorgensen (1994; 2000); Marques et al. (1997; 2003); Fabiano et al. (2004); Salas et al. (2006). Sin embargo, como indicador ecosistémico ha sido considerado insuficiente, pues valora la energía de diferente origen como del mismo tipo.

Es por esto y a modo de contrastar las evaluaciones energéticas utilizadas hasta a la actualidad, Scienceman (1987) propone el concepto "Emergía" (con "m") para definir el método desarrollado por H. T. Odum desde los años 70´s, con el objeto de diferenciarse de los modos de evaluación energética conocida hasta el momento (Odum, 1988, 1996).

La Emergía en cierto modo complementa la exergía y se define con la ecuación:

Emergía = Transformicidad * Exergía

Emergía se define como la energía disponible de un tipo previamente utilizada directa e indirectamente para hacer un servicio o producto (Odum, 1996), esto es también llamado “memoria energética” (Odum, 1986, 1988, 1996) y es una manera de incluir todas las entradas a un sistema sobre una base común (Brown y Ulgiati, 2004). En otras palabras, es la energía disponible de un tipo previamente utilizada (o degradada mediante transformaciones) de manera directa o indirecta para hacer un producto o servicio (Odum, 1986, 1988; Scienceman, 1987). La energía disponible es una propiedad de la menor cantidad de energía en el producto transformado (Odum, 1996) y al emergía hace referencia a la calidad (ver Figura 1.1-1).

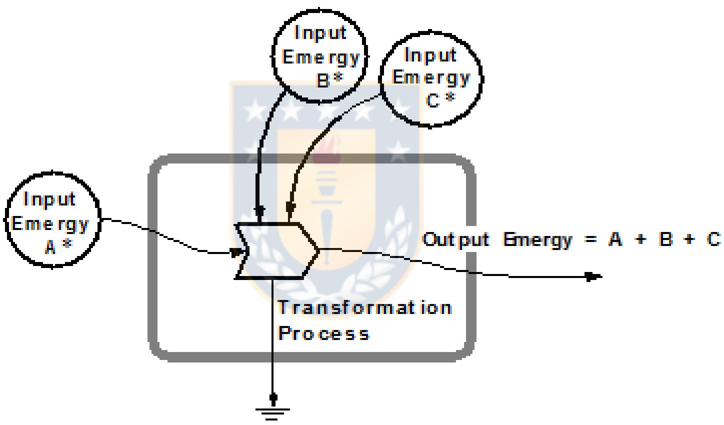


Figura 1.1-1 Esquema de un sistema delimitado conceptualmente con entradas A, B y C (Ex., Brown et al. 2009).

Por lo tanto, en A*, B* y C* tenemos mayor energía, pero menor emergía. Una vez que la energía con baja calidad (o de entrada en este ejemplo) es transformada por diferentes procesos dentro de un sistema como en la Figura 2.1 1, el producto de salida A+B+C tendrá mayor emergía que en A*, B* o C*.

El sentido de incorporar todos los ingresos energéticos en un sistema y no tan solo los que se encuentran “dentro” del mismo, es considerar las entradas ambientales y sociales y estimar cómo la variación de estos flujos provenientes desde “fuera” puede alterar el funcionamiento ecosistémico (Odum, 1996). Dado que, cuando uno de los componentes en un sistema es modificado, la energía y los flujos de materia cambian, lo cual puede traducirse en una disminución de su complejidad (Ulgiati y Brown, 2009). En este sentido la "Síntesis de Emergética" es un método de contabilidad ambiental basada en un concepto holístico de sistemas, donde se acopla la sociedad humana y la evolución dentro de su contexto natural.

Síntesis de Emergía

El procedimiento para estimar la emergía es conocido como "síntesis emergética" y se basa en la transferencia de energía de un ecosistema en orden jerárquico. Esta jerarquía ordena la energía disponible y sus formas de disipación o concentración dentro de un sistema, permitiendo a la vez la retroalimentación y generación de productos (o servicios) según la energía disponible (Odum, 1988, 1996; Brown y Ulgiati, 2004). Esto responde al orden jerárquico de todas las estructuras, comenzando por el cerebro respecto al cuerpo humano, como los ecosistemas, los paisajes, y los sistemas económicos, sociales y culturales (Odum, 1995; 2001; Brown et al. 2004), como ocurre en este tipo de estructuras, la relación entre sus componentes es primordial para el buen funcionamiento. Frente a un cambio, en alguno de sus vínculos, puede que algún componente desaparezca y toda la jerarquía se modifique o se simplifique.

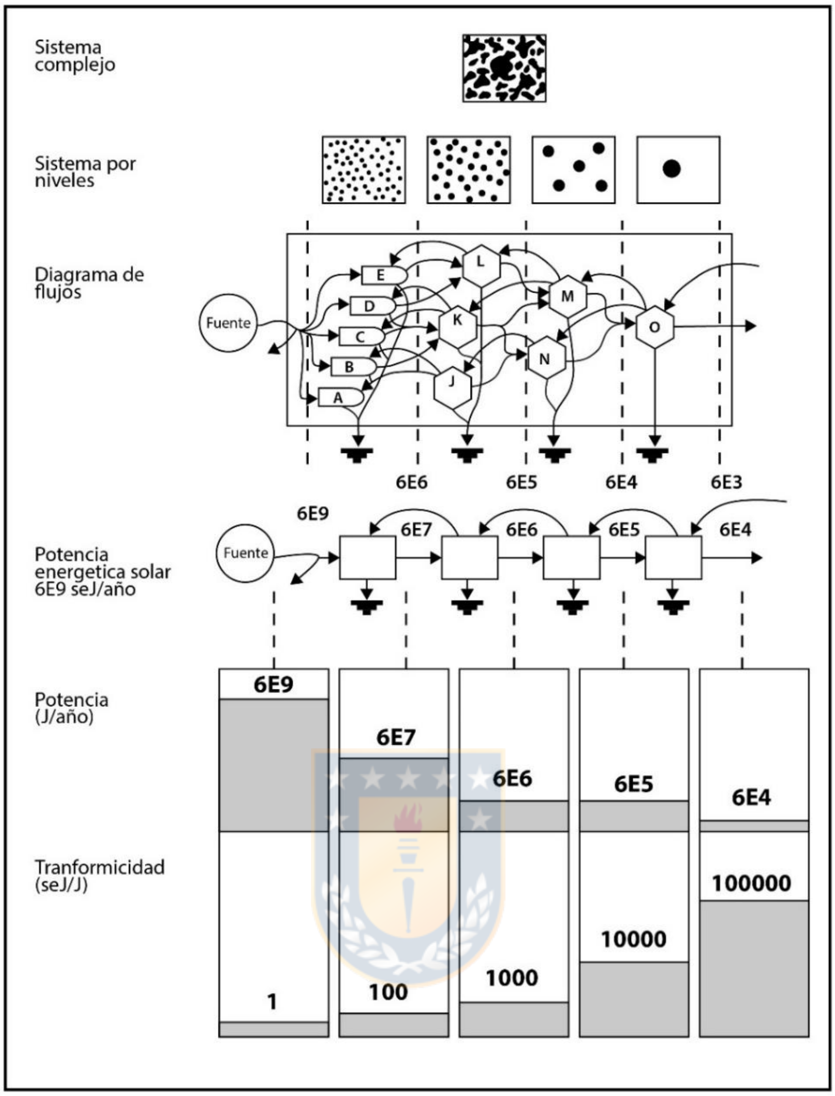


Figura 1.1-2 Ejemplo de jerarquía considerada en el proceso de transformación de la energía (Extraído de Lomas, 2009).

El modo de ubicar jerárquicamente un componente en la síntesis de emergía es estimando la cantidad de energía que este necesita para formar un producto, es decir, el componente superior entrega la energía necesaria al inferior y así sucesivamente. Este concepto se liga a la calidad de energía dentro del ecosistema, la cual aumenta cuando avanzamos en la jerarquía, ya que a medida que transferimos la energía se hace más concentrada. Por lo tanto, identificamos el componente ("o") que se encuentra en una posición más alta, dentro de la jerarquización, como el que posee menor calidad energética (Figura 1.1-2).

Todo lo anterior, deriva en el concepto desarrollado por H.T. Odum en los años 70, *Transformicidad*, que se define como la medida de *Calidad de la Energía* (Odum, 1967, 1971, 1973, 1988, 1996; Brown y Ulgiati, 2004), y su ubicación en la jerarquía de la energía o la emergía requerida para hacer productos similares en diferentes condiciones y procesos. La *Transformicidad* a veces puede jugar el papel de indicadores de eficiencia y, a veces el papel de indicadores de posición jerárquica (Ulgiati y Brown, 2009).

El ordenamiento hasta el momento descrito comienza considerando las tres entradas externas principales de energía sobre la tierra o línea de base (Odum, 1996; Brown y Ulgiati, 2004, 2010, 2016a, 2016b; Brown et al. 2016; Campbell, 2016): a) la energía solar, b) la energía de las mareas y c) el calor de la tierra profunda. Desde este punto comenzamos la trasferencia energética y los cálculos contables de emergía. La emergía generalmente se mide en *equivalentes solares* (energía proveniente del sol) (Odum, 1988, 1996, Brown y Ulgiati, 2004) a partir de la base propuesta por Odum, que estima que la transformicidad para el sol corresponde a 1, asignando, de este modo, una unidad de medida única para diferentes formas de energía en emjoules solares (emergía x joules), abreviada *sej* (Odum, 1996; Brown y Ulgiati, 2004, 2016). Esto permite visualizar y calcular la transferencia emergética de los distintos componentes que modifican los ecosistemas, tanto de origen natural o antrópico (ver Tabla 4.3-1).

Consideraciones sobre la emergía para aplicación en caso de estudio

La "síntesis emergética" posee innumerables aplicaciones: evaluaciones económicas (Ferreyra, 2001; Campell y Cai, 2007; Yang et al. 2019), procesos industriales (Vassallo et al. 2009; Almeida et al. 2010), desarrollo urbano sustentable (Su et al. 2013), sustentabilidad ecológica (huella ecológica) (Siche et al. 2010; Zhao et al. 2013), maricultura (Odum y Arding, 1991; Vasallo et al. 2007), cultivos agrícolas (Jiang et al. 2007; Tilley y Martin, 2006), ganadería (Rótolo et al. 2007), bosques y plantaciones (Tilley y Swank, 2003). Del mismo modo, Campbell (2000) utilizó este sistema para determinar el estado de salud e integridad ecológica de un ecosistema proponiendo tres índices de emergía teóricos, para medir aspectos de integridad y la salud. Por otro lado, en ecosistemas de humedal se ha evaluado la salud y sustentabilidad por Tilley y Brown (2006), Vivas y Brown (2006), Chen et al. (2009) Zhou et al. (2009) y Brandt-Williams et al. (2013). Ellos evaluaron emergéticamente la estructura, función y condición de ecosistemas de marisma basado en el muestreo de 10 marismas. Para ello, utilizaron datos de campo recogidos durante 10 años y evaluaron vegetación, invertebrados y muestreo de calidad del agua. A partir de sus resultados concluyeron que el flujo de emergía de la cuenca presenta gran perturbación humana y concluyen que la síntesis emergética es una herramienta potencial para la evaluación rápida de la situación ambiental de humedales costeros.

Dado que la síntesis emergética ha sido utilizado en la evaluación de humedales costeros, se transforma en una potencial herramienta para evaluación y gestión de estos ecosistemas posterior a una perturbación. Actualmente las zonas costeras son un tema de interés urgente para los países desarrollados o industrializados de todo el mundo (ICSU, 2010). Sin embargo, estos generalmente, sólo evalúan el estado del ecosistema frente a alteraciones de origen antrópico. No obstante, los ecosistemas litorales pueden ser también modificadas por perturbaciones de origen natural (e.g. huracanes, tsunamis, terremotos, inundaciones), causando variadas modificaciones en los componentes bióticos y abióticos del sistema, lo cual deriva en considerables pérdidas de los SE proporcionados por estas zonas (Jaramillo, 2012).

1.1 Humedal Tubul-Raqui como caso de estudio

Los movimientos de corteza que causan terremotos de gran intensidad, como el ocurrido el 27 de febrero de 2010 (27F) en el centro sur de Chile, pueden originar humedales costeros o modificar significativamente aquellos que existían previo al evento (Castilla, 1988; Espinoza y Zumelzu, 2016). Todo ello, dependerá de la cercanía y ubicación del epicentro en relación con la plataforma continental, lo que puede generar dos tipos de fenómenos; el alzamiento o la subsidencia (Mouslopoulou et al. 2016).

En el caso del Hundimiento de la zona litoral (subsidencia), ello es comúnmente observado a nivel mundial. En Chile el mayor fenómeno de subsidencia registrado ocurrió durante el terremoto de 1960, en donde el movimiento sísmico generó hundimiento de 2,7 m en Valdivia (Plafker y Savage, 1970). Dada la morfología costera a esta latitud, el ingreso del mar, causado por el hundimiento, originó un ecosistema estuarino altamente productivo y que, con posterioridad, permitió el desarrollo de variados SE (e.g. paisajísticos, turísticos, ecológico, entre otros; Cisternas et al. 2000). Lo contrario ocurre, cuando existe alzamiento cosísmico, en un área con presencia de humedales costeros. Según lo observado el 27F, la elevación de la plataforma continental puede causar, a diferente escala, una disminución en zona de contacto entre estos ecosistemas y el mar, lo que modifica, en mayor o menor medida, las características hidrológicas de estuarios, marismas, lagunas u otros.

El alzamiento costero, posterior al terremoto de 2010, fue evidenciado en diversos humedales de la Región de Biobío *i.e*. Rocuant, Andalién, Carampangue, Lenga, Tubul-Raqui (Vargas et al. 2010; Valdovinos et al. 2010). Entre ellos, el humedal Tubul-Raqui es el que manifiesta mayores alteraciones posterior al evento sísmico con un alzamiento de 1,6 msnm, lo cual alteró la dinámica de las mareas sobre la marisma, provocando la pérdida o disminución de variados SE disponibles previo a la catástrofe (e.g. recolección de *Gracilaria* spp*.*, *Tagelus dombeii* y *Ensis macha*), es decir, en esta localidad se aprecia cómo una alteración ambiental de origen natural modificó las condiciones económicas y sociales de la comunidad (Valdovinos et al. 2011; Parra et al. 2013).

Los cambios socio-ecológicos observados indican que el humedal disminuyó su relación con el hombre al modificarse las condiciones estuarinas del humedal y se relaciona con él a través de otras actividades que permanecen después del terremoto como la ganadería. En este sentido se espera que la emergía además de proporcionarnos una visión holística de los cambios observados, sea capaz de reflejar numéricamente la perdida de los servicios ecosistémicos. Ello con el objeto de ampliar las alternativas de evaluación frente a eventos poco explorados como las perturbaciones naturales de gran magnitud.

2 HIPÓTESIS

Hipótesis 1

El alzamiento cosísmico causado por el terremoto de 2010 que impactó a la marisma Tubul-Raqui, causó modificaciones en la estructura y funcionamiento del ecosistema acuático.

Hipótesis 2

El alzamiento costero que impactó el humedal Tubul-Raqui causó cambios significativos en la cobertura de las unidades de paisaje del humedal costero

Hipótesis 3

Producto de las modificaciones socio-ecológicas observadas en la marisma Tubul-Raqui tras el terremoto, se esperan encontrar variaciones a la baja en el valor emergético de la marisma, con disminución en los indicadores de intensidad del uso.

3 OBJETIVOS DEL ESTUDIO

3.1 Objetivo general

Poner a prueba diferentes metodologías usadas tradicionalmente en evaluación ambiental para evaluar una perturbación natural de gran magnitud como el terremoto en el humedal Tubul-Raqui en 2010 y complementar su alcance mediante el uso de la emergía como estimador de cambios pre y post terremoto. Todo lo anterior con el objeto de generar nuevas herramientas de gestión ambiental frente perturbaciones naturales.

3.2 Objetivos específicos

- Evaluar cuali y cuantitativamente el impacto del terremoto de 2010 en un humedal costero
- Evaluar el alcance de métodos de evaluación ambiental tradicionales frente a una perturbación natural de gran magnitud.
- Determinar si el LDI es capaz de reflejar los cambios socio-ecológicos del ecosistema por el terremoto 27F.

4 METODOLOGÍA

4.1 Estructura de la tesis.

4.1.1 Capitulo introductorio.

Capítulo 1: Los Humedales Costeros, conceptos y definiciones generales, con énfasis en un sistema tipo marisma.

4.1.2 Evaluación de la perturbación.

Capítulo 2: Descripción cuantitaliva y cualitativa

Basado en: The Tubul-Raqui Coastal Wetland: A Chilean Ecosystem of High Conservation Value Severely Disturbed by the 2010 Earthquake. 2017. In: Fariña J., Camaño A. (eds) The Ecology and Natural History of Chilean Saltmarshes. Springer, Cham. Valdovinos C., **N. Sandoval**, D. Vásquez and V. Olmos.

Capítulo 3: Indicadores bentónicos

Basado en: Impacts of coseismic uplift caused by the 2010 8.8 Mw earthquake on the macrobenthic community of the Tabul-Raqui Saltmarsh (central-south Chile). 2019. Estuarine Coastal and Shelf Science, 226 :1-11. **Sandoval N.,** C. Valdovinos, J.P. Oyanedel y D. Vásquez.

Capítulo 4: Indicadores geomorfológicos

Basado en: Morphological impacts of the Chilean megathrust earthquake Mw 8.8 on coastal wetlands of high conservation value. 2020. Estuarine Coastal and Shelf Science, 245 :1-3.. D. Vásquez, **N. Sandoval**, P. Fierro, C. Valdovinos.

Capítulo 5: Indicador emergético

Basado en: Evaluation of changes in soil use in a marsh perturbed by the 8.8 Mw earthquake of 2010 in Chile: A new use of the of the Landscape Development Intensity index. 2020. Ecological Modelling. **Sandoval N.,** P. L. Lomas, D. Vásquez, P. Fierro, C. Valdovinos (enviada).

4.2 Descripción del área de estudio.

En este estudio se evaluó el humedal costero el Humedal Tubul-Raqui de la Provincia de Arauco (37°13´S; 73°26´O), perturbado por el terremoto 8,8 Richter ocurrido el 27 de febrero de 2010, derivado un alzamiento tectónico (Figura 4.2-1).

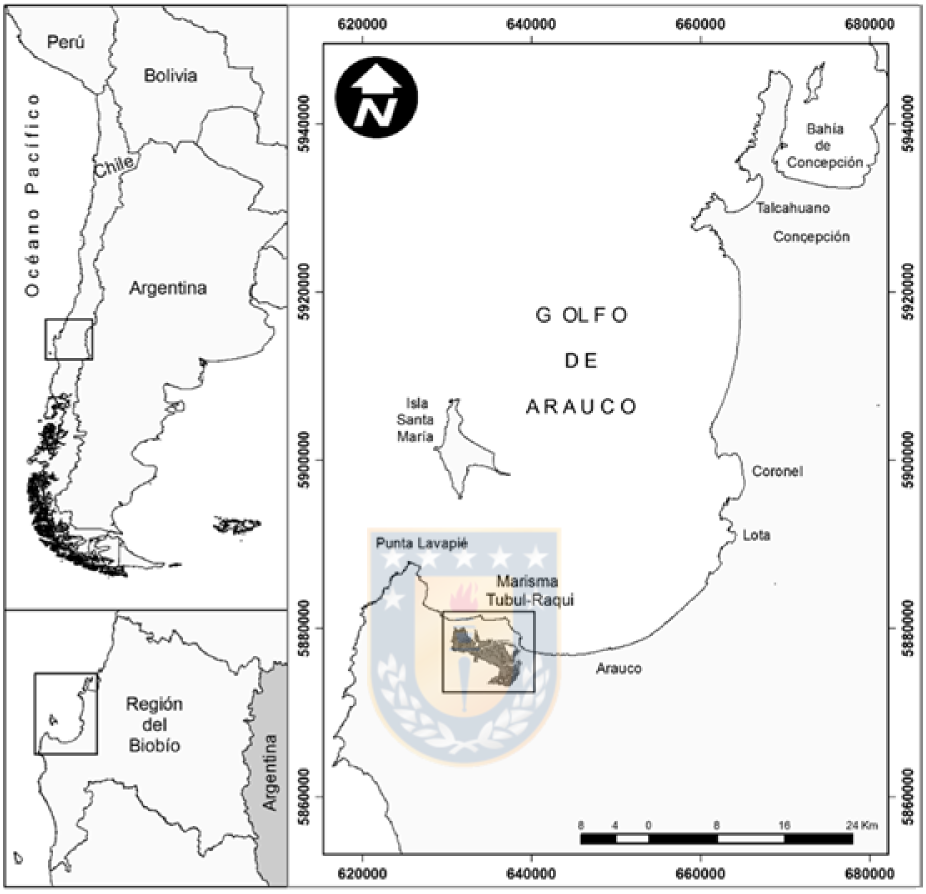


Figura 4.2-1 Ubicación área de estudio.

4.3 Emergía

4.3.1 Conceptos básicos de la "síntesis emergética".

Odum (1996), define los siguientes conceptos:

- *Transformicidad*: Se define como la emergía por unidad de energía disponible (exergía). Por ejemplo, si se requieren 4.000 emjoules solares para generar un julio de madera, a continuación, la transformicidad solar de la madera es 4.000 emjoules solares por julios (abreviada SEJ/J). La energía solar es la más grande, pero la más dispersa entrada de energía a la tierra. La Transformicidad solar de la luz solar absorbida por la Tierra es 1,0 por definición.

- *Componente estructural del ecosistema*: Componente con alto valor emergético e interacciones de energía dentro del diagrama de flujo.
- *Emergía de recursos no renovables*: La emergía de energía y material almacenados como los combustibles fósiles, los minerales y los suelos que se consumen a tasas muy superiores a las tasas a las que se producen por procesos geológicos.
- *Emergía renovable*: La emergía de los flujos de energía de la biosfera que son más o menos constantes y recurrentes, y que conducen los procesos biológicos y químicos de la tierra y contribuyen a los procesos geológicos
- *Producción*: La producción se mide en emergía es la suma de todas las entradas de emergía a un proceso.

4.3.2 Procedimientos para el cálculo de la emergía

4.3.2.1 Diagrama de flujo

Los pasos que seguir en la evaluación emergética comienzan con la elaboración de un diagrama de flujo energético que nos permite visualizar las interacciones energéticas, las entradas y salidas del sistema según lo propuesto por H.T Odum (1996) (Figura 4.3-1). La escala en la se genera el diagrama guarda relación con nuestra pregunta a responder y para ello se utiliza la simbología de la Figura 4.3-1.

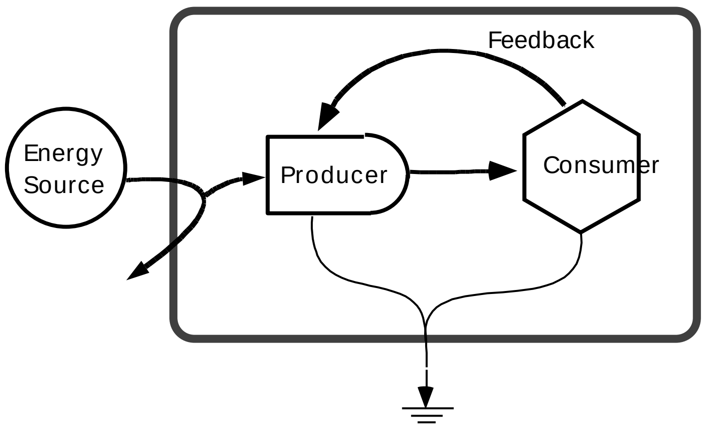
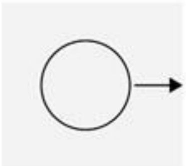
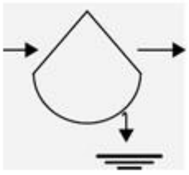
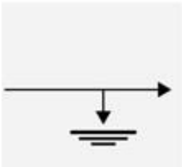
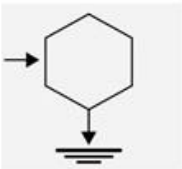
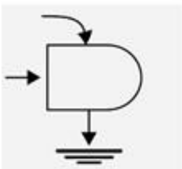
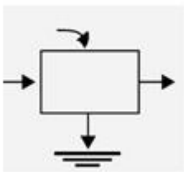
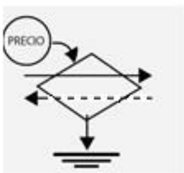


Figura 4.3-1 Ejemplo simple de configuración de diagrama de flujo que muestra la de relación entre producción y consumidor en un ecosistema (Odum,1996).

Simbología 4.3-1 Descripción de elementos representados en los diagramas de flujos (adaptado de Odum, 1996).

	**Círculo de energía**: Vía cuyo flujo es proporcional a la cantidad de almacenamiento en dirección ascendente.
	**Fuente**: Energía externa relacionada a un tipo de acción sobre el sistema
	**Depósito de reserva de energía (Tanque)**: Compartimiento de almacenamiento de energía dentro de los sistemas, que almacena una cantidad como el saldo de entradas y salidas; un estado variable
	**Disipador de calor**: La dispersión de la energía potencial en calor, acompaña todo proceso de transformación real y de almacenamiento, la pérdida de energía potencial de un mayor uso del sistema.
	**Consumidor**: Unidad que transforma la calidad de la energía, la almacena, y se alimenta autocatalíticamente.
	**Productor:** Unidad que recoge y transforma la energía de baja calidad proveniente desde el sol mediante la fotosíntesis.
	**Caja**: Símbolo misceláneo, se usa para cualquier unidad o función etiquetada.
	**Transacción**: Unidad que indica la venta del producto o del servicio (línea continua) a cambio del pago de dinero (línea de puntos).

4.3.2.2 Fórmulas para cálculos de flujos de energía renovables

Posterior a la identificación de los componentes del ecosistema, ya sean renovables o no renovables se procede a los cálculos de flujos de energía (Joules), estas ecuaciones combinan los valores establecidos en literatura con las características de cada ecosistema. Los resultados obtenidos serán utilizados posteriormente para el cálculo de emergía al multiplicarlo por la *transformicidad*.

Ejemplos de ecuaciones usadas para el cálculo de energía (Joule/año) de diferentes componentes (Odum, 1996):

Luz solar:

(Área del país) (Promedio de insolación) = (_m^2) (_$J/m^2/y$) =__J/año

Marea absorbida en estuarios:

(Área elevada) (0.5) (Marea/año) (altura^2) (Densidad) (Gravedad)= (_m^2)(0.5) (706/año) (__m)^2 (1.0253 x10^3 kg/m^3) (9.8 m/sec^2)

Energía cinética del viento sobre la superficie en uso:

(Altura)(Densidad) (Coeficiente de difusión) (Gradiente de viento) (Área) = (1000m) (1.23 kg/m^3) (_m^3/m/seg) 3.154 x 10^7 seg/año) = (_m/seg/m)^2(_m^2)

Energía química potencial en el río:

(Volumen flujo) (Densidad)(G), *Donde G es Gibbs energía libre del río relativo a agua de mar* G = (8.33 J/mol/grados) (300°C) / (18 g/moles) en ((1 x 10^6 – *S*) ppm) / 965,000 ppm) J/g, d*onde S son los sólidos disueltos en partes por millón.*

4.3.2.3 Cálculo de Transformicidad

Por definición, *Transformicidad* resulta al dividir la emergía por la energía, es decir, emergía (sej)/energía (J)= (sej/j). Una vez obtenida la *Transformicidad* se estima el valor de Emergía Total del sistema en equivalentes solares (ver ejemplo Tabla 4.3-1), de este modo, todas las entradas y salidas del sistema tendrán una misma unidad (sej/año).

Tabla 4.3-1 Ejemplo de cálculo de Emergía (Em) total en un sistema (modificado de lomas, 2009).

INGRESO AL SISTEMA	DATO ENERGÍA (JOULE/AÑO)	TRANSFORMICIDAD (SEJ/JOULES DEL PRODUCTOS)	EMERGÍA SOLAR (SEJ/AÑO)
LUZ DIRECTA DEL SOL **a**	6,22E+16	**1**	6,22E+16 a
ÍTEM **b**	X	XX	X Em b
ÍTEM **c**	X	XX	X Em c
ÍTEM **d**	…	XX	…d
ÍTEM ….**z**	…	XX	…z
			$\sum_{z}^{a} \mathbf{Em} = \boldsymbol{Em\ total}$

5 RESULTADOS

CAPITULO 1

Basado en:

Los Humedales Costeros, conceptos y definiciones generales, con énfasis en un sistema tipo marisma.

Natalia Sandoval, Daniela Vázquez, Bárbara Miller, Claudio Valdovinos.

5.1 Capítulo 1: Los Humedales Costeros, conceptos y definiciones generales, con énfasis en un sistema tipo marisma.

5.1.1 Los Humedales Costeros

Recientemente el Ministerio del Medio Ambiente declara que en Chile existen 18 mil humedales, de los cuales sólo el 2% de ellos, se encuentran bajo alguna figura de protección (MMA, 2017). El interés de las autoridades por conservar estos ecosistemas responde a un enfoque mundial de proteger aquellas zonas que aún son consideradas en estado natural, que se caracterizan por concentrar una alta biodiversidad y que a la vez proporcionan, a la comunidad humana, variados servicios ecosistémicos (SE), tales como servicios de abastecimiento, regulación, culturales, entre otros (MEA, 2005).

Un *humedal costero* (HC) es una zona de anegamiento cercana al litoral generalmente presente en el área terminal de una cuenca hidrográfica. Esta denominación encierra una variedad de sistemas acuáticos que interactúan de manera directa e indirecta con el mar (Fariña y Camaño, 2012), entre los cuales reconocemos: bofedales, manglares, estuarios, marismas (mareales y de agua dulce) y lagunas costeras. En el hemisferio sur es frecuente observar principalmente tres de ellos, que describimos a continuación:

Los estuarios corresponden a zonas de interacción directa entre un sistema acuático continental y el océano. Frecuentemente esta relación ocurre cuando uno o más ríos desembocan en el mar en zonas de baja pendiente, lo cual favorece el encuentro entre el agua dulce y salina. Conforme a las condiciones de caudal del río o al estado de la marea, la confluencia de las aguas tendrá un carácter diferenciado dependiendo de la energía de los cuerpos de agua, lo cual delimitará tres zonas con límites móviles: una zona propiamente lótica, una zona de transición donde el agua dulce posee una cuña salina y una zona terminal estuarina donde el mar recibe el agua dulce, pero en condición de pleamar, la energía del cuerpo marino se sobrepone y domina las características físicas, químicas y biológicas de la columna de agua, posterior a esta zona nos enfrentamos al océano (Piccolo y Perillo, 1997).

Las lagunas costeras son sistemas lénticos que generalmente responden a una conexión intermitente con el mar (Adam, 2009). Estos cuerpos de agua dulce, de extensión y profundidad variable, son generalmente delimitados por una barrera natural (duna costera, arena de playa, rocas u otro), lo que impide que este sistema se comunique directamente con el océano (Piccolo y Perillo, 1997). Ahora bien, producto de procesos sísmicos, erosivos u otros, puede disminuir o desaparecer la barrera y comunicar ambos cuerpos de aguas, lo que puede dar origen a estuarios temporales, para luego volver a cerrarse.

Las marismas mareales, son sistemas vegetacionales halófitos ubicados en zonas encajonadas cercanas al mar (Mitsch y Gosselink, 2007). De acuerdo con su génesis, pueden desarrollarse: gracias a la interacción de agua dulce (proveniente de aguas subterráneas y/o lluvia), y el mar que inunda el continente en pleamar, o bien, por vincularse a zonas estuarinas. En este último caso un sistema de alta energía permite que el agua proveniente desde la desembocadura ascienda por el o los ríos que conforman el HC, hasta un área donde la masa de agua duce salina es retenida, entre las raíces, sedimentos y canales presentes en medio de la vegetación. Estos componentes pueden formar extensos embalses naturales, que desciende en profundidad cuando baja la marea.

En relación con lo anterior, poco se conoce de la representatividad de cada HC en Chile. Más bien, diferenciamos números generales como lo descrito por Marquet et al. (2011) que indican que existen aproximadamente 412 humedales costeros que conforman una extensión de 38.167 ha. Pese a no tener antecedentes de cuántos de ellos corresponden a lagunas, estuarios o marismas, es posible destacar las características comunes que hacen a estos sistemas zonas de alto valor de conservación. En los humedales costeros es posible encontrar especies de origen marino o continental, por lo que son reconocidos como zonas ecotonales (Negrín, 2011; Vásquez, 2013). La ocurrencia de especies biológica es el atributo *per se* de un HC, ya que las características fisicoquímicas de calidad del agua y su geomorfología son altamente variables y pueden ser modificadas significativamente por su relación con los cambios de marea, por eventos sísmicos de gran magnitud y por presión antrópica. Siendo esta última, la mayor causante de la desaparición de estos ecosistemas en el último siglo (Dugan, 1992).

5.1.2 Diferenciación energética entre un estuario, laguna costera y marisma mareal.

Los tipos de humedales costeros pueden ser definidos en relación con la intensidad de interacción entre el medio terrestre y marino, lo cual puede ser modelado mediante diagramas de flujos de energía.

La energía en un ecosistema es transferida de un nivel a otro. Ahora bien, la energía que logra ser transferida al siguiente eslabón y es procesada por el mismo, es considerada energía concentrada, la que a medida que avanza en un sistema es capaz de generar un producto o servicio. Esta concentración se traduce en calidad y es llamada emergía o calidad de la energía (Joule/emjoule) (Odum y Odum, 2000). de Groot et al. (2012), define a los humedales costeros como los ecosistemas más productivos del mundo, seguidos por arrecifes de coral y bosques templados. Esto ocurre, porque variadas energías renovables (energía solar, eólica, mareomotriz, hidráulica, entre otras) confluyen en un mismo ecosistema, lo cual influye en su emergía, es decir en la calidad de energía que se transforma en un producto final.

A continuación, se expone un ejemplo de transferencia de energía mediante diagramas de flujos (Figura 5.1 1, Figura 5.1 2, Figura 5.1 3). En esencia, la importancia ecológica y productividad de los humedales costeros es siempre mayor a otros sistemas acuáticos. No obstante, existen diferencias en relación con la energía que ingresa al sistema, lo que influye, entre otras cosas, en la abundancia y presencia de determinados productores primarios, que finalmente modelan tanto las interacciones en el medio acuático como las salidas o SE. Para este ejemplo, usamos un modelo tipo, el cual considera el servicio ecosistémico de abastecimiento (comercialización de filtradores y algas estuarinas) como eje diferenciador entre la configuración energética de un HC tipo estuario, marisma y laguna costera.

De izquierda a derecha, en cada diagrama, podemos diferenciar los flujos de entrada al sistema (componentes abióticos), que configuran las interacciones dentro del mismo (componente biótico), los tamaños de los símbolos muestran mayor o menor energía.

En el caso del estuario (Figura 5.1-1) se distinguen seis energías de entrada de similar intensidad por lo que los círculos son de igual tamaño entre luz solar, viento, marea entre otros. Una vez incorporada esta energía por los productores primarios, donde se encuentran las algas estuarinas, se transfieren al siguiente eslabón, jerárquicamente ubicado en el diagrama (de izquierda a derecha). Una vez avanzada la energía y por tanto su concentración o emergía es posible visualizar dos salidas que representan los SE de venta de productos (representados en un recuadro) hacia mercado nacional e internacional. Es decir, las algas estuarinas que se desarrollan en este ecosistema producto de la intrusión marina, junto con los filtradores son comercializados por la comunidad a diferentes mercados. Donde las algas son el principal producto de exportación.

Ahora bien, si observamos el diagrama de flujo de energía en una marisma mareal (Figura 5.1-2), se aprecia que las energías de entradas, en este ejemplo, son las mismas que en el estuario, es decir, está conformada también por ríos y mar. No obstante, el sistema se diferencia del anterior por la presencia de plantas halófitas como productor primario, este componente determina las interacciones bióticas en el sistema, lo cual es representado en el tamaño de los consumidores ubicados en la parte final (extremo derecho del diagrama) o consumidores terminales. Aquí las aves y micromamíferos tienen mayor representación que en un estuario. Por tanto, este tipo de HC es configurado por la presencia exuberante de vegetación halófita, lo que influye en la diversidad de especies de aves, micromamíferos y otros.

Finalmente, el diagrama que representa la laguna costera (Figura 5.1-3) muestra diferencias notorias en la energía de entrada. Donde el tamaño de los círculos representa una menor interacción con ríos y mar, ya que estas pueden estar o no presentes en este tipo de HC. Las lagunas costeras pueden tener una condición dulceacuícola permanente o interactuar con la intrusión salina proveniente desde mar. Por ello, este diagrama muestra una mayor presencia de plantas y algas dulceacuícolas, por sobre las especies comercializables (algas estuarinas). Estas diferencias se reflejan también en el tamaño de las poblaciones de consumidores terminales (aves, micromamíferos, peces estuarinos, entre otros), lo que a su vez incide en el servicio ecosistémico de salida, que en este caso es sólo local.

Pese a lo anterior, cada tipo de HC puede transformarse en otro mediante una modificación, hidrológica o morfológica. Del mismo modo, en un mismo sistema pueden interactuar complementariamente dos tipos de humedal litoral. Por ejemplo, un estuario puede dar origen a una marisma y conjuntamente formar un solo HC.

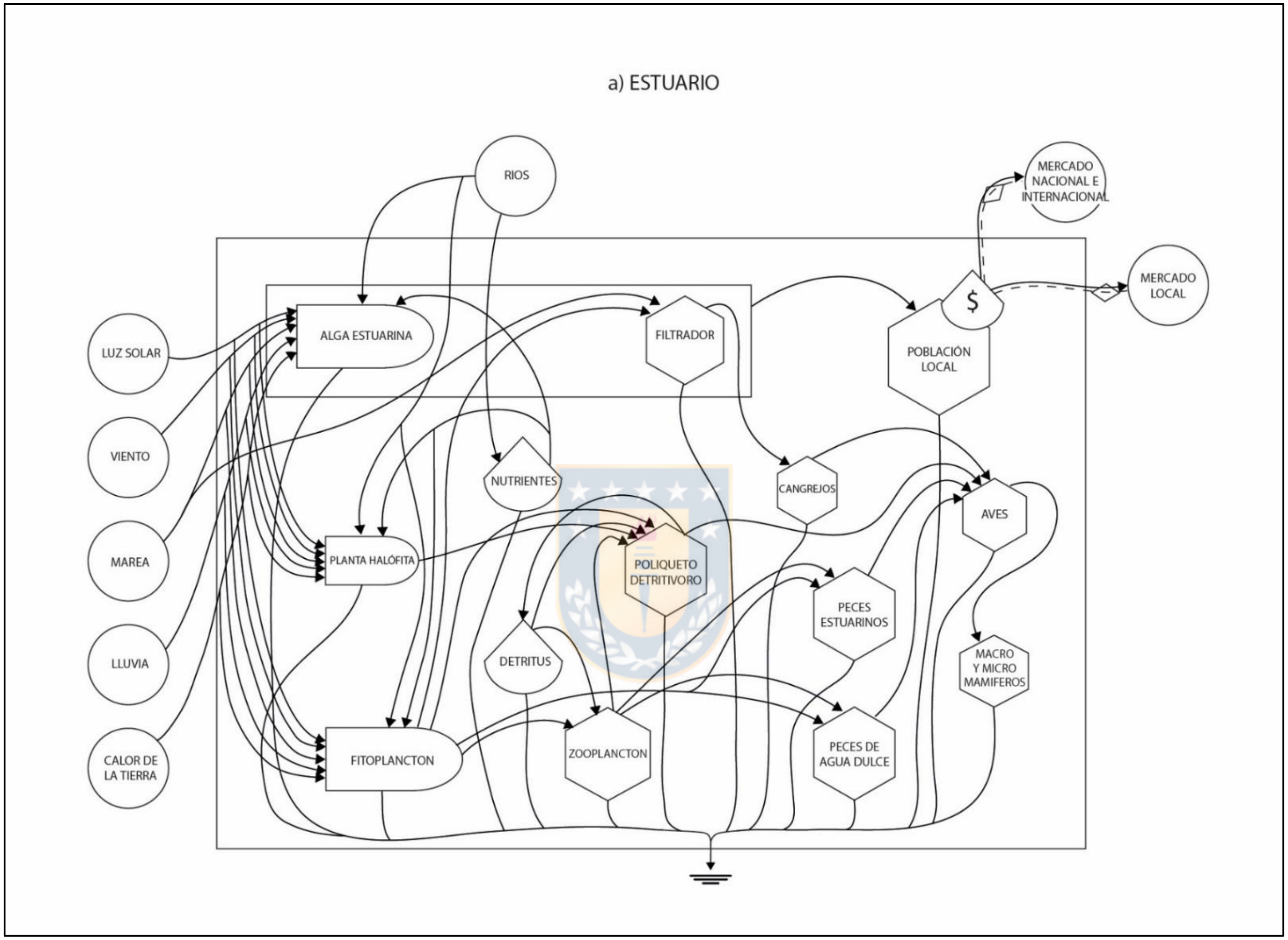


Figura 5.1-1 Diagrama de transferencia de energía en un estuario con Servicio Ecosistémico de abastecimiento.

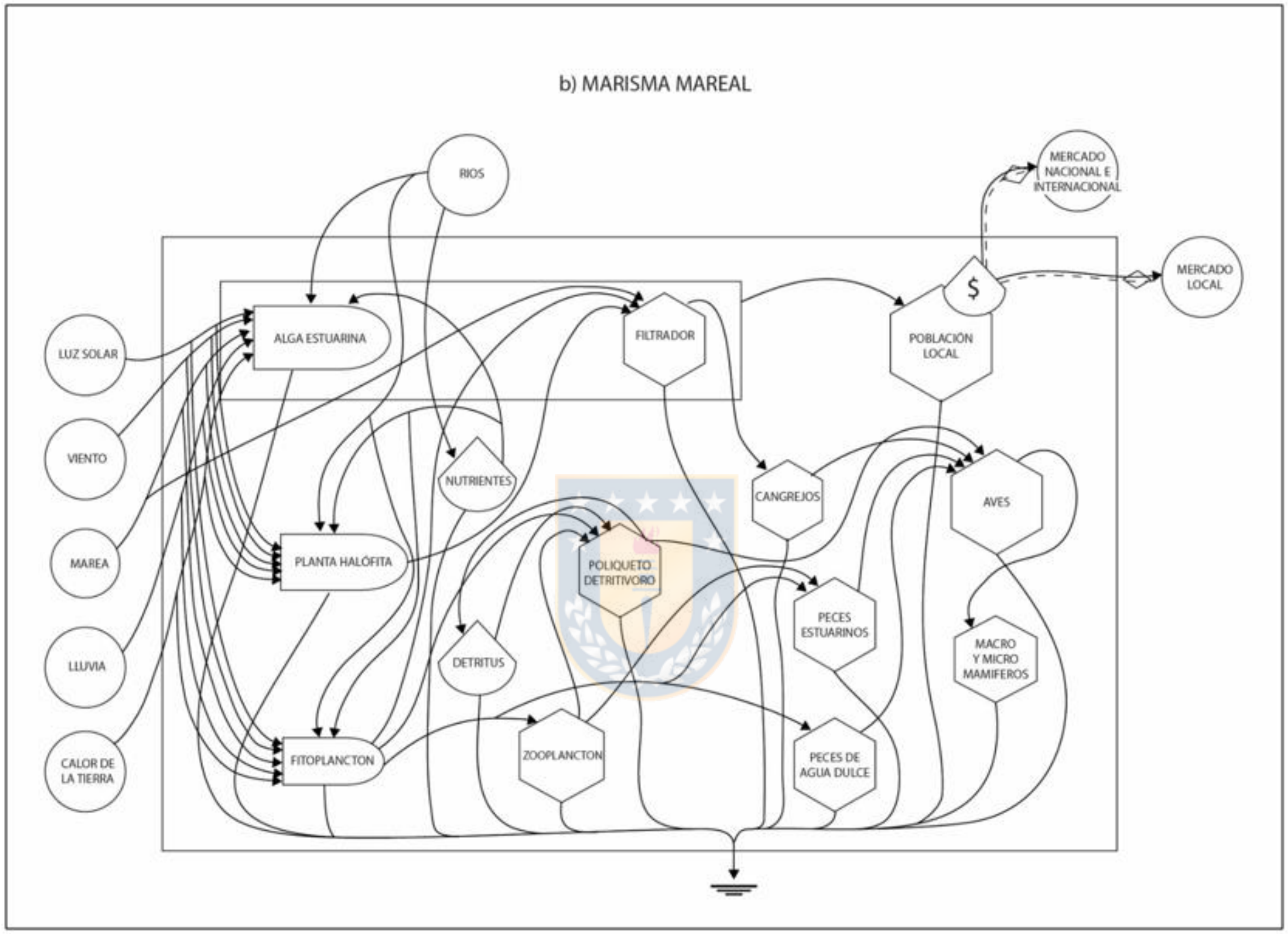


Figura 5.1-2 Diagramas de transferencia de energía de una marisma mareal con Servicio Ecosistémico de abastecimiento.

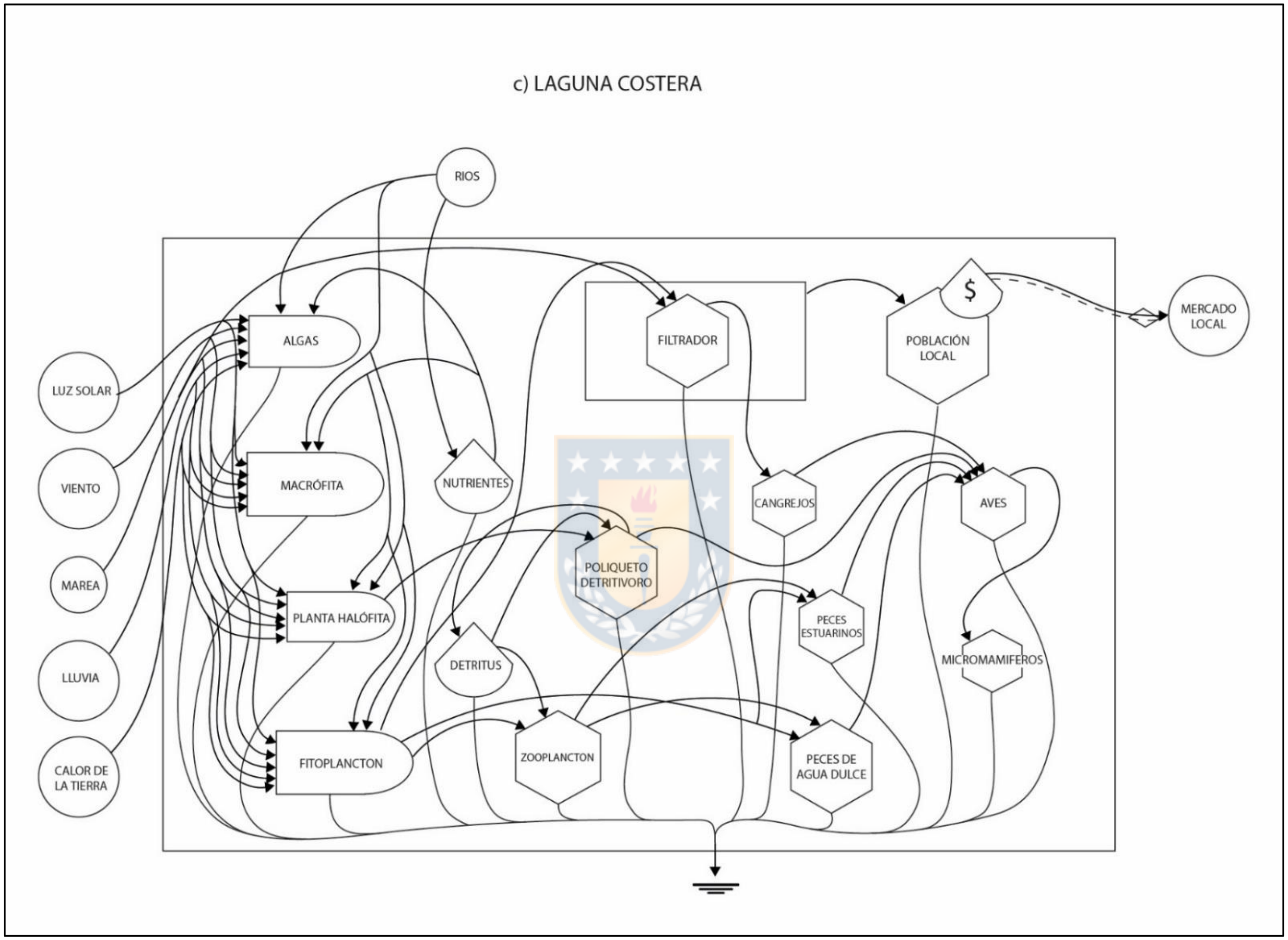


Figura 5.1-3 Diagrama de transferencia de energía de una Laguna costera con Servicio Ecosistémico de abastecimiento.

5.1.3 Funcionamiento y clasificación de un humedal costero tipo marisma

En este capítulo, describiremos, en rangos generales, el funcionamiento, formación y características ecológicas de un HC tipo marisma. En Chile, estas formaciones son escasas, de reducida extensión y poco conocidas (West, 1981). Además de ello, estos sistemas, junto con los estuarios, son altamente sensibles a los movimientos de corteza producidos por los terremotos, que frecuentemente impactan las costas suroeste de Sudamérica (Quezada et al. 2012). En estos eventos, el alzamiento o subsidencia causada por un sismo de gran intensidad, puede determinar la formación y permanencia de estos ecosistemas en el tiempo.

Cuatro elementos son esenciales para el desarrollo y expansión de una marisma: la existencia de una superficie relativamente plana (en relación a la línea de costa) que debe ser inundada periódicamente por la acción de las mareas; una fuente adecuada de sedimentos disponible durante el período de inundación de las mareas; una baja velocidad del agua que permita la sedimentación del material transportado; y finalmente debe existir una fuente de semillas u otros propágulos necesaria para el establecimiento de una cobertura vegetal (Boorman, 2003) (Figura 5.1-4).

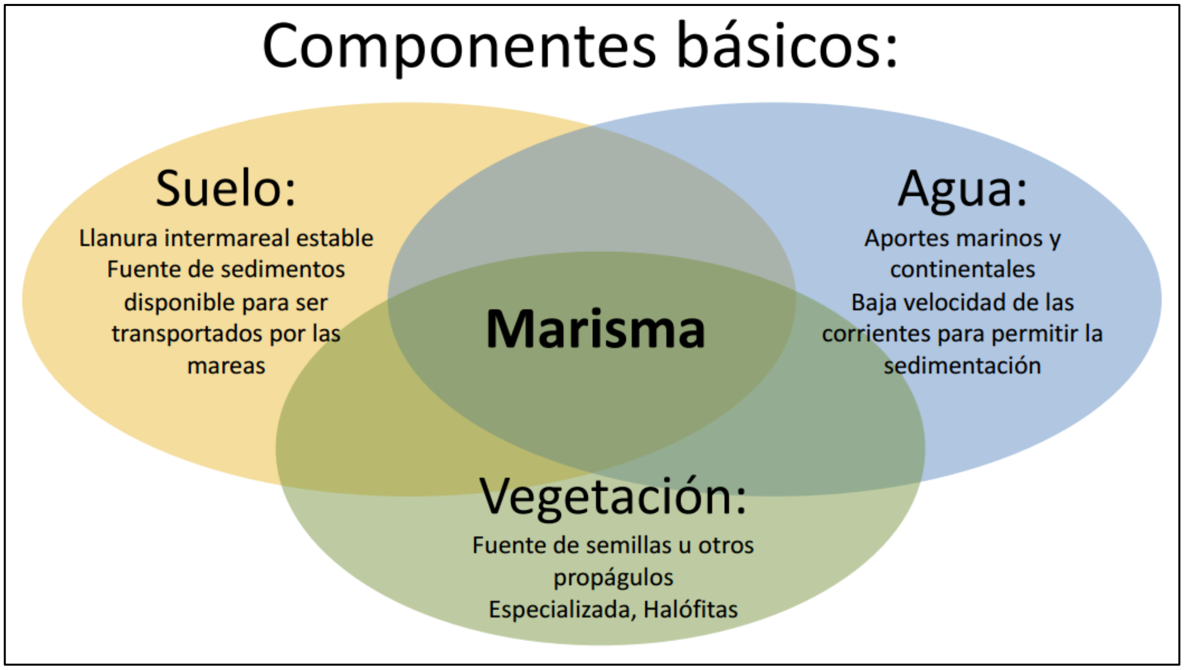


Figura 5.1-4. Los tres componentes básicos de una marisma costera.

Las marismas de marea de mayor tamaño presentes en Chile comienzan en la región del Biobío (36° Lat. S.) y se extienden hacia el Sur. Estas pueden ser clasificadas conforme al tipo de vegetación halófita dominante en el ecosistema como: Marismas de *Spartina*, M. altas de Totora, M. de Hierba de la Paloma-Pasto azul, M. de Torora azul, M de Pimpinela y M. de Pradera salobre de junquillo marino (Ramírez y San Martín, 2005) o también de acuerdo con su origen. Según la clasificación genética de Guilcher (1975) se reconocen tres tipos de marismas:

a) Las que se pueden formar en la parte abrigada de un estuario, como la marisma de Tubul-Raqui, en la región del Biobío o la marisma de Queule en la región de la Araucanía;
b) Las que se generan detrás de flechas arenosas, como en la Bahía de Caulín en Chiloé;
c) Las que se constituyen en la sección más interna de una bahía, como las marismas de Putemún en el interior del Fiordo de Castro en Chiloé.

5.1.4 Protección de los humedales costeros de Chile

Producto de la alta fragilidad de los ecosistemas litorales, algunos de ellos han sido incluidos bajo diferentes figuras de protección. En Chile las formas de proteger legalmente la biodiversidad de un Humedal son:

a) Declararlo Santuario de la Naturaleza por medio del Ministerio de Medio Ambiente.
b) Que el área completa o parte de ella pertenezca a Bienes Nacionales del Estado.
c) Que el área completa o parte de ella pertenezca a un Parque o Reserva del Sistema Nacional de Áreas Silvestres Protegidas del Estado (SNASPE).
d) Proteger su biodiversidad por medio de la prohibición de caza a través del Servicio Agrícola y Ganadero (SAG).
e) Recientemente promulgada la Ley. 21.202 que modifica la ley N° 19.300 e incluye diversos cuerpos legales con el objetivo de proteger los humedales urbanos

Complementariamente a ello, existen tratados internacionales que protegen ecosistemas que sostienen ecológicamente a especies de interés global, como lo son el tratado internacional Ramsar firmado en 1971 y los Sitios de Importancia Hemisférica, cuya estrategia de conservación fue declarada en 1986 con el objeto de proteger aves playeras. En la Tabla 5.1-1 se presentan las figuras de protección de los humedales costeros de los cuales se tiene catastro en Chile, ya que de aquellos que se encuentran en las zonas más australes es muy complejo extraer su contexto ecosistémico, por lo que no existe información robusta respecto a su configuración y localización (CEI, 2010).

5.1.4.1 Caso de estudio: El humedal tipo marisma Tubul-Raqui

El humedal Tubul-Raqui ubicado en la región del Biobío, frente al golfo de Arauco (37°13´ Lat. S y 73°26´ Long W) corresponde al espartal más grande del centro sur de Chile y su especie vegetacional dominante es *Spartina densiflora* (Valdovinos et al. 2011). Este ecosistema litoral posee una extensión de aproximadamente 2.238 ha (Vásquez, 2017) y de acuerdo con las consideraciones realizadas por y Teneb et al. (2004), forma parte de una zona de transición bioclimática, de característica mediterránea templada con influencia oceánica.

La marisma está compuesta por los ríos Tubul y Raqui. El río Tubul posee una extensión de 18 km, y el Raqui, 15 km de longitud, ambos son un aporte importante de agua dulce al humedal llegando a profundidades de 4 y 2 m respectivamente en épocas de mayor pluviosidad (Stuardo et al. 1993). La presencia de estos ríos genera una interacción en la zona costera con las aguas salinas provenientes desde el océano, lo que otorga condiciones hidrológicas particulares, siendo la salinidad el factor estructurador del sistema (Odum, 1996; Chainho et al. 2006; Valdovinos et al. 2011).

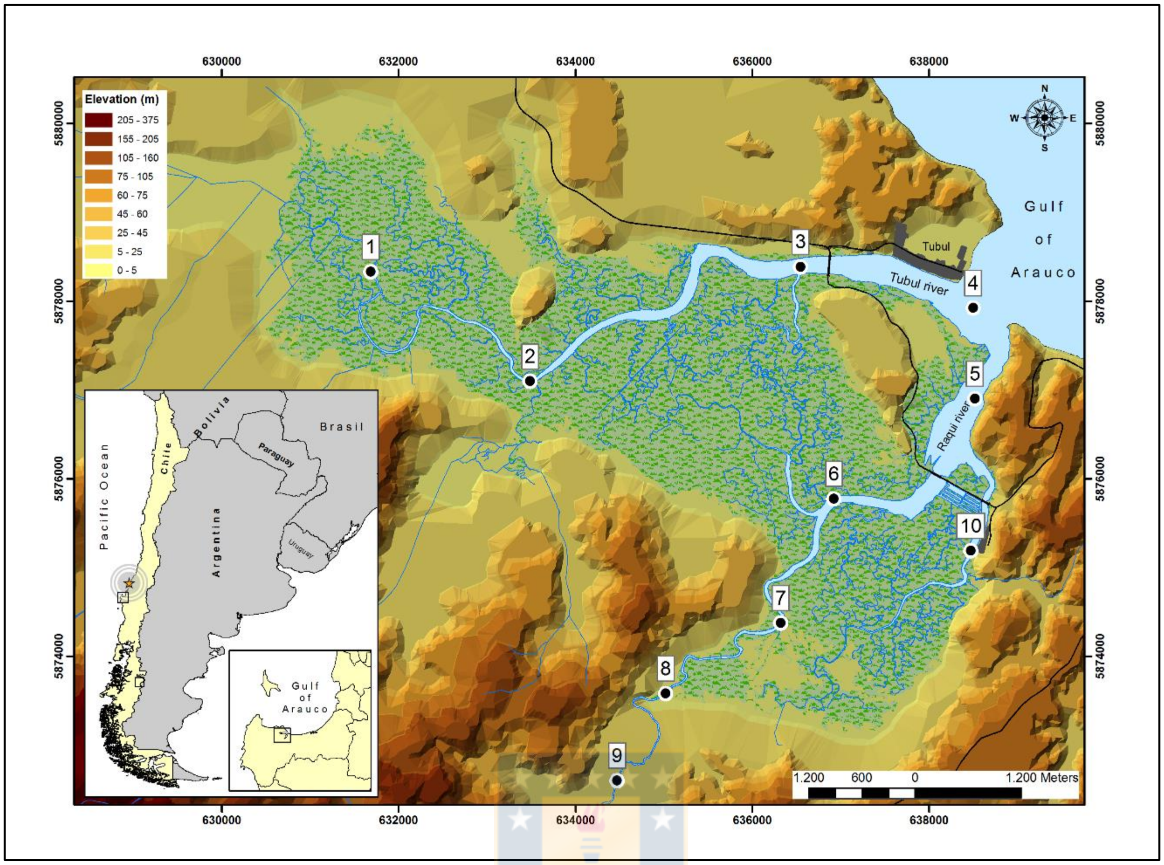
Ambos ríos están muy influenciados por los escurrimientos superficiales y la pluviosidad anual. Hasta hoy día no existen estudios en el sector de aportes de aguas subterráneas. El sistema recibe un mayor aporte de agua dulce principalmente de manera pluvial, a través del río Raqui, aún en verano, mientras que en el río Tubul se constata una mayor influencia marina (Stuardo et al. 1993).

Tabla 5.1-1 Humedales Costeros con alguna figuras de protección al año 2020. S.I.H: Sitio de Importancia Hemisférica; SNASPE: Sistema Nacional de Áreas Silvestres Protegidas del Estado; S.N: Santuario de la Naturaleza; B.N.P: Bien Nacional Protegido de Chile; P. Ley Caza: Prohibición ley de Caza; RN: Reserva Nacional; PN: Parque Nacional.

Humedal Costero	**Coordenadas**		**FIGURA DE PROTECCIÓN**					
			Internacional		**Nacional**			
	S	**W**	**RAMSAR**	**S.I.H**	**SNASPE**	**S. N**	**B. N.P**	**P. LEY CAZA**
Desembocadura río Lluta*	18º24′49″	70º19′28″		X		X		
Desembocadura río Loa*	21º25′29″	70º19′28″					X	
Desembocadura río Copiapó	27º18′49″	70º55′45″					X	
Desembocadura río Huasco*	28º26′43″	71º12′03″						X
Humedales de Tongoy	30º15′18″	71º29′29″				X	X	
Las Salinas de Huentelauquén	31º37′11″	71º33′19″	X	X				X
Laguna Conchalí	31º52′45″	71º29′50″	X			X		
Estero Catapilco	32º37’55″	71º25’44″						X
Tunquén*	33º15′41″	71º39′43″				X		
Laguna El Peral	33º30′21″	71º36′21″				X		
Estuario Río Maipo	33º37′08″	71º37′39″		X		X		
El Yali	33º45′23″	71º43′30″	X		RN			X
Estuario Rapel	33º54′38″	71º50′07″						X
Laguna Cahuil*	34º28’44″	72º01’26”						X
Laguna Torca y Vichuquén	34º45′28″	72º04′52″			RN	X		
Red de humedales del río Mataquito (Putú, Junquillar, Huenchumalli)	35º03′02″	72º10′06″				X		X
Reloca	35º39′26″	72º35′59″				X		X
Lenga	36º46′20″	73º09′14″				X		X
Desembocadura Río Carampangue*	37º14′15″	73º17′40″					X	

Humedal Costero	Coordenadas		FIGURA DE PROTECCIÓN					
			Internacional		Nacional			
	S	W	RAMSAR	S.I.H	SNASPE	S. N	B. N.P	P. LEY CAZA
Tubul-Raqui-Isla Raqui*	37°14′36″	73°26′15″					X	X
Desembocadura río Imperial/ Lago Budi	38°45’30″	73°25’30″						X
Desembocadura río Queule o Boldo	39°23’47″	73°12’51″						X
Desembocadura río Maullín	41°37’09″	73°43’26″						X
Estuario Reloncaví	41°42′17″	72°25′02″			PN			
Orientales de Chiloé	42°30′00″	73°34′00″		X				
Bahía Lomas	52°18′01″	69°12′00″	X	X		X		

*Áreas incluidas en el plan de protección nacional 2020-2022 MMA.



Mapa 5-1 Humedal Costero tipo marisma Tubul-Raqui. La estrella representa el epicentro del terremoto de 2010.

5.1.5 Características morfométricas, origen y biogeografía

Desde el punto de vista geomorfológico las marismas corresponden a macroformas costeras de acreción, de escasas pendientes, sedimentos muy finos, morfológicamente complejas y dinámicas. Ello debido a que, en su génesis y evolución, se combinan procesos propios del continente y del océano, por lo que su origen no puede atribuirse a un sólo factor. Las marismas contemporáneas constituyen formas costeras relativamente jóvenes a escala geológica, desarrollándose durante el Holoceno en los últimos 8.000 años, como respuesta al aumento en el nivel del mar (Milliman y Emery, 1968; Redfield 1967). Así su génesis también se atribuye en muchos casos a fenómenos de subsidencia (Nonn, 1987). En Chile la neotectónica es un factor importante que considerar en la formación y evolución geomorfológica de las marismas, las que deben ser capaces de resistir y reajustarse a los cambios verticales originados por los terremotos, expresados en subsidencia o alzamiento cosísmico en función de la cercanía a la fosa (Quezada et al. 2012). Ejemplo de ello, es la creación masiva de humedales producto de la subsidencia del Río Cruces después del terremoto Mw=9.5 de 1960 (Reinhardt et al. 2010; Jaramillo et al. 2012). De manera contrapuesta, son los efectos producidos por el terremoto Mw=8.8 del 2010 en la costa de la región del Biobío. Debido a su cercanía a la fosa, la mayor parte de la costa registró un alzamiento costero de 1 a 2 m, produciendo el desecamiento de ríos y humedales. En este evento la marisma Tubul-Raqui, fue severamente afectada desde el punto de vista geomorfológico, registrando la disminución del 31,7% del área total de las unidades morfológicas después del alzamiento co-sísmico del 27/F del 2010 (Figura 5.1-5) (Vásquez et al. 2017). Por último, cabe mencionar que hoy en día la acción antrópica es responsable de generar transformaciones en las marismas, por lo que el hombre es considerado un eficaz agente geomorfológico en la evolución reciente de las mismas (Palma, 1997). Acciones como dragado, relleno, canalización y reclamación de la tierra para la agricultura son algunas prácticas comunes que modifican y alteran la morfología de las marismas, especialmente cuando modifican el suministro de sedimentos y/o la entrada de agua al sistema.

Figura 5.1-5 Desecamiento del Humedal Costero tipo marisma Tubul-Raqui producto del alzamiento cosísmico provocado por el terremoto 8.8 Mw de 2010. Fuentes: Imagen pre-terremoto; extraída de Google Earth 2009, imagen post-terremoto; fotografía aérea gentileza Arauco S.A.

5.1.6 Características ecológicas e importancia del este ecosistema.

Las marismas mareales son de gran importancia ecológica y económica. Producto de su alta productividad juegan un rol primordial en la configuración de las redes tróficas de estuarios y mares adyacentes (Woodhouse y Knutson, 1982). Además de ello, su dinámica de interacción río-mar controla las condiciones fisicoquímicas y biológicas del sistema, vinculado a zonas de energía altamente variable y a la salinidad que se comporta como modelador de la distribución de especies en el ecosistema (Stuardo et al. 1993). En este sentido, las zonas de mezcla entre el agua dulce y salada proporcionan una alta heterogeneidad de hábitat (Carrasco, 2003) lo que favorece la presencia de variadas especies permanentes o migratorias que ocupan estas zonas como refugio, alimentación y reproducción (Gibbs, 1993; Gauthier et al. 2005).

La principal variante en este tipo de HC es la presencia de especies vegetaciones altamente tolerantes a las condiciones salinas presentes en el agua y sedimentos. En Tubul-Raqui existen extensos pastizales conformados por *Spartina densiflora* (esparto) y *Sarcocornia fruticosa* (sosa alacranera)**,** ambas son plantas hemicriptofíticas y halófitas, que además de tolerar la salinidad, resisten el anegamiento periódico y fluctuante por la influencia de las mareas, lo que le confiere la condición de biotopos extremos (Rojas, 2005). Las adaptaciones morfológicas que presentan estas plantas permiten la creación de hábitat en diferentes niveles (Figura 5.1-6). Un primer nivel aéreo formado por la vegetación emergente, que sirve de zonas de refugio y nidificación especialmente para las aves, un nivel sub-emergente que está presente en el interfaz, entre la vegetación que es inundada de manera variable en condiciones de pleamar y el sedimento, aquí especies acuáticas o semiacíaticas depositan sus huevos y se refugian de manera de resistir a la variabilidad de la corriente. Finalmente, existe un tercer nivel formado por la interacción del flujo hídricos y la estabilidad del sedimento contenido entre las raíces de la vegetación lo que da origen a canales de diferentes dimensiones, esta zona permite la conectividad dentro del humedal, donde las especies vágiles (e-j. peces, cangrejos, anfibios) pueden desplazarse y las bentónicas desarrollarse en un hábitat rico en materia orgánica y nutrientes (Packham y Willis 1997).

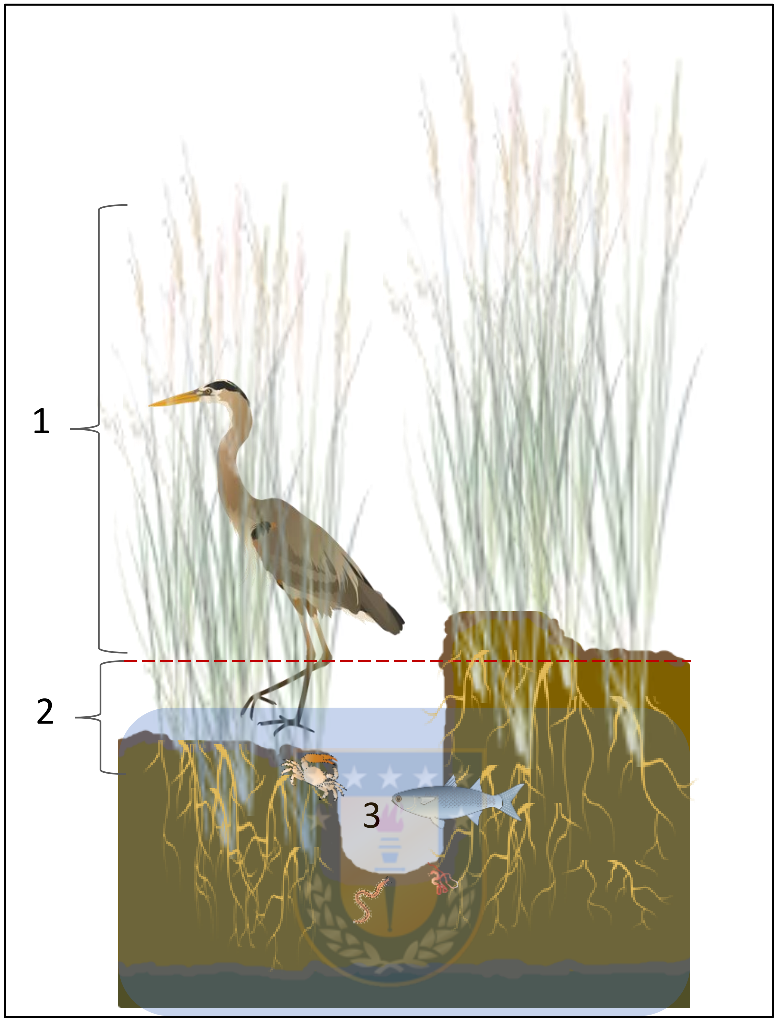


Figura 5.1-6 Hábitats formados por la vegetación en una marisma mareal. 1) nivel emergente, 2) nivel sub-emergente y 3) canal (interacción entre flujo hídrico y sedimentos contenido por las raíces de la vegetación halófita). La línea roja segmentada representa el límite máximo del agua en pleamar.

Además de estos elementos existen otras formaciones que aumentan la heterogeneidad espacial (Figura 5.1-7). Entre ellos, las pozas salinas, que corresponden a depresiones o cubetas de fondo plano presentes en la marisma media. Estas se encuentran completamente inundadas durante la mayor parte del año, en especial durante otoño y primavera. No obstante, a menudo presentan condiciones hipersalinas y anóxicas, lo que impide que sean colonizadas por la vegetación. Respecto a su morfogénesis, aún no existe un consenso global en la literatura sobre el mecanismo que explica su formación (e.g. Yapp et al. 1917; Chapman 1938; Pestrong 1965; Perillo et al. 1996; Escapa et al. 2015), siendo atribuido a diversos procesos físicos, tales como la deposición de desechos traídos por las mareas, colapso de bancos, drenaje sub-superficial, erosión superficial por olas generadas por el viento o cualquier mecanismo que impida el crecimiento de vegetación en estas depresiones.

Figura 5.1-7. Unidades hidro-morfológicas presentes en la marisma Tubul-Raqui.

En este escenario, se presenta una gran biodiversidad en el Humedal Tubul-Raqui. Hasta el año 2009 eran descritas 83 especies de aves pertenecientes a 31 familias, de las cuales 3 se encuentran en peligro de extinción (Carrasco, 2003; 2004; CEA 2006, Vergara et al. 2007 y SGS, 2009) (Pese a las modificaciones del ecosistema producto del terremoto de 2010, que afectó principalmente a las especies del medio acuático, por la pérdida de hábitat causada por la desconexión entre los ríos Tubul y Raqui y el mar (Valdovinos y Sandoval, 2011), la marisma sigue proporcionando un medio físico y químico que permiten una alta diversidad de flora y fauna acuática representada en los grupos fitobentónicos, fitoplanctónicos, invertebrados bentónicos de fondos blandos y peces (EULA-Chile 2011, Martínez et al.

2012). De estos, las especies macroinvertebrados acuáticos cobran gran relevancia como fuente de alimentación para las aves del lugar. Si bien son un grupo menos diversos, son altamente abundantes y de gran biomasas (Valdovinos et al. 2012), entre los que destacan las especies tolerantes a la salinidad como poliquetos (e.g. *Perinereis gualpensis*, *Capitellidae* sp.), anfípodos (*Paracorophium hartmannorum*), bivalvos (e.g. *Tagelus dombeii*), crustáceos (e.g. *Hemigrapsus crenulatus*), así como también los peces (e.g. *Eleginops maclovinus*, *Mugil cephalus*) (Della-Croce y Valdovinos, 1994).

Tabla 5.1-2), mientras que otras forman parte de especies migratorias de gran relevancia a nivel mundial y que utilizan el humedal como área de descanso o nidificación entre ellas: *Rynchops niger* (Rayador), *Numenius phaeopus* (Zarapito), *Limosa haemastica* (Zarapito pico recto) (Carrasco, 2004). En cuanto a la representatividad de otros vertebrados en el área, se han descrito cuatro especies de mamíferos, siete especies de reptiles y dos especies de anfibios, de los cuales, *Myocastor coypus* (coipo) y *Tachymenis chilensis* (culebra de cola corta) están calificadas como vulnerables (DS 5/1998 MINAGRI), y *Batrachyla taeniata* (sapito de antifaz) casi amenazada (DS 42/2011 MMA).

Pese a las modificaciones del ecosistema producto del terremoto de 2010, que afectó principalmente a las especies del medio acuático, por la pérdida de hábitat causada por la desconexión entre los ríos Tubul y Raqui y el mar (Valdovinos y Sandoval, 2011), la marisma sigue proporcionando un medio físico y químico que permiten una alta diversidad de flora y fauna acuática representada en los grupos fitobentónicos, fitoplanctónicos, invertebrados bentónicos de fondos blandos y peces (EULA-Chile 2011, Martínez et al. 2012). De estos, las especies macroinvertebrados acuáticos cobran gran relevancia como fuente de alimentación para las aves del lugar. Si bien son un grupo menos diversos, son altamente abundantes y de gran biomasas (Valdovinos et al. 2012), entre los que destacan las especies tolerantes a la salinidad como poliquetos (e.g. *Perinereis gualpensis*, *Capitellidae* sp.), anfípodos (*Paracorophium hartmannorum*), bivalvos (e.g. *Tagelus dombeii*), crustáceos (e.g. *Hemigrapsus crenulatus*), así como también los peces (e.g. *Eleginops maclovinus*, *Mugil cephalus*) (Della-Croce y Valdovinos, 1994).

Tabla 5.1-2 Listado de especies de aves presentes en el humedal costero Tubul-Raqui que se encuentran bajo criterio de conservación EN: En Peligro, NT: Casi Amenazada o V: vulnerable. Aquí también fueron incluidas aquellas especies que están clasificadas en más de una lista de criterio de conservación categorizadas distintamente como LC: Preocupación menor, IC: Insuficientemente conocida y/o R: Rara.

FAMILIA / Especie (Nombre común)	**UICN**	**MMA (DS 17/2018)**	**MINAGRI R. Ley de Caza (DS 5/1998)**
LARIDAE			
Thalasseus elegans (Gaviotín elegante)	NT		
PHALACROCORACIDAE			
Phalacrocorax gaimardi (Lile)	NT		IC
PELECANIDAE			
Pelecanus thagus (Pelícano)	NT	NT	
ARDEIDAE			
Ardea cocoi (Garza cuca)	LC	LC	R
Ixobrychus involucris (Huairavillo)	LC	LC	R
ANATIDAE			
Speculiaris specularis (Pato anteojillo)	NT	NT	
Spatula platalea (Pato cuchara)	LC	NT	IC
Cygnus melancorypha (Cisne cuello negro)	LC	NT	**EN**
Coscoroba (Cisne coscoroba)		NT	**EN**
THRESKIORNITHIDAE			
Plegadis chihi (Cuervo de pantano)	LC	NT	**EN**
Theristicus melanopis (Bandurria)	LC	LC	V
FURNARIIDAE			
Sula variegata (Piquero)	LC	LC	IC

UICN (Unión Internacional para la Conservación de la Naturaleza), MMA (Ministerio de Medio Ambiente) y MINAGRI (Ministerio de Agricultura).

Junto con el valor ecológico de este ecosistema, existen variados servicios ecosistémicos que la comunidad local vincula a la presencia de la marisma (Marín et al. 2014). Una actividad productiva relevante realizada por la población de la caleta Tubul, pero asociada al ecosistema marino costero propiamente tal, es la actividad pesquera artesanal (Valdovinos et al. 2010). En este sentido, el aporte de nutrientes y materia orgánica que arrastran los ríos Tubul y Raqui desde la marisma hasta la zona litoral junto con el contenido propio del as aguas del Golfo, hacen de esta zona una de las áreas costeras de mayor producción primaria estimadas en Chile (19,9 g C m^{-2} d^{-1}, Daneri et al. 2000), lo que ha permitido la extracción de diferentes productos comercializables desde 1989. En Tubul, el principal recurso extraído es el "huepo" o "navaja" (*Ensis macha*) y la "navajuela" (*Tagelus dombeii*), además de otros moluscos y bivalvos (Valdovinos et al. 2010; Hernández et al. 2011). Esta actividad permanece hasta hoy, a diferencia de la producción de algas rojas "pelillo" (*Gracilaria spp.)*, que después del alzamiento costero de 2010, no fue posible volver a cultivar en la zona estuarina del humedal (Valdovinos y Sandoval, 2011).

En cuanto a la condición actual de la marisma, Martínez (2014) evaluó mediante el Índice de Estado de Conservación de Ecosistemas Lénticos Someros (ECELS) el humedal costero, donde consideró aspectos relativos a la morfología del humedal: construcciones, infraestructuras y usos humanos; aspecto del agua: vegetación de helófitos y vegetación sumergida y flotante. Bajo este criterio el HC Tubul-Raqui clasifica en estado medio y se sugiere someter la zona a planes y diseños de manejo que permitan proteger el ecosistema en un mediano plazo.

5.1.7 Características fisicoquímicas del agua y sedimentos

5.1.7.1 Sedimentos

Numerosos son los procesos físicos, químicos y biológicos que modelan los sedimentos presentes en una marisma. En el humedal costero Tubul-Raqui, la interacción del mar y sus mareas alternantes, con las corrientes contrapuestas de los ríos que desembocan en el mismo, hacen de este ecosistema un escenario extremadamente dinámico respecto al transporte y composición de sedimentos. Esta interacción, junto a procesos de floculación, bioaglomeración de partículas finas, mezcla de sedimentos por organismos y actividades humanas, intervienen en la composición del sustrato de fondo (Olsen et al.1978). Aquí se produce un intercambio único de materia orgánica, nutrientes y contaminantes (Negrin, 2011), por lo que cumplen un rol destacado en la biogeoquímica de los elementos debido a que, en estos sistemas, se produce la transformación de nutrientes de su forma inorgánica a orgánica a través de la producción de biomasa por parte de la vegetación halófita (Negrin, 2011). Por tanto, hacen de las marismas una de las zonas más ricas y fértiles del mundo.

Los sedimentos en la parte inferior de la marisma Tubul-Raqui, zona cercana a la desembocadura, se caracteriza principalmente por arenas finas y en la zona intermedia encontraremos limos de tamaño medio (Folk, 1974). En cuanto a la arena, esta es transportada por arrastre de las mareas y por el viento, según su tamaño granulométrico, los limos (medios y finos) se transportan por suspensión. Dado que la mayor parte de este ecosistema presenta niveles de energía medios y bajos, predomina el transporte en suspensión (Constabel, 1993) por sobre el de arrastre, que se limita a la zona estuarina del sistema.

La selección de los sedimentos en ambos ríos del humedal fue moderada (Río Tubul y Raqui), lo que indica en términos generales la actuación de una corriente relativamente constante (Folk, 1974). Ahora bien, pese a los cambios presentados por la marisma posterior al terremoto, los resultados presentados en la El porcentaje promedio de materia orgánica total (MOT), se presenta diferente entre ambos ríos, obteniéndose un 3% de MOT en Raqui y un 11% en Tubul. Esta variación posiblemente se relacione a una menor influencia marina en el río Raqui, en comparación al río Tubul, ya que en este último se observó algas estuarinas, lo cual nos indica que la presencia de estas pudo influir considerablemente en los valores de Materia Orgánica. De todas formas, esto es usualmente observado en estos ecosistemas debido a su alta productividad (Establier et al. 1984).

Tabla 5.1-3 se condicen con la dinámica fluvial histórica, descrita para la zona media inferior del estuario, la cual según Rojas (1985), se caracteriza por ser una zona de mediana energía cinética y de pobre selección por la ausencia de una marcada influencia de la erosión del mar y viento de la costa. Respecto a la asimetría del sustrato de fondo, la cual señala la predominancia de una población de sedimentos respecto a la otra, esta fue clasificada preponderantemente asimétrica positiva, lo que indica que los sedimentos presentan mayor presencia de material fino.

El porcentaje promedio de materia orgánica total (MOT), se presenta diferente entre ambos ríos, obteniéndose un 3% de MOT en Raqui y un 11% en Tubul. Esta variación posiblemente se relacione a una menor influencia marina en el río Raqui, en comparación al río Tubul, ya que en este último se observó algas estuarinas, lo cual nos indica que la presencia de estas pudo influir considerablemente en los valores de Materia Orgánica. De todas formas, esto es usualmente observado en estos ecosistemas debido a su alta productividad (Establier et al. 1984).

Tabla 5.1-3 Promedio de parámetros granulométricos de los sedimentos superficiales muestreados en de los ríos Tubul y Raqui. Donde la textura Lm: Limo , Af: Arena fina y Am: Arena media.

PARÁMETRO / SISTEMA	Ríos	
	Tubul	Raqui
Tamaño medio (ϕ)	5,71	2,08
Textura predominante	Lm	Af/Am
Selección (ϕ)[1]	1,14	0,60
Asimetría[2]	0,32	0,41
Curtósis[3]	3,01	3,48
Materia Orgánica Total (%)	10,74	2,92

5.1.7.2 *Calidad del agua*

La cuenca que contiene el Humedal Tubul-Raqui presenta una superficie total de 274 km^2, de ella, la subcuenca del río Tubul ocupa el 37,5%y la del rio Raqui el 64,3 % de la superficie total (Valdovinos et al. 2010).

La condición hidrológica del humedal Tubul-Raqui ha sido modificada a lo largo de su historia. El primer registro de las alteraciones hidrofísicas de este ecosistema fueron descritas por el naturista Charles Darwin, posterior al terremoto de 1835 que afectó a Concepción. Donde al igual que lo ocurrido en 2010, el litoral sufrió un alzamiento cosísmico, que influyó en la capacidad de ingreso de embarcaciones de gran tamaño a la marisma (Melnick et al.

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[1] Selección: variabilidad en el tamaño de los clastos
[2] Asimetría: Predominio de una población de sedimentos respecto a otra
[3] Curtosis: Medida comparativa entre la selección en el centro de la distribución y en los extremos o colas.
ϕ : -log 2d mm

2006). En el megaterremoto ocurrido 175 años después, el Humedal costero es impactado nuevamente por un alzamiento de la plataforma continental dimensionada en 1.6 m. s. n. m (Valdovinos y Sandoval, 2011). Aquí la conectividad ríos-mar se vio alterada significativamente por lo que intrusión marina, característica de este sistema, disminuyó presentando efectos inmediatos que permanecen hasta hoy. De ellos, la disminución de la profundidad en la marisma, que previo al evento, alcanzaba hasta 4 m y permitía la navegación de embarcaciones menores en marea alta por los ríos que conforman el humedal y el estero Las Peñas, actualmente sólo puede ser realizada por botes a remo, en un área reducida (ríos Tubul y Raqui) y con nulo transito acuático hacia el estero.

Sin duda la variación de profundidad de 4 m a 1.6 m promedio, tienen diferentes alcances en la calidad del agua. Previo al evento perturbador, la condición salina alcanzaba 32.2 UPS y avanzaba hasta 10 km en el río Tubul y 7 km en el río Raqui, actualmente el ingreso del mar llega aproximadamente a 3.5 km aguas arriba del río Tubul, en pleamar. Junto con la salinidad se observó otros cambios en la condición de la columna de agua los meses posteriores, entre ellos el pH que, si bien disminuyó, se mantuvo entre valores básicos y neutros en zonas típicas de intrusión (E: 2, 3, 4, 5, 6, 7 y 10) (ver Mapa 5-1). El Oxígeno Disuelto, en tanto, producto de los altos procesos de descomposición causados por el terremoto y Tsunami disminuyó su valor histórico hasta 4.8 mg/L en la estación 3. Los otros parámetros evaluados presentaron variación, pero no con valores significativos históricos (mayores antecedentes pueden ser consultados en Valdovinos et al.(2012)). Conforme a la descripción realizada por Díaz-Jaramillo et al. (2014) los parámetros de Salinidad, Oxígeno Disuelto, pH y Temperatura presentan un promedio 26.98 (PSU), 8.8 (mg/L), 7.80, 16 (°C) respectivamente, en zonas cercanas a la boca (estaciones:3, 4 y 5), lo cual confirma la recuperación gradual del sistema cuatro años después.

En consideración a los nutrientes, Amonio, Nitrógeno, nitratos y nitritos son similares entre ambos ríos. Sólo los fosfatos presentan valores mayores en el río Tubul (Carrasco 2004; CEA, 2006) lo que guarda relación con su cercanía a las casas presentes en caleta Tubul, donde muchos residuos líquidos domésticos llegan hasta el río. Los restantes nutrientes presentan concentraciones dentro de los rangos “normales” para agua de mar, en ambos ríos según Stuardo, et al. (1993).

Referido a las estaciones 1, 8 y 9 estas corresponden a zonas alejadas del estuario por lo que su condición histórica es dulceacuícola. En estas zonas la variación en nutrientes y sólidos disueltos se relacionan a la actividad ganadera del sector, donde frecuentemente se observan animales que se acercan a los cursos de agua a beber. No obstante, esta actividad aún se realiza a microescala por lo que no se observan efectos negativos permanentes en la calidad del agua.

Tabla 5.1-4 Rangos históricos de parámetros de Calidad de Agua en las estaciones 3 (río Tubul) y 5 (río Raqui) entre agosto de 2008 y diciembre de 2011. Los máximos y mínimos consideran los cambios sufridos por el ecosistema en el terremoto 8.8 Mw de 2010.

Parámetro/ Río	Río Tubul		Río Raqui	
	mínimo	máximo	mínimo	Máximo
Temperatura (°C)	8.2	18.6	8.3	18.5
Salinidad (UPS)	0	32.2	0	28.1
pH	7.0	8.1	7.0	8.2
Clorofila *a*	<1	15.32	<1	12.30
P-Total	0.02	0.28	0.02	0.30
N-Total	0.14	1.48	0.12	1.27
Amonio	0.01	0.28	0.01	0.37
SST (mg/L)	3.1	46.00	2.7	46.40
SSI (mg/L)	<1	29.20	<1	37.00
SSO (mg/L)	2.6	19.40	1,6	11.60

Sólidos Suspendidos: Totales (SST), Inorgánicos (SSI) y Orgánicos (SSO).

5.1.8 Principales amenazas

Se ha descrito a nivel mundial que los humedales, independiente de su clasificación, están sometidos a presiones que amenazan su permanencia en el tiempo (Mitsch, 1994; Adam, 2002; Valiela et al. 2009). Pese a los múltiples servicios que proporcionan, muchos de ellos se encuentran deteriorados principalmente por causas antrópicas (Martínez, 2014), aunque a las perturbaciones naturales pueden tener diferentes efectos sobre el ecosistema (Valdovinos y Sandoval, 2011).

Una perturbación natural es considerada un disturbio a mayor escala (Connell,1978). Por ejemplo, en el caso del HC Tubu-Raqui en el terremoto de 2010, un disturbio de la placa tectónica causó una perturbación en la marisma. Los ecosistemas y sus comunidades biológicas se desarrollan en relación con los disturbios (Sousa,1984). No obstante, en la actualidad las presiones antrópicas actúan sinérgicamente sobre la perturbación natural, por lo que se solapan eventos perturbadores de diferente origen causando daños muchas veces no dimensionados sobre la biodiversidad.

En este sentido, cabe mencionar que el alzamiento costero provocado por el sismo no es el único evento perturbador que ha sufrido la marisma desde el 2010 Junto con ello, innumerables incendios, en su mayoría provocados por humanos, han afectado la vegetación hálófita, del ecosistema, disminuyendo aún más el hábitat, ahora para las especies terrestres. La mayoría de las quemas que ocurren en el humedal son intencionales, para permitir generar suelos para la colonización de especies vegetales dulceacuícolas las cuales serán consumidas por el ganado presente en la zona (Valdovinos et al. 2010) (Figura 5.1-8). Por ello, es necesario tomar medidas urgentes que permitan proteger este ecosistema, que, si bien ha sido modelado por perturbaciones naturales y antropogénicas, aún constituye un sitio de alto valor para la biodiversidad y para la comunidad local.

Previo al terremoto de 2010, se realizaron varios intentos por avanzar en una figura de protección apropiada para un área de gran extensión y biodiversidad. El año 2006 el Ministerio de Agricultura por medio del Decreto Exento 265/2006 establece periodo de veda o de prohibición de caza en el área denominada humedal Tubul-Raqui. A modo de apoyar esta y otras iniciativas desarrolladas en el lugar, el año 2005 el HC es incluido en el grupo de 10 ecosistemas de la región del Biobío considerados como prioritarios para su conservación, según la Estrategia Regional y Plan de Acción para la Biodiversidad, región del Biobío. Esta estrategia fue desarrollada entre 2005 - 2015 y su documento diagnóstico se encuentra en evaluación (MMA b, 2017). Posterior a ello, el Ministerio de Bienes Nacionales por medio del Decreto Exento 454/2009, destina los Lotes A y B, situados en el lugar Isla Raqui-Tubul para la conservación del patrimonio de biodiversidad. Siendo este reducido territorio, en relación con el área del ecosistema, la única zona que actualmente es destinada legalmente para este uso.

Figura 5.1-8 ***Spartina densiflora*** **quemada en incendios provocados (amarillo) y especies de gramíneas colonizadoras en el Humedal Costero (verde).**

Actualmente la zona costera, que históricamente sólo tenía interés pesquero, es un territorio donde cada vez se concentran más intereses económicos como el turismo, infraestructuras, acuicultura, energías renovables (Freire, 2005). En relación con ello, la provincia de Arauco fue seleccionado dentro de las 20 áreas con potencial eólico de Chile, según lo declarado por el Ministerio de Energía en 2014 (Santana et al. 2014). Los parques eólicos son considerados una fuente de energía limpia que busca contribuir al desarrollo sostenible y la conservación ambiental. Sin embargo, sus impactos en los ecosistemas marinos son muy poco conocidos. Las zonas altas que bordean el HC Tubul-Raqui tienen prospectada la instalación de dos Parque Eólicos de inversión superior a 250 millones de dólares, las cuales contemplan la instalación de líneas de alta tensión que llevarán la energía al Sistema Interconectado Central, cuyas rutas se encuentran en proceso de evaluación en el Servicio de Evaluación de Impacto Ambiental.

Entre los posibles impactos que la implementación de los parques eólicos puede traer sobre ecosistemas de alto valor de conservación pueden estar la disminución en el valor paisajístico, el impacto sobre la avifauna, procesos erosivos y daños en la vegetación entre otros (Tapia et al. 2005). Nos obstante, estos están relacionados a la zona de implementación y las especies que interactúen con el área seleccionada para su instalación (Espejo, 2004). Lo complejo es establecer lineamentos ambientales previos, para zonas específicas, por ejemplo, para determinar el tránsito de especies como las aves que cambian sus rutas migratorias de año a año (Nielsen, 2007).

En este sentido, es necesario establecer planes de seguimiento ambiental en los Humedales Costeros, con el objeto de generar antecedentes históricos que nos permitan dimensionar los cambios y efectos de diferentes impactos (naturales o antrópicos) sobre los ecosistemas más productivos, dinámicos y vulnerables del mundo.

5.1.9 Referencias

Adam, P. 2002. Saltmarshes in a time of change. Environmental Conservation. 1:39-61.

Adam, P. 2009. Australian saltmarshes in global context. In: Saintilan N. (Ed). Salt marsh ecology – Australia (248 pp). Autralia.

Boorman, L. A. 2003. Saltmarsh review. An Overview of Coastal Saltmarshes, Their Dynamic and Sensitivity Characteristics for Conservation and Management Joint Nature Conservation Committee, Peterborough, UK. JNCC Report, No. 334.

Bormann, F.H. and G.E. Likens. 1979. Catastrophic disturbance and the steady state in northern hardwood forests. Amer. Sci. 67(6):660-669.

Carrasco, P. 2003. Variaciones de la estructura del ensamble de aves a lo largo de a un gradiente ambiental en el humedal Tubul-Raqui, VIII región, Chile. Seminario de investigación para optar al grado de Licenciatura en Biología, Facultad de Cs. Naturales y Oceanográficas, Universidad de Concepción. 56 pp.

Carrasco, P. 2004. Propuesta de manejo para la conservación del humedal Tubul-Raqui, VIII Región, Chile. Tesis para optar al Título Profesional Biólogo Con Mención en Bases y Gestión del Medio Ambiente, Facultad de Cs. Naturales y Oceanográficas, Universidad de Concepción.73 pp.

CEI-GAPMA. 2010. Programa Nacional para la Conservación de Humedales insertos en el Sistema Nacional de Áreas Silvestres Protegidas del Estado Corporación Nacional Forestal. 100 pp.

Centro de Ecología Aplicada (CEA) - Conama. 2006. Estudios de línea de base Humedal Tubul-Raqui. Informe final. 102 pp.

Centro EULA-Chile. 2011. Diagnóstico y propuesta para la conservación y uso sustentable de los humedales lacustres y urbanos principales de la región del Biobío. Universidad de Concepción, Concepción. 140 pp.

Chainho, P., Costa, J.L., Chaves, M.L., Lane, M.F., Dauer, D.M. and Costa, M.J. 2006. Seasonal and spatial patterns of distribution of subtidal benthic in vertebrate communitities in the Mondego river, Portugal a poikilohaline estuary. Hidrobiología. 555:59-74.

Chapman, V. J. 1938. Studies in Salt-Marsh Ecology Sections I to III. Journal of Ecology, 26(1):144-179.

Connell, M. L. 1978. Diversity in tropical rain forest and coral reefs. Science. Washington. D.D. 199:1302-1310.

Constabel, S. A. 1993. Ambientes Sedimentarios de los Estuarios Tubul y Raqui, VIII Región, Chile. Tesis para optar al Grado de Doctor en Ciencias Ambientales. Centro EULA-Chile. Universidad de Concepción. 96 pp.

Darwin, C.R., 1835. Darwin's Beagle Diary (1831–1836), p. 546. http://darwin-online.org.uk/.

Dawes, C.J., 1991. Botánica Marina. Limusa. 652 pp.

de Groot, R., Brander, L., van der Ploeg, S., Costanza, R., Bernard, F., Braat, L., Christi, M., Crossman, N., Ghermandi, A., Hein, L., Hussain, S., Kumar, P., McVittie, A., Portela, R., Rodriguez, L.C., ten Brink, P., van Beukering, P. 2012. Global estimates of the value of ecosystems and their services in monetary units. Ecosystem Services. 1,50–61.

Della-Croce, N.y Valdovinos C. 1994. Caracterización ambiental del área marina costera bajo la influencia de las cuenca hidrográfica del río Biobío, Chile central (1989-1992). En Della-Croce N. (Ed.). El río Biobío y el área marina adyacente. Univ. Di Genova, Italia. 85-163.

Dugan, PJ. Ed.1992. Conservación de Humedales. Un análisis de temas de actualidad y acciones necesarias. UICN. Gland Suiza. 100 pp.

Escapa, M., Perillo, G. M. and Iribarne, O. 2015. Biogeomorphically driven salt pan formation in Sarcocornia-dominated salt-marshes. Geomorphology. 228: 147-157.

Espejo C. 2004. La energía Eólica en España. Investigaciones Geográficas. 35: 45-65.

Establier, R, Blasco, J., Gómez, A. y Escobar, D. 1984. Materia orgánica en los sedimentos de la Bahía de Cádiz y sus zonas de marismas y salinas. Investigación Pesquera. 48 (2): 285-301.

Fariña, J. M.y Camaño, A. 2012. En: Fariña, J. M.y Camaño, A. (Eds.) Humedales Costeros De Chile: Aportes Científicos a Su Gestión Sustentable. “PREFACIO”. Ediciones UC. Santiago.437pp.

Fariña, J. y A. Camaño. 2012. Humedales costeros de Chile: Aportes científicos a su gestión sustentable. Ediciones Universidad Católica de Chile, Santiago, Chile. 437 pp.

Folk, R. Petrology of Sedimentary Rocks. Hemphill Publishing Co. Austin, Texas 1953. 182 p.

Freire, J. 2005. Parques eólicos marinos y gestión de la zona costera. Universidade da Coruña Facultad de Ciencias Campus da Zapateira. Spain. El problema. http://www.agenergia.org/files/resourcesmodule/@random49917eec3c3bd/1234272543_Freire05_eolicos_marinos.pdf.

Gamboa M., Reyes R. y Arrivillaga J. 2008. Macroinvertebrados bentónicos como bioindicadores de salud ambiental. Boletín de malariología y salud ambiental. 48: (2), 109-120.

Gauthier, G., Oisgiroux, J.F., Reed, A., Be’chet, A. and Langer, L. 2005. Interactions between land use, habitat use, and population increase in greater snow geese: what are the consequences for natural wetlands? Global Change Biology.11(6):856-868.

Gibbs, J. P. 1993. Importance of small wetlands for the persistence of local populations of wetland associated animals. Wetlands. 13: 25-31.

Guilcher, A., y Condeminas, E. 1975. Morfología litoral y submarina. Omega. 264 pp.

Jaramillo, E., Dugan, J. E., Hubbard, D. M., Melnick, D., Manzano, M., Duarte, C. and Sanchez, R. 2012. Ecological implications of extreme events: footprints of the 2010 earthquake along the Chilean coast. PLoS One. 7 (5): e35348. doi: 10.1371 / journal. pone.0035348.

Kurihara H, Ishimatsu A, Shirayama Y. 2007. Effects of elevated seawater CO2 concentration on the meiofauna. J Mar Sci Technol 15:17– 22.

Liu JL, Wu H, Feng JX, Li ZJ, Lin GH (2014) Heavy metal contamination and ecological risk assessments in the sediments and zoobenthos of selected mangrove ecosystems, South China. Catena 119:136–142.

Marques, M. J., Martinez-Conde, E. and Rovira, J. V. 2003. Effects of zinc and lead mining in the benthic macroinvertebrate fauna of a fluvial ecosystem. Water Air Soil Pollut. 148:363–388.

Marquet, P., Abades, S., y Barría, I. 2012. In Fariña J. y Camaño A. (Eds.), Humedales costeros de Chile: Aportes científicos a su gestión sustentable: Distribución y Conservación de Humedales Costeros: Una Perspectiva Geográfica. (pp.1-20). Ediciones UC.

Martínez, C., Rojas, O., Aránguiz, R., Belmonte, A., Altamirano, Á. y Flores, P. 2012. Riesgo de tsunami en caleta Tubul, Región del Biobío: escenarios extremos y transformaciones territoriales posterremoto. Revista de Geografía Norte Grande. 53: 85-106.

Martínez, J. A. 2014. Catastro y estado de conservación de los humedales marinos/ costeros en la región del Biobío. Tiempo Y Espacio. Universidad del Bío-Bío Chillán – Chile. On-line.

MEA (Millennium Ecosystem Assessment). 2005. Ecosystems and Human Well-being:

Synthesis. Island Press, Washingon, DC.

Melnick, D., Bookhagen, B., Echtler, H. and Strecker, M. 2006. Coastal deformation and great subduction earthquakes, Isla Santa María, Chile (37°S). Geological Society of America Bulletin. 118 :1463–1480.

Milliman, J. D., and Emery, K. O. 1968. Sea levels during the past 35,000 years. Science. 162(3858):1121-1123.

Mitsch, W. (ED.) 1994. Global Wetlands old world and new. Amsterdam, Elsevier. 967 pp.

Mitsch, W.J. and Gosselink, J.G. 2007. Wetlands (4ta. ed.). John Wiley and Sons. 581 pp.

MMA (a). 2017. http://portal.mma.gob.cl/chile-tiene-18-mil-humedales-y-solo-el-2-de-ellos-cuenta-con-algun-tipo-de-proteccion/. Publicado: lunes 27 de febrero de 2017.

MMA (b). 2017. http://biodiversidad.mma.gob.cl/?page_id=647. Visitado: 4 abril de 2017. 18:00 hrs.

Negrin, V.L., Spetter, C.V., Asteasuain, R.O., Perillo, G.M.E. and Marcovecchio, J.E. 2011. Influence of flooding and vegetation on carbon, nitrogen, and phosphorus dynamics in the pore water of a Spartina alterniflora salt marsh. Journal of Environmental Sciences. 23 (2): 212-221.

Nonn, H. 1987. Geografía de los litorales. Akal. Madrid. 199 págs.

Odum, E.P., 1996. Environmental Accounting. Emergy and Environmental Decision Making. John Wiley and Sons, Inc., New York.

Odum, H.T. and Odum, E.P. 2000. The Energetic Basis for Valuation of Ecosystem Services. Ecosystems. 3:21–23.

Odum, H.T.1986. In Polunin N. (Ed). Emergy in Ecosystems. Ecosystem Theory and b Application (337-369 pp). Wiley, New York. 446 pp.

Olsen, C.R., Simpson, H.J., Bopp, R.F., Williams, S.C, Peng, T. H.and Deck B.L., A 1978. Geochemical analysis of the sediments and sedimentation in the Hudson estuary. Jour. Sed. Petrol. 48:401-418.

Packham, J. R., and Willis, A. J. 1997. Ecology of dunes, salt marsh and shingle. Springer Science and Business Media.335 pp.

Palma, R. B. 1997. Vegetación y paisaje en la costa atlántica de Andalucía. Univ.De Sevilla, Sevilla. Vol.16.

Perillo, G. M., Ripley, M. D., Piccolo, M. C. and Dyer, K. R. (1996). The formation of tidal creeks in a salt marsh: new evidence from the Loyola Bay Salt Marsh, Rio Gallegos Estuary, Argentina. Mangroves and Salt Marshes. 1(1): 37-46.

Pestrong, R. 1965. The development of drainage patterns on tidal marshes. Stanford University publications. 10:(2).

Piccolo, M.C y Perillo, G. M.1997. Geomorfología e hidrografía de los estuarios. El Mar Argentino y sus recursos pesqueros. 1:133-161.

Pickett, S.T.A., White, P.S., 1985. Natural disturbance and patch dynamics: an introduction. In: Pickett STA, White PS (eds) The ecology of natural disturbance and patch dynamics. Academic Press, Orlando, 3–13 pp.

Quezada, J., Jaque, E., Belmonte, A., Fernández, A., Vásquez, D. y Martínez, C. 2012. Movimientos cosísmicos verticales y cambios geomorfológicos generados durante el terremoto Mw=8,8 del 27 de febrero de 2010 en el centro-sur de Chile. Rev.Geo.Sur. 2:11-45.

Rader, R. B., Batzer, D. P. and Wissinger, S. A. 2001.Bioassessment and Management of North American Freshwater Wetlands. Ed: Russell B. Rader , Edited by Darold P. Batzer, Edited by Scott A. Wissinger. John Wiley & Sons Inc, New York, United States.

Raffaelli, D.G., Hawkins, S.J. 1996. Intertidal Ecology. Springer.356 pp. 10.1007/978-94-009-1489-6.

Redfield, A. C. 1967. Postglacial change in sea level in the Western North Atlantic Ocean. Science 157, 687-692.

Reinhardt, E. G., Nairn, R. B. and Lopez, G. 2010. Recovery estimates for the Rio Cruces after the May 1960 Chilean earthquake. Marine Geology. 269(1): 18-33.

Rojas, C. 2005. Clasificación y evaluación florística y vegetacional de los humedales del estero Putemún, comuna de Castro, X Región de Los Lagos. Tesis presentada a la Facultad de Ciencias de la Universidad Católica de Temuco para Optar al Grado de Licenciado en Recursos Naturales. 103 pp.

Rojas, C. H. 1985. El estuario del río Queule: Un ambiente sedimentario en el Sur de Chile. Revista de Biología Marina. 20(2): 139-157.

SAG-Servicio Agrícola y Ganadero. 2009. La Ley de Caza y su Reglamento. Ministerio de Agricultura. 99 pp.

Santana, C., Falvey, M., Ibarra, M. y García, M. 2014. El Potencial Eólico, Solar e Hidroeléctrico de Arica a Chiloé, Proyecto Estrategia de Expansión de las Energías Renovables en los Sistemas Eléctricos Interconectados (MINENERGIA / GIZ). Santiago-Chile. 158 pp.

Sousa, W. 1984. The role of disturbance in natural communities. Annual Review of Ecology and Systematics. 15:353-391.

Stuardo, J., Valdovinos, C., Figueroa, R. y Occhipinti, A. 1993. Los ambientes costeros del golfo de Arauco y áreas adyacentes. Gestión de los recursos hídricos de la cuenca del río Biobío y del área marina costera adyacente, Centro EULA-Chile. 157 pp.

Tapia, L., Fontán, L., García-Arrese ,A., Nieto, C. y Macías, F. 2005. Metodología para la evaluación de los efectos sinérgicos generados por parques eólicos sobre la avifauna:

un caso práctico. Ecología.19: 301-312.

Teneb, E.A., Cavieres, L.A., Parra, M.J. y Marticorena, A. 2004. Patrones geográficos y de distribución de árboles y arbustos en la zona de transición climática mediterráneo-templada de Chile. Revista Chilena de Historia Natural 77:51-71.

Valdovinos, C. y Sandoval, N. 2011. Cambios ambientales del humedal Tubul-Raqui derivado del alzamiento cosísmico y tsunami, asociado al terremoto Mw 8,8. Informe técnico de la Unidad de Sistemas Acuáticos, Centro de Ciencias Ambientales EULA, Universidad de concepción, Chile.

Valdovinos, C., Muñoz, M.D., Sandoval, N., Vásquez, D., y Olmos, V. 2010. Desastres naturales y biodiversidad: El caso del humedal costero Tubul-Raqui. Sociedad Hoy.10:33-51.

Valdovinos, C., Sandoval, N., Vásquez, D. y Olmos, V. 2012. In Fariña J. y Camaño A. (Eds.), Humedales costeros de Chile: Aportes científicos a su gestión sustentable: El Humedal Costero Tubul-Raqui: Un ecosistema chileno de alto valor de conservación severamente perturbado por el terremoto del 2010. (pp. 391-438). Ediciones UC.

Valiela, I., Kinney, E., Culberston, J., Peacock, E. and Smith, S. 2009. In: Duarte C. (Ed). Global losses of mangroves and saltmarshes. Global loss of coastal hábitats. Fundación BBVA, Bilbao, España. 4:107-138.

Vásquez, D. 2013. Metodología para la Delimitación y Zonificación de Humedales Costeros de Tipo Mediterráneo. Revista de Geografía Norte Grande. 6:13-32.

Vásquez, D. 2017. Efectos geomorfológicos y ambientales del terremoto Mw=8,8 del 27 de febrero del 2010 sobre los humedales costeros de la región del Biobío: el caso de la marisma Tubul-Raqui. Tesis para optar al Grado de Doctor en Ciencias Ambientales. Centro EULA-Chile. Universidad de Concepción.

Vásquez, D., N. Sandoval, P. Fierro, C. Valdovinos. 2020. Morphological impacts of the

Chilean megathrust earthquake Mw 8.8 on coastal wetlands of high conservation value. Estuarine, Coastal and Shelf Science 245, 106922. https://doi.org/10.1016/j.ecss.2020.106922.

Vergara, O., Saavedra, M.F. y Ortiz, J.C. 2007. En: CONAMA (Ed.). Fauna Presente en el Humedal Tubul-Raqui, Provincia de Arauco, Sitio Prioritario para la Conservación de la Biodiversidad. Capítulo I: Anfibios del Humedal Tubul-Raqui. CONAMA Región Biobío (6-8 pp.). Concepción. 72 pp.

Warwick, R. M. 1993. Environmental impact studies on marine communities: pragmatical considerations. Australian Journal of Ecology. 18:63-87.

West, C. 1981. The nature and future of the coastal salt marshes of South America. XIII International Botanical Congress. Sydney. 21:28.

West, C. 1981.The nature and future of the coastal salt marches of South America. XIII International Botanical Congress. Sydney. 21-28.

Woodhouse, W.E. and Knutson P.L. 1982. In: Lewis R.R. (Ed.). Creation y restauration of coastal plant communities. Atlantic coastal marshes (Ch 2: 45-109). CRC press, Boca Raton, Florida.

Yapp, R. H., Johns, D. and Jones, O. T. 1917. The salt marshes of the Dovey Estuary. The Journal of Ecology. 65-103.

CAPITULO 2:

DESCRIPCIÓN DEL IMPACTO DEL TERREMOTO Y TSUNAMI 27F SOBRE UN HUMEDAL COSTERO

Basado en:

The Tubul-Raqui Coastal Wetland: A Chilean Ecosystem of High Conservation Value Severely Disturbed by the 2010 Earthquake. In: Fariña J., Camaño A. (eds) The Ecology and Natural History of Chilean Saltmarshes. Springer, Cham. Doi 10.1007/978-3-319-63877-5

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(2017)

5.2 Capítulo 2: The Tubul-Raqui Coastal Wetland: A Chilean Ecosystem of High Conservation Value Severely Disturbed by the 2010 Earthquake

Claudio Valdovinos, Natalia Sandoval, Daniela Vasquez, and Viviana Olmos

Abstract Given the great extent of the Tubul-Raqui marshland, in addition to its high biodiversity and biological productivity, combined with a low degree of human disturbance, this wetland corresponds to one of the most important ones in Chile. This chapter describes its main features and effects caused by the February 2010 earthquake. The wetland continues to provide nesting and shelter sites for numerous resident and migratory bird species, many of which have conservation problems. The major anthropogenic threats to the conservation of the wetland and its different habitats have historically been bird hunting and deforestation of river shores that affect the sedimentation of the rivers that feed it. As for the structure of the physical habitat, water quality and aquatic biota of the wetland, since the earthquake of 2010 a series of relevant environmental changes have occurred. Some of them were expressed immediately during the earthquake, while others continue to manifest themselves. The main changes resulting from the earthquake have resulted from its uprising of about 1.6 m above sea level, which has led to the total drying of the network of internal channels that irrigate the wetland, and partial one of the main channels of the rivers Tubul and Raqui. This has also limited the exchange with the sea, generating a decrease in the salinity of the waters to the interior of the wetland. The two most important benthic species for the artisanal fishery, the "Pelillo" seaweed (*Gracilaria* sp.), and the "navajuela" bivalve (*Ensis macha*), were severely affected and there is still no evidence of any degree of recolonization. Although the ecosystem was severely affected by the earthquake, it retains properties that allow it to remain within the country's most important coastal wetlands.

Resumen Dada la gran extensión del humedal Tubul-Raqui, además de su alta biodiversidad y productividad biológica, combinada con un bajo grado de perturbación humana, este humedal corresponde a uno de los más importantes de Chile. En este capítulo, se describen sus principales características y efectos causados por el terremoto de febrero de 2010. El humedal continúa proporcionando sitios de anidación y refugio para numerosas especies de aves residentes y migratorias, muchas de las cuales tienen problemas de conservación. Las principales amenazas antropogénicas para la conservación del humedal y sus diferentes hábitats han sido históricamente la caza de aves y la deforestación de las riberas de los ríos que afectan a la sedimentación de los ríos que lo alimentan. En cuanto a la estructura del hábitat físico, la calidad del agua y la biota acuática del humedal, desde el terremoto de 2010 han producido una serie de cambios ambientales relevantes, algunos de ellos se expresaron inmediatamente durante el terremoto, mientras que otros siguen manifestándose. Los principales cambios resultantes del terremoto han sido consecuencia de su levantamiento de ~ 1,6 m sobre el nivel del mar, lo que provocó la desecación total de la red de canales internos que irrigan el humedal, y parcial de uno de los canales principales de los ríos Tubul y Raqui. Esto también ha limitado el intercambio con el mar, generando una disminución de la salinidad de las aguas al interior del humedal. Las dos especies bentónicas más importantes para la pesca artesanal, el alga "Pelillo" (Gracilaria sp.), y el bivalvo "navajuela" (Ensis macha), fueron severamente afectadas y aún no hay evidencia de ningún grado de recolonización. Aunque el ecosistema se vio gravemente afectado por el terremoto, conserva propiedades que le permiten permanecer dentro de los humedales costeros más importantes del país.

Keywords Biodiversity • Conservation • Marshland • Earthquake • Tubul • Raqui • Chile

5.2.1 Introduction

Coastal wetlands are recognized worldwide as the ecosystems of interest for the conservation of biodiversity (Valiela et al. 2009). In addition, they provide multiple ecosystem services for our society, among which are the production of commercially important species, especially algae and mollusks (Valdovinos 2004). Along the coast of Chile, it is possible to find numerous types of estuarine wetlands located from the arid regions of the north, to the southern fjords. Each one of them presents ecological characteristics according to its latitude, coastal geomorphology, tidal regimes, freshwater contributions, recent geological history and degree of human intervention (Valdovinos 2004). A series of coastal and marine wetlands (see Stuardo and Valdovinos 1989) exist on the shores of the Biobio Region, located in south-central Chile, which, according to the classification system of the Ramsar Convention (2006), and corresponding to the typologies of “estuaries”[4] and “intertidal marshes and estuaries”[5]. The latter typology includes ecosystems that are considered to be among the scarcest and most important of Chilean coasts, especially for harboring numerous unique species, many of which present conservation issues (Stuardo et al. 1992). These ecosystems depend on a delicate balance between terrestrial, freshwater and coastal marine systems, and because are located on the coastal border, they are affected by the tidal cycles that allow the entry of marine waters into the continental area (Valdovinos 2004).

In the Biobio Region, these ecosystems are mainly represented by the Tubul- Raqui, Rocuant-Andalien, Lenga and Carampangue wetlands, which are home to a diverse avifauna, including an important set of seasonal migratory birds and extensive meadows or “Espartales” of the halophyte plant *Spartina densiflora* Brongn 1829. This species is of fundamental importance in these ecosystems, acting as an “bioengineering species” that models and stabilizes the river banks from the effects of the tides, and corresponds to the

[4] Type F, which includes permanent estuarine waters and estuarine delta systems.

[5] Type H, which includes marshes and flooded areas with salt water, halophytic grasslands, salt beds, flooded areas with salt water, freshwater and brackish areas flooded by the tide.

main energy source of the wetland, contributing large amounts of organic detritus that enters the aquatic and terrestrial trophic chains. The most important ecosystem of these coasts, due to its high biodiversity and services offered to society, is the Tubul and Raqui wetland (Figura 5.2-1).

Associated with the coastal basin of the hydrographic system formed by the Tubul and Raqui rivers, located at the southern end of the Arauco Gulf (37 ° 13′S – 73 ° 26′W), 17 kilometers south of the city of Arauco (Valdovinos, 2001), this wetland is considered the most important in the region, due to its large extent, which reaches approximately 2238 ha and is a hot spot of biodiversity.

In this wetland, the Tubul and Raqui rivers, of coastal origin and presenting a pluvial regime, flow into the sea. The wetland is typically an intertidal marsh-type estuary, in which there is a marked salinity gradient as a consequence of the transition between inland and coastal marine waters (Long and Mason ,1983). Given these salinity conditions, the wetland has been an important part of the livelihood of the local human population concentrated mainly in the Tubul creek, through the cultivation and extraction of the algae Gracilaria spp., which until the February 2010 earthquake was intensively cultivated in the estuary.

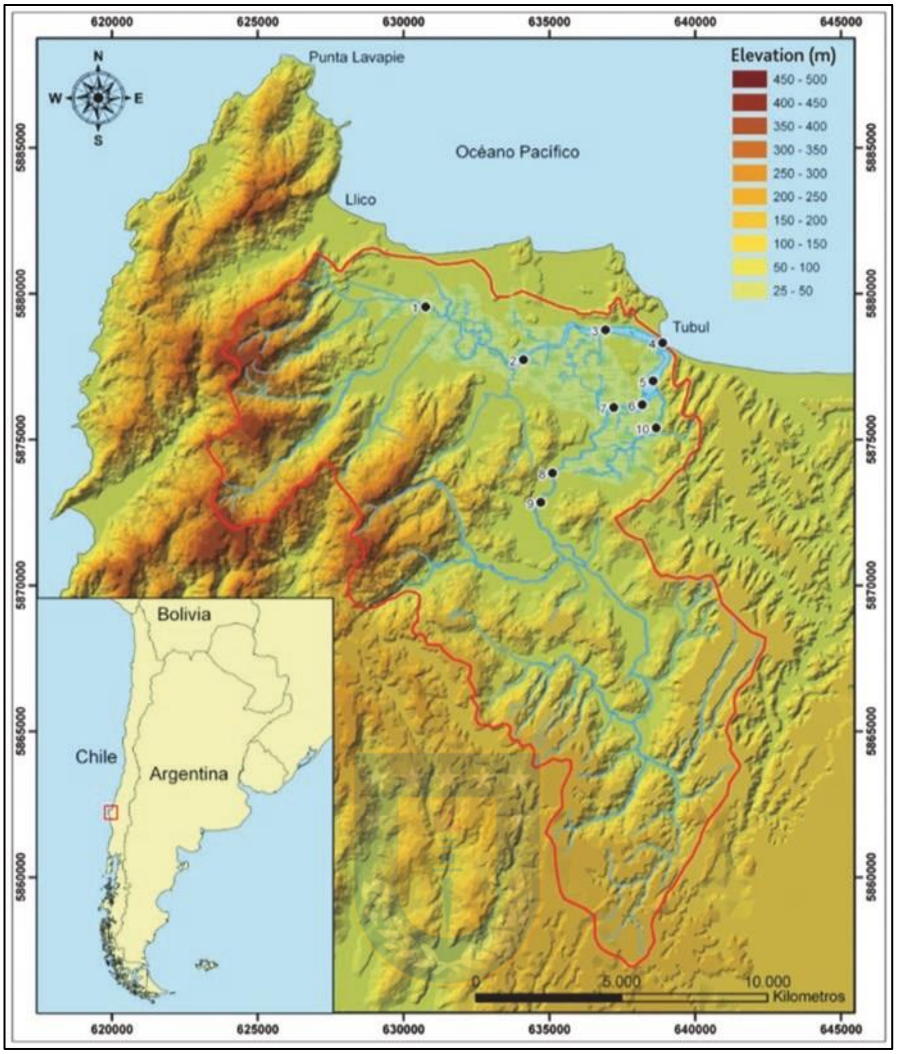

Figura 5.2-1 Geographic location, relief and water network of the Tubul-Raqui wetland basin (Modified from Vasquez 2009), and location of sampling stations considered by Valdovinos and Sandoval (2011)

According to Vasquez (2009), the system that hydrically feeds the wetland, is inserted in a sequence of platforms of marine erosion located in the vicinity of the western slope of the Coastal Mountain range. This unit has a high rate of forestation and exhibits three levels of marine abrasion platforms: superior (>100 m), medium (50–100 m) and lower (<50 m), which are intensely eroded, allowing it to be covered with a large plain where they the Tubul and Raqui rivers reside. Both rivers are of pure pluvial regime, determined by a temperate morphoclimatic coastal wetland. The fluvial plain is characterized by being of local origin and having a flat bottom, weak slopes and is open towards the northwest, which favors the development of the extensive coastal marsh that receives contributions of coastal marine waters, and through the flow of tides penetrates towards the continent through the fluvial system, which is why such characteristics develop at its river mouths with mixohaline conditions of high biological productivity. At the outer edge of the coast to the north of the wetland, there is a narrow plain parallel to the coast that has a shoreline and small freshwater wetlands inland.

The Tubul-Raqui wetland was severely affected by the earthquake that occurred on February 27, 2010, when it has suffered a vertical rise of approximately 1.6 m above sea level, which meant significant changes in its aquatic component, especially in the area of intertidal marshes that were partially out of the water. The objective of this chapter is to present a descriptive synthesis of the main ecosystem characteristics of the Tubul-Raqui wetland, with emphasis on its structural aspects and conservation value, and to present a synthesis of the major changes in the wetland, following the February 2010 earthquake.

For the development of this chapter, a bibliographic background was gathered from the study area, with emphasis on its physical-natural characteristics. Using those, cartographies were created to represent and integrate each of the variables through the use of the GIS platform. The basic information used in this chapter was obtained from the following studies: Biro (1979), Ferraris (1981), Pineda (1985), Alveal (1988), Werlinger and Alveal (1988), Stuardo et al. (1992), Carvalho-Lagos and Jimenez (2009), Carrasco-Lagos (2003, 2004), CEA (2006, 2009), Melnick et al. (2006), Conama (2007), Nielsen and Valdovinos (2008), Parada (2008), EULA *(*2008), Vergara et al. (2008), Vasquez (2009) and Valdovinos and Sandoval (2011).

5.2.2 Ecosystems Characteristics

5.2.2.1 Climate Framework and Geomorphology of the Basin

According to Vasquez (2009), the Tubul-Raqui wetland is in a climatic transition zone between a warm temperate Mediterranean climate and a humid or rainy temperate climate, which develops immediately south of the Biobio River. Specifically, in the area of the Tubul-

Raqui wetland, the climate is humid coastal temperate. According to Constabel (1993), in this zone there are anywhere from 2 to 5 months of cold and humid weather, and during those times, approximately 75% of the precipitations are concentrated, reaching 1300 mm annually between autumn and spring. The summer periods are quite dry, reaching between 5–6% of the annual precipitations. The relative humidity shows an oscillation around 80%, which is due in large part to the marine influence.

According to Pineda (1985), the Cretaceous-Tertiary sedimentary basin of Arauco, located in the present Arauco peninsula and the corresponding continental shelf, is characterized by an alternating the marine and continental sedimentary sequences. In this basin the following formations are recognized: Quiriquina (Senonian), Pilpilco (upper Eocene), Ranquil (Miocene) and Tubul (Pliocene). Vasquez (2009) has pointed out that the Arauco peninsula corresponds to an elevated continental slope, in which the Meso-Cenozoic sequences have been exposed. Pineda (1985) has proposed that during the Neogene (Pliocene) - Pleistocene, as a consequence of the pyogenic movements of the Pliocene, part of the area of the Gulf of Arauco basin has been raised and affected by a strong erosion, and at the same time as in the other areas, the sea transgressed on Miocene and Eocene sections. The marine sequences deposited during the Pliocene structured the Tubul Formation (see Nielsen and Valdovinos 2008). As Vasquez (2009) points out, from a geomorphological point of view, the Tubul-Raqui wetland has developed on an extensive fluvial-marine sedimentation plain of the coastal edge of the Arauco Province, an area that, in the last 50 years, has been severely affected by tectonic subsidence and sinking movements. The increase in flooded areas and/or the enhancement of flooding processes is due in large measure to the gradual obstruction of drainage caused by intense tectonic activity. This plain is developed with a flat morphology, with weak slopes, whose low plateau is only interrupted by the presence of a small marine terrace of lower level (<50 m), which helps to divide the hydrographic systems that are only interconnected in the opening, after surrounding the small terrace. Much of the wetland rests on a recent quaternary, in deposits of black sands, and river and beach sediments. Bordering this wide plain, there are three levels of terraces of marine abrasion (Figura 5.2-2), which have been mainly modeled by the interaction of tectonic activity and climate. The main characteristics of these terraces are the following:

Lower level marine erosion terrace (<50 m): It is located around the wetland in the northeastern sector, presenting a semi-annular distribution, with a flat morphology at the top. This terrace is structured in sedimentary rocks of the Ranquil formation of Miocene age. Due to its morphology and the level of erosion that it exhibits, in its inner part a small plain of flat topography has developed, and it houses small marshy areas, fed by the drainage of a smaller estuary, that receives the contributions from numerous ravines activated only during the winter season. On this terrace there is also a scarce, semi-stabilized dune system.

Mid-level marine abrasion terrace (50–100 m): It is distributed in the east and southeast sector of the wetland. It is flatter than the previous one and is better preserved in terms of its morpho structure, but it is more intervened anthropically, due to the construction of access roads such as highways and the presence of dispersed human settlements. This terrace is dissected by valleys with flat bottoms that have taken advantage of fault lines to inscribe their morphology, exhibiting small, but well inscribed valleys that flow towards the Gulf of Arauco.

These valleys feed small strips of coastal marshes, which have no connection to the great wetland of Tubul-Raqui. This terrace denotes vestiges of the old direct contact with the ocean, with the presence of the dead high sea cliffs, which are currently used as nesting shelters for seabirds. The mid-level terrace is built on rocks of the Tubul formation, Pliocene age.

Top-level marine abrasion terrace (100–300 m): It is situated on the entire west part of the wetland, and is structured by sedimentary rocks of the Ranquen, Milongue and Trihueco formations, of Eocene age.

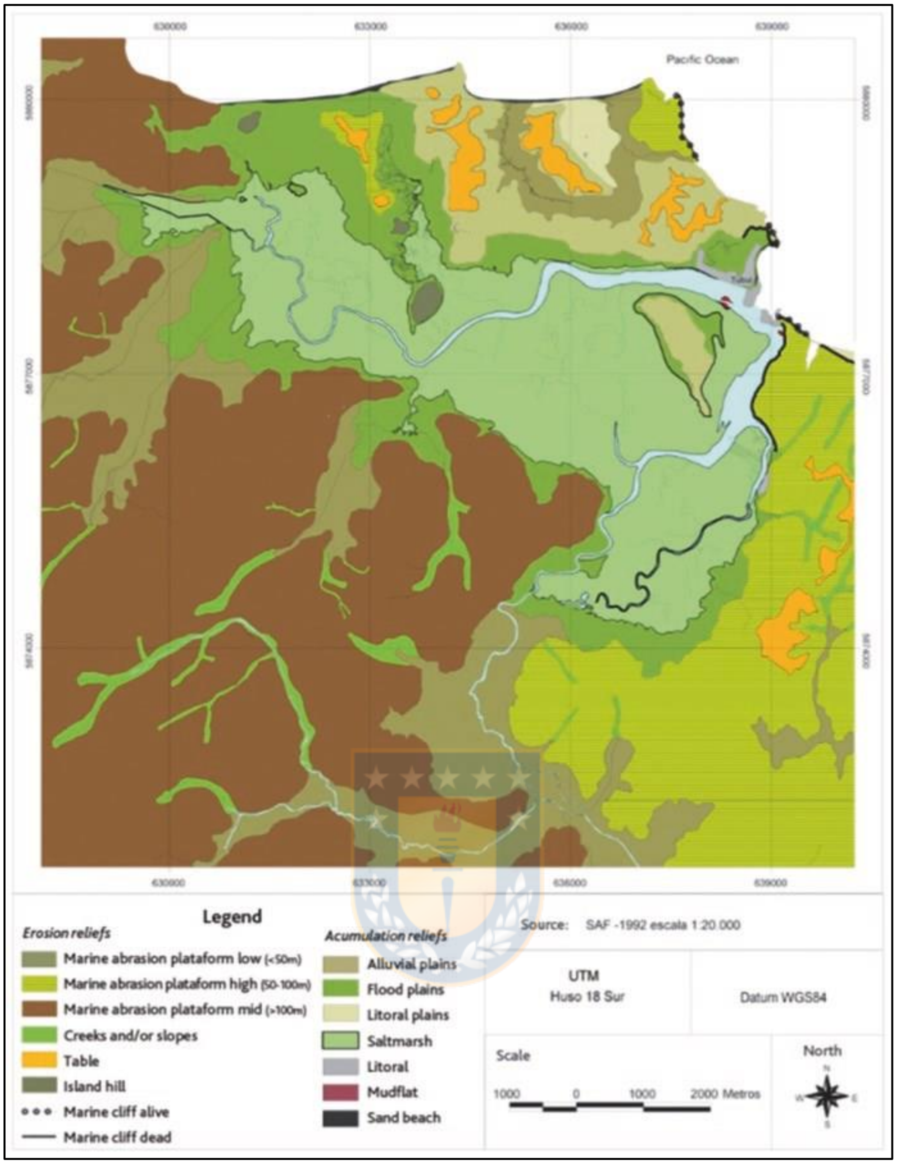

Figura 5.2-2 Geomorphology of the Tubul-Raqui wetland basin (Modified from Vasquez 2009)

5.2.2.2 Water Network and Hydrology

The coastal basin formed by the hydrographic system of the Tubul and Raqui rivers is inserted in the corridors of the Arauco Gulf. According to Vasquez (2009), the basin as a whole has a total area of 274 km^2, with a perimeter of 81 km. The sub- basin of the Tubul River occupies 37.5% of the total area of the basin, and 64.3% of the River Raqui. The basin of the Tubul-Raqui wetland is located on the remains of marine terraces, modeled during repeated episodes of transgressions and marine regressions, opening to the sea with the combination of estuaries and marshes of the region (Figura 5.2-3). The general characteristics of the formation of this coastal sector and its two sub-basins are considered by Pineda (1985) to be of Recent Pliocene origin, which by processes of filling, deposition of sediments and basements, were structured with the current characteristics.

According to Alveal (1988), who studied the distribution of Gracilaria spp. In the estuary, the Tubul River had an approximate course of 17–19 km long, with influence of the high tide over the first 6 km, from the mouth upwards. The Raqui River is about 15 km long and shallower than the Tubul, with maximum depths of up to 2 m, and water runoff throughout the year. The Tubul River presents sediments formed by the fine sand, in great part, from the bed of the river, and very fine sand in the margins in front of the estuary, with anoxic sludge in areas of scarce circulation. On the other hand, in the area near the mouth of the river Raqui, thinner sediments (very fine sands and silty clay) are developed in front of secondary streams, and a large part of the riverbed is covered with fine sand, especially on the left riverbank, and with medium sand in the central parts and to the right. The great estuary formed by the union of both rivers at its mouth, called the Tubul-Raqui estuary, corresponds to the micromareal regime, with seasonal contributions of fresh water. In general, it presents a greater contribution of fresh water through the Raqui River, even in summer, while in the Tubul River there is a greater marine influence (Stuardo et al. 1992). The morphometric analysis of the Tubul-Raqui basin conducted by Vásquez (2009) shows a compact index of 1.37, indicating that it is a basin whose shape resembles more to the circular form than to the elongated shape, which also explains the relatively rapid response to extreme rainfall events. It should be noted that the two main channels are heavily influenced by surface runoff and annual rainfall.

According to the drainage hierarchy proposed by Strahler (1981), the Tubul River is of the order 3, whereas the Raqui River is of order 4, reason why this river is better fed than the first, receiving the confluence of a series of smaller estuaries, including Las Peñas and Los Puentes. On the other hand, the Tubul-Raqui coastal basin presents the typical dendritic drainage pattern for the exortic basins of continental Chile. This drainage pattern is characterized by an irregular branching of tributaries, and is typically present in those places where the rocky substrate is relatively homogeneous and does not offer greater resistance to river erosion, its shape being determined mainly by the slope direction of the ground. This type of drainage pattern can be observed in some sectors of the headwaters of the basin, and especially in the lower course where both hydrographic systems meet, due to the fact that there is a greater predominance of moderate slopes here. On the other hand, and due to the antecedents of the basin previously indicated, it can be recognized that in much of the middle and lower course there is a predominance of the subparallel drainage pattern, which is determined by the remarkable structural control of the zone described by Pineda (1985). As mentioned previously, this area was the subject of alternating epigenetic descents and ascents, possibly during the Eocene era, characterized by a strong tectonics of extension faults, which are currently active, and which are responsible for giving rise to structures of “horts” and “graben” type. However, it is also necessary to take into account that a large number of drains of the lower course, that present a rectilinear physiognomy, have been altered by human action and channeled to be used in agricultural and livestock activity in the area.

From a hydrological point of view, the estuarine system formed in a large part of the marsh, receives its main contributions of fresh water through the river Raqui, even in the summer season, and in the Tubul River is generally found a greater marine influence, as described by Stuardo et al. (1992). As it will be discussed below, this situation has been greatly disrupted following the February 2010 earthquake, which produced major changes in the interaction between inland and marine waters, as a result of the waterbed elevation. According to Stuardo et al. (1992), the maximum depths of the system exceeded 2 m, and today, after the earthquake, they are approximately 0.4 m.

5.2.2.3 Soils and Vegetation

According to the CIREN-CORFO (1999; fide Vasquez 2009), the largest studied area is occupied by soils belonging to class VII, with very severe limitations, which makes them unsuitable for crops, but not for forestry and grazing. Much of the area occupied by this type of soil is severely degraded or eroded. According to Mardones (1971), this is mainly due to intensive agricultural and grazing practices of the late ninetieth and early twentieth centuries, and to the planting of exotic forestry species, replacing more than 80% of the original native vegetation. Due to this, approximately 54% of the soils are in an advanced state of erosion, despite not having strong slopes sectors, except in the river ravines. The main soil series present in the area of the Tubul-Raqui wetland basin corresponds to the following: Miscellaneous Swamp (MP), Caripilun Series (CR), Las Puentes Series (LPU) and Larkote Series (LQT).

In the Tubul-Raqui wetland basin, part of the original forest cover has been heavily modified and exploited more than a century ago (Constabel 1993), as well as being heavily intervened and fragmented, currently occupying the ravines and some of the highest marine platforms (Figura 5.2-3).

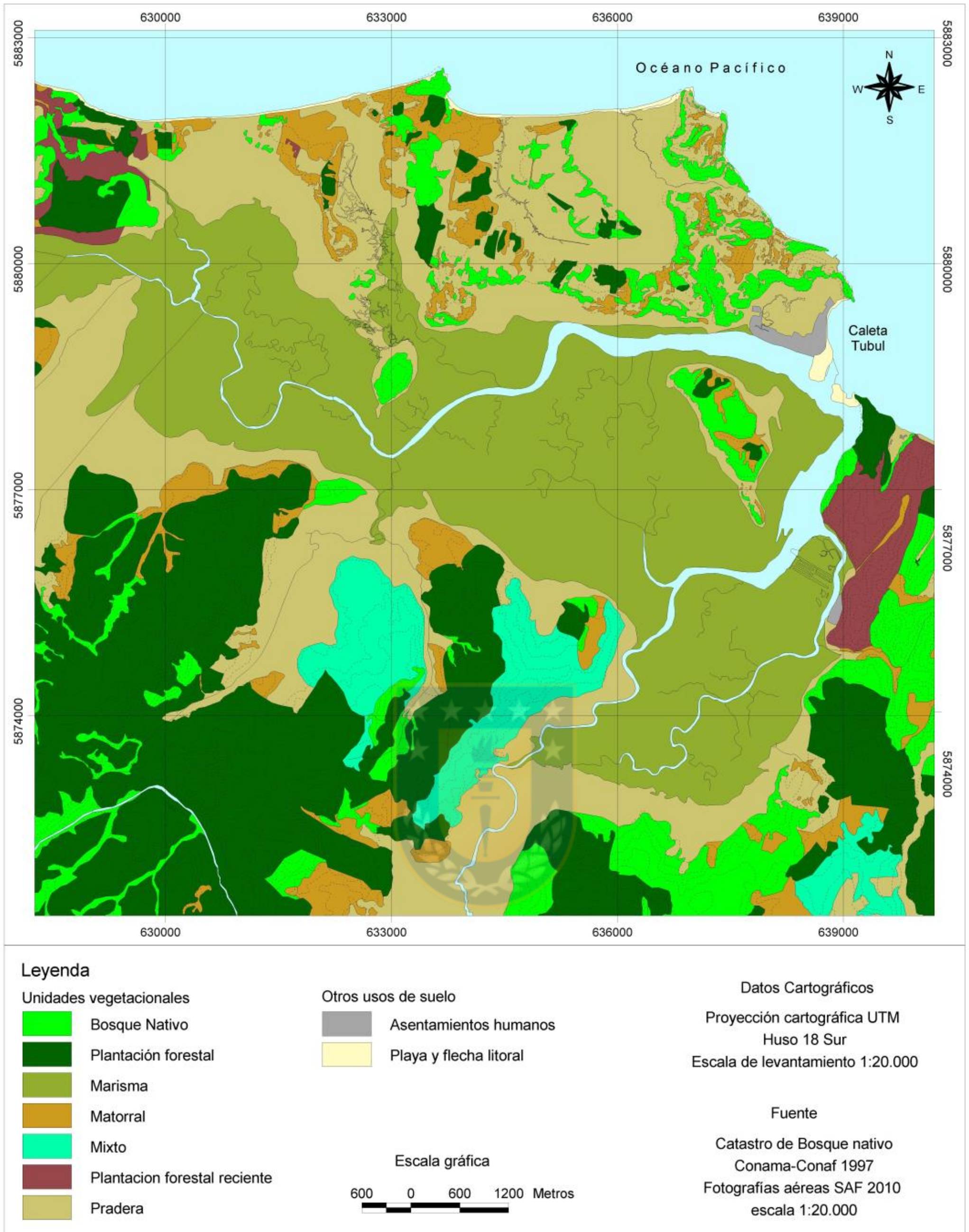

Figura 5.2-3 Vegetation units in the Tubul-Raqui wetland basin (Modified from Vásquez 2009)

Much of the native woodland vegetation has been replaced by plantations of Pinus radiata and Eucalyptus globulus, and may now be relegated to small patches of native vegetation mixed with forest plantations and/or in the interior of the ravines. The small platform that separates the Tubul and Raqui rivers in the lower course is an example of this, presenting small stretches of forest plantations in the eastern slope, in contact with small areas of agricultural development. In contrast, the western slope is colonized by species of vegetation native to the sclerophyllous forest and the hydrophilic coastal forest, being much more in contact with the wetland environment that has developed in the extensive marsh areas.

In most of the platform slopes that surround the wetland, there are relics of native forest with dominance of *Peumus boldus*, *Myrceugenia exsucca*, *Myrceugenia obtusa* and *Podanthus mitiqui* that also includes less abundant species such as *Lithraea caustica*, *Aetoxicum punctatum*, *Aristotelia chilensis* and *Griselina scandens* (Carrasco-Lagos 2003).

With respect to the coastal wetland environment itself, it is composed of a large marsh lying on the coastal plain of fluvial-marine sedimentation with quaternary sediments. The marshes are salt marshes that suffer two daily floods, product of the tidal cycles. Waterlogging creates anaerobic conditions in sediments, and physiological salinity drought, which generates extreme ecological conditions (San Martin et al. 1992). In these areas, only salinity – adapted species survive, such as the one known as Sarcocornio – *Spartinentum densiflorae* (according to San Martín et al. 1992), which includes the species *Spartina densiflora* and *Sarcocornia fruticosa*, the first species much more abundant than the second (Stuardo et al. 1992). These two species are very closely related to the marshes of the south central Chile, being arranged in strata. The upper stratum tends to be dominated by S. densiflora, reaching maximum heights of 1 m, whereas the stratum basal <1 m, is dominated by *S. fruticosa*. To the interior sectors of the rivers, and with minimal marine influence, the vegetation is mixed with grass of *Cotula coronopifolia*, *Polyonum persicaria*, *Taraxacum officinale*, *Rumex* sp., *Trifolium repens*, *Eleocharis pachycarpa*, *Cyperus eragroslis*, *Plantago lanceolata*, *Flypochaeris* sp. *Carex* sp. species, and in smaller abundance of *Mentha aquatica* (Carrasco-Lagos 2003). In addition, towards the head of the rivers, it is possible to observe species such as Juncus procerus and *Scirpus californicus*, the latter of great abundance in the innermost sectors of the Tubul River (Carrasco-Lagos 2003).

According to Vasquez (2009), the wetland is developed in a coastal plain with flat topographic features, with a presence of a small terrace of marine abrasion that divides the central sector of the wetland near the mouth of the Tubul and Raqui rivers. The high topography that surrounds the wetland by the west, east and south, corresponds to terraces of marine abrasion with maximum heights of 300 m, such as the internal terraces towards the continent. However, these slopes lead to the wetland sector with extremely moderate slopes, which are probably due to the intense erosion work carried out by the ocean during the phases of marine regressions and transgressions. Even so, it is still possible to observe that the geomorphological unit immediately adjacent to the wetland corresponds to flood plains, strongly influenced by the hydrology of the wetland itself, and the hydrology of the entire basin of the Tubul and Raqui rivers. These plains are characterized by sweet pasture species and are mainly used for the development of the agricultural and livestock activities that are carried out in the area, presenting a considerable change regarding the humidity level between the months of autumn-winter and spring- summer. During the winter, these plains are extremely humid, even becoming completely saturated by surplus water from the recurrent rainfall recorded throughout the south-central zone, unlike the dry months, when the plains receive water sporadically through concentrated, small ravines surrounding them, and in some cases, are even affected by water stress.

The vegetation of the Tubul-Raqui marshes is constituted by emerged, non- arboreal communities of vascular plants with roots, that occupy territories where the salinity, derived from the coastal marine influence, generally exceeds 1–4 UPS, and where the periodic emptiness generated by the tides, happens at least once a year, normally during the equinoctial tides. The perennial species and almost all halophytes dominate in the marshes, although there are other species of wide distribution, but those exhibit different character (Adam 1990). The scarce number of species able to tolerate the high salinity of these ecosystems determines the amount of small, but diverse vegetation (Chapman 1974; Adam 1990; Jiménez 1996). In the Tubul-Raqui wetlands, S. densiflora dominates (Figura 5.2-4), and corresponds to a salt-tolerant grass, although it is also possible to find succulent halophyte *Sarcoconnia fruticosa* in some sectors, and in many cases it is possible to observe a combination of both species, which gives rise to complex mosaics of vegetation.

The species Spartina densiflora, because of its wide coverage, density and biomass, is a fundamental species in the structuring of the Tubul-Raqui wetland (Figueroa and Valdovinos 1997). This is one of the 16 species of the genus Spartina

Figura 5.2-4 General view of the grassland dominated by *Spartina densiflora* that is observed with a darker tone (Photograph: C. Valdovinos, April 2010)

Schreber described in the world, all perennial rhizomatous and tolerant to salinity (Mobberley 1956; Jiménez 1996). This genus is widely distributed in both hemispheres, inhabiting mainly the coastal systems of America, Africa and Europe (Chapman 1977). According to Jimenez (1996), the species of this genus possess excretory glands of salt, and although they develop preferentially in saline soils, it is not only limited to them. According to Chapman (1977), the marshes dominated by Spartina represent very relevant communities within the estuaries, being very successful in the colonization of recent sedimentary deposits. Species of this genus are vigorous herbaceous plants, which can form large prairies in areas of estuarine sand and sludge (Chapman 1974). Its sediment retention capacity has motivated its planting in many areas of the world, having been introduced by man, as settlers, in different sectors of the Asian coast and Oceania (Chung 1990). According to Begon et al. (1987), the genus Spartina is one of the few groups of C4 plants that, despite the high temperatures required for their optimum growth, extend their geographic range to temperate climate latitudes, occupying saline ecosystems, in which the osmotic conditions especially favor these species with a high efficiency in the use of water.

Spartina densiflora Brong is of South American origin and is very abundant in certain parts of the Chilean coast, as in the Tubul-Raqui wetland, where it constitutes almost monospecific communities (Mobberley 1956; Figueroa and Valdovinos 1997). The taxonomic status of this species has been the subject of some controversy. In this paper, we have followed Mobberley (1956) and Cabrera (1970), who consider *Chauvinia chilensis* Steud., *S. montevidensis Arech.*, *S. patagonica* Speg. and *S.* j*uncea* Willd. Var. Montevidensis St. Yves as synonyms of this species, According to Costa and Davy (1992), *S. densiflora* is geographically distributed along a wide latitudinal gradient on the American coasts, encompassing both hemispheres and the Pacific and Atlantic Oceans (ca 32 ° N – 51 ° S). Within this territory it presents a shared distribution, although clearly skewed towards the Atlantic coast of the Southern hemisphere, where it extends uninterruptedly by the marshy coastal environments for thousands of kilometers. In the southern hemisphere, it is found in much of the temperate and subtropical zone of South America, on the coasts of southern Brazil, Uruguay, Argentina, in addition to central and southern Chile. In the Northern Hemisphere its distribution is limited to small nuclei on the shores of the Gulf of Mexico. Both regions are separated by a wide strip, with limits very close to the tropics. Among the 86 vascular species considered in the review of coastal marsh communities in Latin America by Costa and Davy (1992), *S. densiflora* is the one that encompasses a greater latitudinal gradient. Other marsh species that present a similar distribution pattern in this geographical area are *Juncus acutus* (L.) and *Sarcocornia fruticosa*.

The “espartales” of the Tubul-Raqui wetland are a key element for the conservation of the wetland, being a bioengineering species that strongly models the structure of aquatic habitats. Fortunately, this is a species tolerant to strong environmental changes, and it was not affected by the of 27 February earthquake. A different situation would have occurred if this species had been affected, causing a series of physical, chemical and biological changes in the wetland.

5.2.2.4 Terrestrial and Riverine Fauna

With regard to amphibians, the species are restricted to the freshwater wetland sectors, with abundant palustrine vegetation dominated mainly by "Junco" (Juncus procerus) and "totora" (*Scirpus californicus*). This group has been recorded in the wetland by Vergara et al. (2008), as being the most frequent species to observe in these habitats, like the "Four Eye Froggy" (*Pleurodema* t*haul*), which are common to find in its larval states in pond areas. Another species registered is *Batrachyla taeniata*, which according to SAG (2009) qualifies in the category of "Vulnerable". Reptiles present in the wetland are suitingly distributed in the sunny areas surrounding the "espartales", although it is also possible to observe them in the vega sectors, during the summer. According to Vergara et al. (2008), there are four species of lizards belonging to the genus Liolaemus (*L. cyanogaster*, *L. tenuis*, *L. lemniscatus* and *L. chiliensis*), and two species of snakes, corresponding to *Tachymenis chilensis* and *Phylodrias chamissonis*. Out of the reptile species, the only species classified in a conservation category is *L. tenuis*, which according to SAG (2009) qualifies as "Vulnerable".

The Tubul-Raqui wetland is a marshy intertidal estuary, with a marked salinity gradient, which allows the existence of strong environmental gradients, and an important diversity of avifauna habitats. That is why this wetland is one of the main nesting and shelter sites for numerous species of birds, resident and migratory, of the Biobio Region. The special geographic and ecological conditions of this wetland permit the presence of a fluctuating number of migratory and resident bird species, among which there are 31 families and 83 bird species (Carrasco-Lagos 2003, 2004; Vergara et al. 2008; Carrasco-Lagos and Jiménez 2009). The most diverse species in the wetland are Anatidae (8 spp.), Laridae (7 spp.), Furnariidae (7 spp.), Tyrannidae (7 spp.), Ardeidae (6 spp.) And Scolopacidae (4 spp.). Among the migratory birds are the *Rynchops riger*, *Numenius phaeopus*, and the *Limosa* *haemastica*. Regarding the conservation status of wetland species, the Hunting Law of the Agricultural and Gaming Services.

SAG (2009) established that the species *Cygnus melancoryphus* and *Coscoroba coscoroba* as "endangered", while the *Theristicus melanopis* qualifies as "Vulnerable". On the other hand, according to the International Union for the Conservation of Nature (IUCN)[6], the species Sterna elegans, *Phalacrocorax gaimardi*, *Pelecanus thagus*, and *Anas specularis* qualify in the category of "near threat", that is, they could soon be classified as "Vulnerable".

According to Vergara et al. (2008), mammals are represented by four species of rodents, corresponding to: *Abrothrix olivaceus*, *Abrothrix longipilis*, *Oligoryzomys longicaudatus*, and *Myocastor coypus*. According to SAG (2009), only *Myocastor coypus* qualifies within the category of "Vulnerable".

5.2.2.5 Aquatic Flora and Fauna

The aquatic flora and fauna present strong gradients in the wetland, which are closely associated with the variations of salinity. In general, it is possible to recognize two large areas, one sweet water with saline <4 UPS and another estuarine or mixohaline, with strong fluctuating salinities in a range of 4 and 30 UPS, depending on the location within the estuary, and its tidal condition.

5.2.2.6 Estuarine Area

The microalgae of the estuarine zone have been studied by CEA (2006), indicating within the peripheral community the presence of 38 species of diatoms, most of which correspond to marine environments. In quantitative terms, the species of greatest abundance registered in the study are *Opephora pacifica* and *Opephora martyi*, which have reached respective densities of 373,713 and 175,913 cel/mm^2, inside the estuary. In a second study carried out by CEA (2009), 44 phytobenthic species were recorded, the majority of them being diatom

[6] http://www.iucnredlist.org/.

species typical of environments. In this study, dominant species in the community were *Fragilaria pinnata* and *Achnanthes thermalis*. As for macroalgae, the dominant species until before the February 2010 earthquake was the *Rodophyta Gracilaria* spp., which as mentioned above, was of great economic importance for the inhabitants of the area (Dellacroce and Valdovinos 1994). Another species present in the area is *Chlorophyta Ulva* (= Enteromorpha) intestinalis, which develops in the quieter areas of the protected areas of the estuary. This species was also affected by the earthquake, though to a lesser extent than the aforementioned species.

In relation to estuarine zooplankton, this was also studied by CEA (2009), finding as a general pattern, a greater diversity of taxa in the estuary area of the Tubul River than in that of the river Raqui. The taxa recorded in the area corresponded to copepods Calanoidae, Cyclopoidae, and copepodite and nuplius states. Among the taxa found, they were notable for their abundance Tumediaptomus (= Diaptomus) diabolicus and Microcyclops sp.

With respect to the benthic invertebrates of the estuarine area, these are less diverse than those in the freshwater zone located in the upper part of the basin. However, their abundances, biomass, whether per unit area or throughout the ecosystem, are clearly higher. Within the sessile or sedentary species present in the estuary, are basically recognized as those that inhabit hard riverbeds, and others that inhabit soft riverbeds.

Before the earthquake, the dominant hard riverbeds species corresponded mainly to riparian root habitats. These correspond to the red wines of Spartina densiflora located in the limits of the spartal and which were, before the earthquake, affected by the tide. Subsequent to the earthquake, these habitats were completely desiccated due to the severe lifting of the wetland, which meant the total loss of its aquatic fauna and its replacement by terrestrial invertebrates (Valdovinos and Sandoval 2011). Before the earthquake, the dominant species in these habitats were the estuarine Bryozoa estuarine *Conopeum* sp., The Amphipoda *Paracorophium hartmannorum* and polychaetes, especially *Prionospio* (*Minuspio*) *patagonica*. These habitats were also occupied as refuge and feeding areas by juvenile stages of the crustacean *Decapoda Hemigrapsus crenulatus*, which were generally abandoned after reaching 20 mm cephalothorax lengths to occupy the soft bottom habitats of the wetland. Another relevant component of hard-bottomed benthos corresponded to *Cirripedia Elminius kingii*, which was also severely affected by wetland drying. This filtering species inhabited preferably woody and rocky substrates present in the intertidal zone of the wetland.

Prior to the earthquake, the intertidal and subtidal soft beds of the wetland were occupied by large densities of polychaetes of the Spionidae and Nereidae families, which reached high biomass, and were especially dominated by *P*. (*M*.) *patagonica* and *Perinereis gualpensis*. In these environments were also located great concentrations of the bivalve *Tagelus dombeii* that were exploited in the area for commercial purposes. These depths were also occupied by the adult crustaceans *H*. *crenulatus*, reaching high densities, and in some sectors, it was possible to find the small estuarine bivalve *Kingiella chilenica*. As it will be discussed later, populations of polychaetes and *H*. *crenulatus* were significantly reduced after the earthquake, due to the desiccation of much of the water floors. On the other hand, the banks of *T. dombey* and *K. chilenica* disappeared completely from the wetland. Little is known about the fish in the estuarine area of the wetland. General observations made in the area by our research group before the earthquake of 2010 confirmed the presence of estuarine and marine species, such as "*Elegonops maclovinus*", "*Mugil cephalus*, *Galaxias maculatus* and *Odontesthes mauleanum*.

5.2.2.7 Freshwater Zone

Since the Raqui River sub-basin is the most important in extension, draining part of the high sectors of the mountain range of Nahuelbuta, its fluvial and caudal geomorphology allows the existence of an abundant and diverse aquatic flora and fauna. This is not observed in the case of the Tubul River, which has lower tributaries that originate at low altitude. Upstream of the estuary, in the river Raqui, it is possible to recognize two clearly defined zones. A ritron zone is in the high part of the basin, characterized by waters of high speed, rocky beds and a typical sequence of rapids and backwaters. The other area is the "potamon" one, located on the plain, characterized by slower flows, sand and gravel beds, and without the sequence of rapids and backwaters. The "ritron" area is very poor in periphytic microalgae, since the river is mainly a gallery and a shadow, due to the important influence of riparian vegetation, both native and exotic species (Pinus radiata and Eucalyptus globulus). There are no systematic studies of the aquatic biota in this area of the basin, and what is described here corresponds to general observations made by our research group during April 2011. Within the aquatic and riparian flora of this sector, the presence of moss of the genus Sphagnum, covering part of some semi-submerged rock substrates is highlighted. This area is very rich in benthic macro-invertebrates, which are represented by immature states of 32 insect families, mainly belonging to the orders Trichoptera (Glossosomatidae, Helicopsychidae, Hydrobiosidae, Hydropsychidae, Hydroptilidae, Limnephilidae and Seicostomatidae), Plecoptera (Austroperlidae, Diamphipnoidae, Eustheniidae, Gripopterygiidae, Notonemouridae and Perlidae) and Ephemeroptera (Leptophlebiidae, Baetidae, Amelotopsidae, Caenidae and Nesameletidae). The crustaceans are represented by the shrimp *Samastacus spinifrons* and the crab *Aegla* sp. Further studies are needed to determine which species this crab belongs to, considering the high diversity of species (and genetics) in this area of the Coastal Mountain range (Habit and Victoriano 2005). It is important to mention that the representatives of Aeglidae are among the most threatened freshwater invertebrates in the country (Pérez-Lozada et al. 2002). As for fish, general observations indicate the dominant presence of the "rainbow trout" (*Onchorhynchus mykiss*), which is an exotic invasive species, and of the native species "painted catfish" (*Tricomycterus areolatus*). The fauna of the ritual area of the river Raqui has a high dependence on its riparian forests. Foliar detritus from these forests has been identified as one of the main energy components of the river ecosystem (e.g. various species of Nothofagus, among others), being an important source of food for invertebrates, which are the food base of fish species observed in the area.

In the potamal zone, which is open given the scarce riparian arboreal vegetation in the area, there is sufficient light to develop the community of periphytic microalgae. Qualitative observations made in the area show the dominant presence of diatoms of the genera Achanthes, Aulacoseira, Cocconeis, Cyclotella, Cymbella, Diatoma, Fragilaria, Gomphonema, Nitzschia, Pinnularia and Synedra. As for the benthic invertebrates, the diversity is considerably lower than the one existing in the potamal zone of the river, registering a total of 15 families of Mollusks (Chilinidae, Amnicolidae, Physidae, Sphaeriidae), Platyhelminthes (Dugesiidae), Oligochaeta (Lumbriculidae, Naididae), Crustacea (Hyalellidae, Parastacidae), Coleoptera (Dytiscidae, Elmidae, Gyrinidae, Hydrophilidae), Diptera (Chironomidae) and Hemiptera (Corixidae).

As for the fish in this area, in addition to recordeding the same two species present in the ritral zone, the presence of the native species *Percichthys trout*, *Geotria australis* and *Galaxias maculatus*.

5.2.2.8 Human Settlements and Economic Activities

According to what was documented by Vasquez (2009), the wetland area is inhabited only by rural population, which amounts to approximately 2500 inhabitants, concentrated mainly in the Tubul creek. According to this census, the poverty level of this cove is 56%. The second locality of population importance is the creek Las Peñas, located on the banks of the River Raqui, counting with a total of 261 inhabitants (according to data from the CASEN, commune of Arauco). The rest of the human presence adjacent to the wetland corresponds to small dispersed settlements, including the small localities of Raqui and Raqui Alto.

The population associated with the wetland is mainly engaged in agriculture and the raising of poultry, cattle and pigs, mainly developed in meadows and/or floodplains. All of them on a small scale, mainly for family consumption, with a small surplus for marketing, where one of the products that have stood out as of lately is the production of handmade cheeses. Agriculture has received some stimulus from the state, through the promotion of private investment in irrigation and drainage. This is why it is possible to observe a large number of pipes that drain part of the wetland. The livestock activity developed today is incipient, since in general, the area does not possess soil conditions favorable to the development of natural or artificial prairies, vital condition for all livestock economy.

A relevant productive activity carried out by the population of the Tubul creek, but associated with the proper coastal marine ecosystem, is the artisanal fishing activity. In Tubul, the main resource extracted is the “huepo” or “razor” (*Ensis macha*) and the “navajuela” (*Tagelus dombeii*), in addition to other mollusks and bivalves. These products are sold to individuals who export them mainly to USA, Japan and Spain. Another important activity is forestry, due to the presence of extensive plantations of exotic species, such as Pinus radiata and *Eucaliptu*s globulus, which have replaced the original native vegetation. The erosion terraces adjacent to the Tubul-Raqui wetland have been gradually colonized since the beginning of the 1990s, due to the predominance of soils IV and VII, whose capacity of use allows the development of this type of activity.

An important economic activity developed in the wetland, prior to the earthquake of February 2010, was the intensive cultivation of “pelillo” (*Gracilaria* spp.). Due to the severe wetland rise caused by the earthquake, a large part of the channels where the crops were made was desiccated, which currently prevents the development of this productive activity. Until February 2010, the main economic activity inside the wetland was the cultivation of this seaweed, practiced solely by the inhabitants of the area, bringing together a total of 500 people. The extraction of “pelillo” has been regulated by the Undersecretary of Navy of the Ministry of Defense through a maritime concession of 320 hectares. The production of “pelillo” harvested before the earthquake was approximately 2000 tons of wet algae, which were exported mainly to Japan.

Livestock is also developed within the basin, through the breeding of cattle that are used for the production of meat and milk for the production of cheeses. Since the dominant vegetation in the wetland is characterized by thick and saline pastures, livestock is limited mainly to areas located between mountainous and “espartal” sectors. Agricultural activity is incipient within the basin and is mainly intended for self-consumption.

5.2.2.9 Use of Soil in the Wetland Area

According to the photo interpretation work carried out by Vasquez (2009), the area of the Tubul-Raqui wetland and its surroundings, presents a total of 10 classes of land uses, corresponding mainly to “forest plantations” (Pinus radiata and Eucalyptus globulus), covering a 33% of the total area of the area, followed by “agricultural use” intended mainly for rotating crops of wheat and oats, corresponding to 22% of the area. The rest of the developed economic activities has an insignificant area compared to the above mentioned ones, not exceeding 1%; among them the “aquaculture use” for the cultivation of seaweed *Gracilaria* spp. (Even before the earthquake of 2010) and “recreational use”, represented by a small resort located in the coastal area. The third dominant land use currently corresponds to “grassland shrubs”, which are located mainly in the remnants of mid-level terraces (50–100 m) and in those sectors of the upper level platforms (>100 m) that have not been reached by the expansion of forestry, and represent 19% of the study area.

The area corresponding to “wetland” has represented up to 16% of the area before the earthquake (there are nowadays extensive drying areas not yet quantified), while the “native forest interspersed with scrub” does not reach 10%, corresponding mainly to remnants of “olivillo”, “oak” and “boldo” forests. The “human settlements and beaches” also do not represent 1% of the area, due to the scarce development of the sandy coast in the area and because most of the human settlements are dispersed.

5.2.2.10 Water and Sediment Quality

The main study of the sediments and their dynamics in the wetland is done by Constabel (1993). This study describes, preferably sandy bottoms in the wetland, and in the vicinity of the estuary mouth, in areas with high hydrodynamics due to tidal currents. On the other hand, in areas of less hydrodynamics in the interior of the wetland, there are predominantly muddy bottoms. In close relation with the dynamics and the contributions of autochthonous and allochthonous organic matter of the system, Stuardo et al. (1992) showed high levels of the organic matter content of the sediments, which vary from 2–4% in the vicinity of its mouth and 10–20% in the interior of the wetland.

Regarding water quality, the various studies conducted in the area prior to the 2010 earthquake (Stuardo et al. 1992; Constabel 1993; CEA 2006; Valdovinos and Sandoval 2011) generally showed a system with strong salinity changes resulting from tidal fluctuations and eutrophic conditions. Also, conditions of slightly lower salinity were observed in the Raqui River rather than in the Tubul River, due to the higher freshwater intake from its drainage basin. An important aspect highlighted by Stuardo et al. (1992) was the marked stratification of the waters at sometimes of the year, despite the low depth of the estuary. This stratification was due to marked density gradients generated by differences in continental and marine density. It should be noted that, despite this stratification and the presence of sediments rich in organic matter at the bottoms, there were no conditions of hypoxia or anoxia in the brackish waters.

After the February 2010 earthquake, Valdovinos and Sandoval (2011) describe the changes observed over time in both the sediments and the estuary water column, which will be described in more detail below. Tabla 5.2-1and Figura 5.2-5present the water quality data of the Tubul and Raqui rivers (obtained by Valdovinos and Sandoval 2011), in the 10 sampling stations indicated in Figura 5.2-1.

These data were obtained before the earthquake (December 2008 and August 2009), and after the event (April, August and December 2010). This table compares the values of temperature, salinity, pH, dissolved oxygen, chlorophyll-a, ammonia, total nitrogen, total phosphorus and suspended solids. This Table shows that the most relevant change occurred after the earthquake was a decrease in salinity, especially in the dry season.

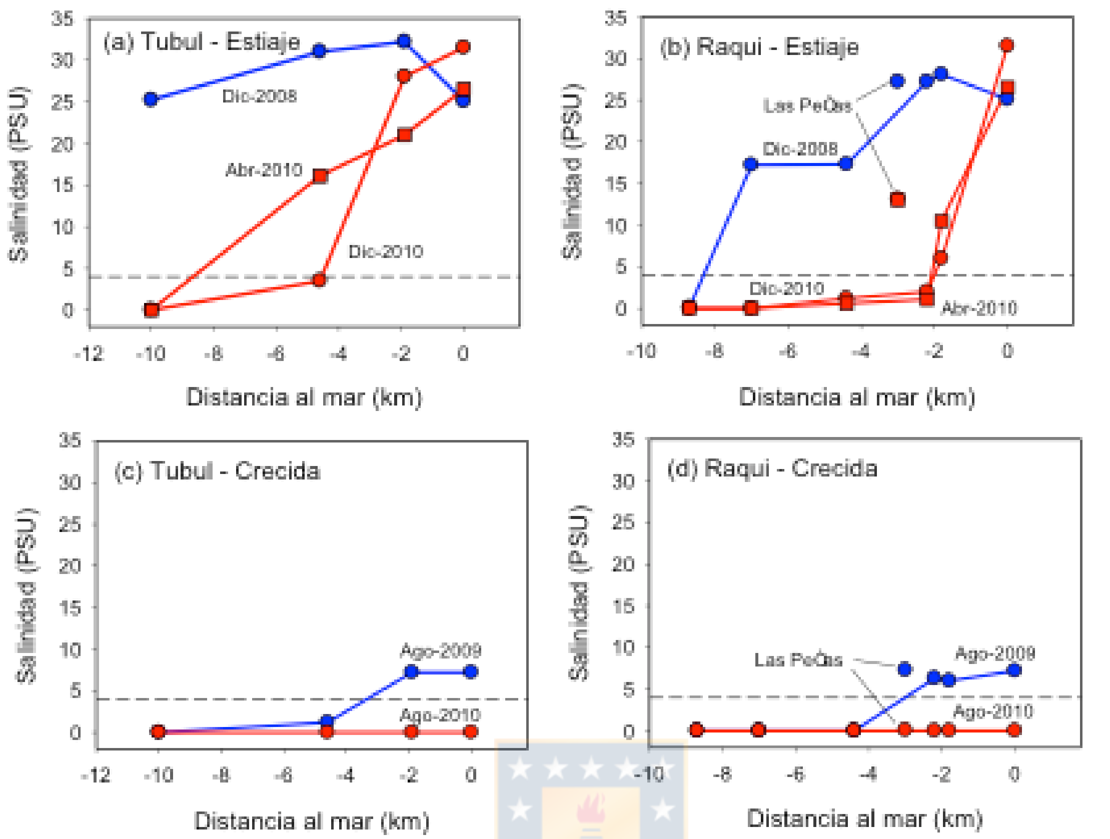

Figura 5.2-5 Water quality in Tubul river, and in the 10 sampling stations indicated in Fig. 10.1. These data were obtained prior to the earthquake (December 2008 and August 2009), and after the event (April, August and December, 2010)

Tabla 5.2-1 Characterization of water quality in Tubul (stations 1-4), Raqui (stations 5-9) and Las Peñas estuary (station 10) rivers, before the earthquake (December 2008 and August 2009), and after the event (April, August and December 2010)

Estación	Fecha	Temp (°C)	Salinity (UPS)	pH	OD (mg/L)	Chlorophyll (ug/L)	Ammonia (mg/L)	P-total (mg/L)	N-total (mg/L)	SST (mg/L)	SSI (mg/L)	SSO (mg/L)
1	Dec-08	14,5	0	7,1	9,8	0,05	0,03	0,02	0,35	2,10	1,79	0,32
	Aug-09	13,4	0	7,7	9,7	0,04	<0,02	0,01	0,40	5,50	4,51	0,99
	Apr-10	14,0	0	6,2	9,8	0,08	0,20	0,09	0,80	3,20	2,80	0,40
	Aug-10	11,2	0	6,1	9,6	0,05	0,05	0,03	0,43	6,70	5,49	1,21
	Dec-10	14,2	0	7,5	9,7	0,09	0,02	0,03	0,09	6,40	4,50	1,90
2	Dec-08	14,7	31,0	7,0	9,5	0,12	0,03	0,04	0,39	8,20	4,67	3,53
	Aug-09	12,9	1,2	7,6	9,6	0,09	0,02	0,05	0,40	10,10	6,16	3,94
	Apr-10	16,1	3,5	6,7	9,7	6,31	0,26	0,51	0,80	39,30	20,70	18,60
	Aug-10	12,9	0	6,7	5,0	2,68	<0,02	0,09	0,41	17,60	12,67	4,93
	Dec-10	18,3	16,1	8,0	9,6	7,58	0,14	0,23	0,99	39,00	23,80	15,20
3	Dec-08	15,4	32,2	7,0	9,2	1,45	0,09	0,03	0,41	9,30	6,70	2,60
	Aug-09	14,1	7,2	7,6	9,3	1,31	0,02	0,05	0,40	10,20	6,94	3,26
	Apr-10	17,2	28,0	7,6	9,5	13,10	0,28	0,28	1,48	40,60	29,20	11,40
	Aug-10	13,1	0	7,1	4,8	3,45	0,02	0,08	0,42	19,40	13,39	6,01
	Dec-10	18,6	21,0	8,1	9,3	15,32	0,07	0,24	0,99	46,00	26,60	19,40
4	Dec-08	15,6	25,1	7,0	8,9	3,00	0,09	0,07	0,55	9,80	7,84	1,96
	Aug-09	11,9	7,2	8,2	8,8	2,10	0,02	0,09	0,49	20,50	15,99	4,51
	Apr-10	15,6	31,5	7,4	8,9	10,20	0,44	0,31	0,64	80,20	63,60	16,60
	Aug-10	13,8	0	7,1	6,6	3,12	0,02	0,12	0,59	30,40	24,02	6,38
	Dec-10	14,6	26,5	7,7	8,7	6,10	0,21	0,28	0,62	74,20	56,60	17,60
5	Dec-08	15,6	28,1	7,0	9,8	1,20	0,08	0,06	0,43	8,30	5,81	2,49
	Aug-09	13,6	6,0	8,2	10,0	1,10	0,03	0,05	0,40	17,20	12,21	4,99
	Apr-10	16,3	6,0	7,3	10,1	12,30	0,37	0,30	0,84	46,40	37,00	9,40
	Aug-10	15,1	0	7,3	8,8	2,95	0,04	0,06	0,30	19,90	18,40	1,50
	Dec-10	18,5	10,5	8,2	9,9	5,30	0,11	0,28	1,27	23,80	12,20	11,60
6	Dec-08	15,1	27,2	7,0	9,7	1,32	0,04	0,04	0,32	7,90	5,61	2,29
	Aug-09	13,7	6,3	7,3	9,9	1,12	0,03	0,05	0,32	16,60	12,12	4,48
	Apr-10	17,1	2,0	7,2	10,3	6,25	0,47	0,30	0,46	30,40	23,40	7,00
	Aug-10	14,2	0	7,2	7,2	2,72	0,07	0,06	0,31	13,60	10,88	2,72
	Dec-10	17,8	1,1	8,1	9,8	4,80	0,13	0,12	0,64	16,40	12,60	3,80
7	Dec-08	15,1	17,3	7,0	9,9	1,01	0,02	0,06	0,67	5,20	3,80	1,40
	Aug-09	13,0	0	7,3	9,9	0,91	0,03	0,05	0,41	12,20	9,52	2,68
	Apr-10	17,0	1,2	7,0	10,3	3,45	0,49	0,28	0,78	36,80	30,00	6,80
	Aug-10	13,9	0	7,1	8,4	1,25	<0,02	0,09	0,48	14,20	11,36	2,84
	Dec-10	17,8	0,6	8,3	9,9	4,70	0,14	0,11	0,60	18,80	14,20	4,60
8	Dec-08	14,8	17,2	7,0	9,8	0,09	<0,02	0,05	0,71	4,80	3,79	1,01
	Aug-09	13,8	0	7,2	9,9	0,07	<0,02	0,03	0,32	9,00	6,93	2,07

Estación	Fecha	Temp (°C)	Salinity (UPS)	pH	OD (mg/L)	Chlorophyll (ug/L)	Ammonia (mg/L)	P-total (mg/L)	N-total (mg/L)	SST (mg/L)	SSI (mg/L)	SSO (mg/L)
	Apr-10	16,9	0	7,0	10,0	0,15	0,30	0,10	0,80	25,30	21,10	4,20
	Aug-10	13,4	0	7,0	9,7	0,09	<0,02	0,04	0,27	9,40	7,61	1,79
	Dec-10	17,3	0	7,6	9,9	0,20	0,13	0,06	0,37	11,80	9,20	2,60
9	Dec-08	13,6	0,1	7,1	9,5	0,09	<0,02	0,05	0,75	3,60	2,56	1,04
	Aug-09	12,9	0	7,1	9,7	0,08	<0,02	0,04	0,30	9,10	6,83	2,28
	Apr-10	16,8	0	6,9	9,8	0,10	0,24	0,08	0,82	19,60	16,20	3,40
	Aug-10	13,4	0	7,0	9,7	0,08	<0,02	0,05	0,32	10,20	9,38	0,82
	Dec-10	17,1	0	7,5	9,1	0,10	0,04	0,08	0,49	12,20	9,80	2,40
10	Dec-08	14,9	27,2	7,0	8,7	5,12	0,08	0,09	0,92	10,10	6,16	3,94
	Aug-09	13,5	7,3	7,3	8,9	3.12	0,04	0,10	0,61	21,00	12,39	8,61
	Apr-10	17,1	13,1	7,2	10,2	15,20	0,52	1,08	2,11	38,80	20,40	18,40
	Aug-10	14,3	0,1	7,2	5,5	4,14	0,18	0,14	0,68	24,20	5,49	19,01
	Dec-10	18,3	13,0	8,4	7,6	12,40	0,06	0,25	1,36	26,80	21,60	5,20

5.2.3 Disturbances Caused by the 2010 Earthquake

In order to present the characteristics of the aquatic and riparian component, it is necessary to make a comparative analysis between the situation existing before the February 2010 earthquake and the current one, since the changes occurred in the wetland have been of great magnitude. This review is based fundamentally on the comparison of the 10 sampling stations that have studied previously the earthquake, by Stuardo et al. (1992), in 1990–1992, and by Valdovinos and Sandoval (2011), in December 2008 and August 2009 (Figura 5.2-1). These same authors repeated the study during the same seasons after the earthquake, in April, August and December of 2010. According to the results obtained by Valdovinos and Sandoval study (2011), regarding the structure of the physical habitat, water quality and aquatic biota of the wetland, a series of environmental changes resulting from the earthquake (Table 10.1) have occurred since the February 27, 2010 earthquake.

Some of them occurred simultaneously during the earthquake, while others are still manifesting. Those generated during these events have been inferred from indirect evidence obtained at 40 days post-earthquake. On the other hand, the changes observed at 40 days, 6 and 10 months, correspond to observations and direct measurements made in the field. The following is a brief discussion of the results obtained by the authors, following the temporal sequence of events and field sampling.

5.2.3.1 Changes that Occurred During the Earthquake

The earthquake magnitude Mw8.8 had an approximate duration of 180 seconds, period in which occurred the lifting of the wetland of ca. 1.6 m above mean sea level. Farias et al. (2010) have described in detail the changes that occurred along the coast of central Chile. This survey would not have been homogeneous throughout the area of the wetland, since some areas would have experienced an uprising at almost two meters. During the earthquake, the cracking of many sectors of the "espartal" ocurred, cracks that in some areas of the river Raqui had a depth of 1.5 m and a width of 0.3 m. During the telluric movement, some of these cracks have released muddy sediments, which covered part of the plants of *S. densiflora*. With respect to water quality, it is likely that during the earthquake, the violent oscillations of the terrain and the water body of the wetland increased the turbidity by re-suspension of the bottom sediments. In relation to the aquatic biota, it is possible that this one has not suffered significant effects, except the burial of some macro invertebrates, by the transport of sediments caused by the elevation swell to the interior of the estuary.

5.2.3.2 Changes that Occurred in the First 10 Hours of the Earthquake

Given the magnitude of the rise of the wetland above sea level, it can be deduced that immediately after the earthquake strong currents of water were generated towards the sea, eroding part of the sand banks of the mouth. Evidence of this has remained on the banks of the lower reaches of the Tubul and Raqui rivers, where much of the sand and gravel fractions were transported downstream, leaving many boulders and large rocks deposited on the banks. The detailed characterization of the sediments and their associated processes had been described for the estuary by Constabel (1993).

Once the wetland was emptied, it was affected by the devastating entrance of tsunami, which reached a maximum of 12 m. This tsunami not only meant the entry of coastal marine water, but also of large amounts of sand deposited on the “espartal” and in the network of inner channels of the wetland, a situation that is frequent in this type of phenomena, as it was verified Cisternas et al. (2000) for the Maullin River estuary, which was affected by the 1960 Tsunami. Given the predominantly NS orientation of the Tsunami and the configuration of the coastline (see Ferraris 1981), the most affected area of the wetland was the sector of the river Tubul, where the tsunami entered by ca. 3 km. Along its Tubul River course, the body of water ripped from the shore entire pieces of espartal, up to 50 m^2 of surface, transporting them upstream, and these are the ones that currently make up islets in the middle of the channel. After the tsunami, the wetland continued to empty, until it was virtually disconnected from the sea by a sand bar, which limited the normal exchange with the coastal waters of the Gulf of Arauco. With regard to water quality, it is logical to think of an increase in salinity during the Tsunami. In addition, an increase in water turbidity is likely due to the re-suspension of fine sediments from the bottom of the wetland, adding to an increase in the organic sexton from the “wash” of the “espartal”.

In relation to the aquatic biota, the most visible destruction was the total destruction of the "Pelillo" (*Gracilaria* spp.) seaweed plantations, and a high mortality of the estuarine crustacean *Hemigrapsus crenulatus*, by dragging these benthic organisms to the terrestrial system and their subsequent desiccation. This crab is one of the most abundant epifaunistic species in Chilean estuarine ecosystems (Grandjean 1985), also living in similar systems in New Zealand (Retamal 1981). It is able to regulate the volume and osmolarity of its body fluids, a physiological condition that allows it to live in estuaries (Retamal 1967; Taylor and Seneviratna 2005). In crustaceans, such regulation involves an energy cost that can generate changes in the oxygen consumption of the animal and the rates of excretion. Exposure to low salinities may also alter ingestion, another of the physiological aspects associated with the behavioral response of organisms. Recently, Urbina et al. (2010) studied the physiological energy of *H. crenulatus*, suggesting that the increase in energy expenditure at low salinity is due to an increase in osmoregulation costs, which are compensated by an increase in the rate of ingestion, which contributes to the success of individuals of this species in dynamic environments, such as estuaries. Subsequent to the Tsunami, it was frequent to observe, in the forest environs bordering the wetland areas, high densities of these dead organisms.

In relation to the "Pelillo", the loss of these plantations was total, which has had important social and economic consequences for the area. The relevance to local communities of this resource has been discussed by Alveal (1988), Werlinger and Alveal (1988), and recently by EULA (2008). Figure 10.6 shows dried remnants of the prairie of these algae.

With regard to birds, Valdovinos and Sandoval (2011) did not consider the study of the aquatic avifauna of the wetland, whose composition had previously been studied in general by Carrasco-Lagos (2003, 2004), and more quantitatively by Parada (2008). Within 40 days of the earthquake, it was possible to verify the presence of some dead birds, presumably directly or indirectly caused by the tsunami. In addition, a high presence of carrion birds as the "Gallinazo" (*Cathartes aura*), have suggested the existence of dead organisms in the area.

5.2.3.3 Changes Registered 40 Days After the Earthquake

At the beginning of April 2010, there was virtually no water runoff from the wetland to the sea. The area of the mouth was sealed by a wide bar of sand, which could not be crossed by small craft. It is necessary to indicate that due to the earthquake, the great bridges on the rivers Tubul and Raqui were destroyed. As a way to improve the connectivity of the Tubul creek, prior to the construction of mechanical bridges, a fill in or an embankment was built on the Raqui River that allows vehicle traffic. Therefore, in the first days of April, until the 6th of the same month, the Raqui River was momentarily fragmented, further favoring the drying up of the lower section of the river (Figura 5.2-6).

Figura 5.2-6 Dry remainders of an algae prairie "Pelillo" (*Gracialaria sp*.), in Raqui river (Photograph: C. Valdovinos, April 2010)

Through aerial and ground inspections, using a remote controlled model equipped with a camera, it was possible to verify the partial drying of 100% of the inner canals that irrigate the wetland, preserving only isolated pools of standing water, or with limited runoff towards the main channels. With respect to the latter, the desiccation of up to 85% of the bottoms of the main channels of the rivers Tubul, Raqui and the Las Peñas estuary was observed. In the remaining waters, a significant decrease in depth of up to ca. 1.8 m, which made it impossible to cross these rivers using a Zodiac, since it was stranded in many sectors of the wetland. All the ground emanating from the wetland due to the coastal uprising showed different degrees of drying cracks and whitish spots corresponding to the deposition of salts. With respect to the Spartina root aquatic habitats, all of them disappeared from the wetland because of the lack of water. The dry bottoms of the wetland have been transformed into corridors for dogs, allowing them access to feed, and for waterfowl nesting areas.

Due to the fact that at the 40 days mark after the earthquake the total loss of the tidal regime inside the wetland, as well as the exchange with the coastal marine waters was maintained, there was a decrease in salinity, especially in the Raqui river sector, but on the other hand, there was an increase of nutrients (ammonium, total nitrogen and total phosphorus) and of chlorophyll-a inside the wetland. This condition of water quality was atypical for this seasonal period of the year, and if these values are compared with those of December 2008, or those described in the literature by Stuardo et al. (1992) and CEA (2006, 2009). There were no conditions of hypoxia or anoxia in the main channels of the estuary, allowing the normal development of aquatic life in those areas where water was conserved. In contrast, in the isolated pools of stagnant water that remained in the network of inner channels of the wetland, there was hypoxia associated with the decomposition of the high levels of organic matter produced by the eutrophication of the system. Due to the desiccation of *S. densiflora* root habitats, high mortality of the aquatic macro invertebrates that inhabited them, such as Bryozoa, Crustacea and Annelida, occurred. This is relevant, as these habitats are areas of shelter and growth of juveniles of the estuarine crab *Hemigrapsus crenulatus*, whose adults are an important part of the diet of birds. In relation to these crabs in an adult state, a 100% mortality was recorded inside the wetland, as they normally seek refuge in the dense formations of the “Pelillo” seaweed, which was also severely affected in the wetland.

With respect to soft bottoms, the total mortality of bivalve banks was recorded.

The most affected species, given their high abundance and biomass in the area, was the "navajuela" (*Tagelus dombeii*), whose thousands of empty shells are still visible in the sediments, indicating a rapid death in the emerged bottoms (Figura 5.2-7). This is a very important commercial specie that is present in the intertidal plains of southern Chile (Clasing et al. 1994; Jaramillo et al. 2007). According to the measurements made of this species by Navarro et al. (2008), it is mainly a suspended feeding organism, reason why its absence would have important implications in the characteristics of the phytoplankton community of the wetland.

Figura 5.2-7 Mortality in the bivalve banks of the "navajuela" (*Tagelus dombeii*), of commercial importance (Photograph C. Valdovinos, April 2010)

Another relevant aspect observed 40 days after the earthquake was that in the main channels of the rivers Tubul, Raqui and Las Peñas estuaries, in which some water was conserved, and benthic communities were registered, although with smaller abundances and species richness than what was reported prior to the earthquake. With regards to the hard substrates present in the wetland, such as bridge pillars and piers, whether wood, concrete or metal, as well as artificial castings, there was the total mortality of the *Elminius kingii* estuarine crustacean reported in all of them. These aquatic organisms normally live in the upper limit of the intertidal zone. Given the severe rise of the coast, all the intertidal bands that conformed these organisms were exposed to the desiccation.

Another organism that disappeared from the area was the small, shallow-bottom estuarine bivalve Kingiella chilenica (Soot-Ryen 1957), which had been recorded prior to the earthquake in the stations of the Tubul and Raqui rivers, although always in very low densities. This is an endemic bivalve that inhabits soft bottoms of marshes and estuaries in the south of Chile (Gallardo et al. 2006).

It is a small clam that reproduces by breeding its embryos, being semelparous with an annual cycle, and whose recruits must survive an inhospitable winter before they grow and reach reproductive maturity in the following summer season (Gallardo et al. 2006). This bivalve has very low scattering capacity because it is not planktonic, and its re-colonization capacity is extremely low.

With respect to the terrestrial system of the wetland, it is important to note that 40 days after the earthquake, although all the “espartal” rose significantly above mean sea level, the plants that make up this formation did not show evidence of having been affected. Species of the genus Spartina are vigorous herbaceous plants, which can form large prairies in areas of estuarine mud and sand (Chapman 1974). Its sediment retention capacity has motivated its planting in many areas of the world, having been introduced by settlers, in different sectors of the Asian coast and Oceania (Chung 1990). According to Begon et al. (1987), the genus Spartina is one of the few groups of C4 plants that, despite the high temperatures required for their efficient growth, extend their geographic range to temperate climate latitudes, occupying saline ecosystems, in which the osmotic conditions especially favor these species with a high efficiency in water use.

5.2.3.4 Changes Registered Six Months After the Earthquake

In the samplings carried out by Valdovinos and Sandoval (2011), 6 months after the earthquake, it was verified that the habitat conditions registered at 40 days after the earthquake were maintained, in regards to the drying of the inner canals, the aquatic root habitats and the lack of exchange with coastal waters. However, there was a slight increase in the level of the water mirror, due to a higher amount of fresh water coming from the drainage basin derived from the winter rains. The observations of the marks of the maximum level of the waters registered on the borders have shown that during the great winter increase there was a wide waterlogging of the wetland. This would probably have been favored by the embankment of the mouth of the estuary, which hindered the flow of fresh water into the sea. The maximum level of flooding of the wetland was evidenced by accumulations of dried remains of *S. densiflora*, which formed clear bands inside the “espartal”. In the middle areas of the wetland there was an erosive process, while in the lower part a thin sedimentation process occurred.

Another relevant change registered in the 6 months of the earthquake was that in several places of the “espartal” there was a sinking of between 8 to 15 cm, and a slight horizontal deformation, due to the loss of water and compaction in the soils in which it develops. This sinking was found by measuring the difference in height between the old maximum tidal level given by the upper limit of distribution of E. kingii on poles contiguous to the “espartal”, and the upper limit of the horizon of *S. densiflora* roots. The difference in height in these two levels is indicative of the sinking of the “espartal”. Under natural conditions, there are no significant differences in height between these two limits.

In contrast to the April sampling conducted in the dry season, and in the same way as that reported in previous years for the winter period, in the August sampling the whole wetland presented freshwater conditions in terms of salinity and other parameters of water quality. However, something that had not been observed in previous samples was an increase of metals (Fe and Mn), in the waters that flowed from the “espartales”. The presence of these metals was evidenced by the red-brown tonality of the waters. Laboratory analysis of some of these samples showed that the metals had outer range concentration that could pose a risk to human health and the ecosystem (Mn 0.1–0.2 mg/L and Fe 4–5 mg/L).

In relation to the aquatic biota, 6 months after the earthquake, the de-faunation of the desiccated areas was maintained. A very significant aspect in the ecosystem, given its relevance in the diet of waterfowl, was a partial re-colonization of amphipods and polychaetes in the areas of the main non-desiccated channels, despite fresh water at the time of sampling. There was no degree of re-colonization by *T. dombeii*, E. kingii and *H. crenulatus*, which had previously disappeared from the area. But one of the species that showed re-colonization was the estuarine polychaete *Perinereis gualpensis*, which in terms of abundance and biomass corresponds to one of the most important polychaete species of estuaries in central and southern Chile (Bertrán 1989; Diaz-Jaramillo et al. 2010). A similar situation occurred with the amphipod *Paracorophium hartmannorum*, which is an important component in the estuarine trophic chains, especially because they are consumed by estuarine fish such as the "Robalo" (*Eleginops maclovinus* (Cuvier, 1830), Jaramillo et al. (2000).

Six months after the earthquake, the "espartal" also showed no evidence of being affected. However, in many areas the recolonization of areas flooded by winter rains by *Parastacus pugnax*, which is typically sweetwater, was found. The dominant presence of the remains of this shrimp (C. Valdovinos, personal obs) was found in many aquatic bird species observed in the riparian areas of the wetland. On the other hand, in the root zones of the "espartal" that before the earthquake constituted habitats for aquatic organisms, it was observed in some sectors that it was being colonized by lycosidae spiders, constructors of fabrics easily visible. Finally, in the same month of August, freshwater fish were recorded near the mouth of the estuary, a situation that had not previously been reported in the area. This is relevant since several of the reported species present conservation problems (see Valdovinos 2006[a], b) and that would have been favored in the winter, due to the increase in the availability of freshwater habitat in the wetland.

5.2.3.5 Changes Registered 10 Months After the Earthquake

Within 10 months of the earthquake, some indicators showed practically no signs of recovery, but others are moving towards a new condition. In the last sampling it was found that the habitat conditions were maintained, such as the desiccation of the inner canals and the root habitats. However, the inner canals that irrigate the wetland, in which some pools isolated from stagnant water were conserved, were practically dried up in their totality in December.

Other habitat variables showed clear evidence of a slight return to the pre- earthquake condition. For example, an increase in the water mirror level in ca. 0.3 m, and thus an increase in the area of flooded bottoms and habitat availability for benthic organisms. In addition, there was an increase in the exchange with sea waters, which was expressed in slight fluctuations in tidal and salinity levels, more evident in the Tubul River than in the Raqui River. Associated with the above, there was an increase of the depth in the mouth of estuary, which facilitated the navigation and the interchange between the estuarine and marine waters. The increase in depth would also be associated with the extraction of sand with heavy machinery in this area, to allow the movement of boats. With respect to water quality, in the.

Sectors that remained flooded had a clear increase in the salinity, depth and changes of level and hydrodynamics associated with the tide cycles. This has favored the development of the aquatic biota in parts of the areas that were originally desiccated by the coastal uprising. In relation to the aquatic and terrestrial biota, during the 10 months of the earthquake, the defaunation of the desiccated areas was maintained. However, the increased recolonization of amphipods and polychaetes was maintained in the areas of the main dried up channels, associated with a return of the brackish water condition. There was no recolonization of *T. dombeii* and *E. kingii*, but of the crab *H. crenulatus*, which is indicative of a trend towards recovery of the estuary. Given the existence of brackish waters in the estuary in the last sampling, unlike the one observed in the August sampling, the presence of freshwater fish in the middle and lower part of the wetland was not recorded.

Benthic invertebrates from estuarine ecosystems inhabit environments where the water column is subject to constant changes due to regular factors (e.g. tides and storms), and more unpredictable or stochastic events (e.g. precipitation and wind) (Urbina et al. 2010). Thus, the different properties of the water column (e.g. temperature, salinity and seston) undergo strong changes in time and space. Salinity is one of the most obvious environmental factors in estuarine systems. In fact, salinity is so important in estuaries that it has come to be considered the "main ecological factor" (Kinne 1966), for its fundamental role in the dynamics and distribution of populations (Kinne 1971; Davenport et al. 1975; Bayer et al. 1976), and in the modulation of reproductive processes (Cunha et al. 1999) and behavioral ones (Spicer and Strömberg 2003), as well as many of the physical processes (Shuhong 2006; Urbina et al. 2010).

With respect to terrestrial vegetation, the "espartales" continued to show symptoms of an appropriate physiological state, even a massive flowering of *S. densiflora* was observed throughout the wetland. Another aspect recorded in the last sampling was the colonization of the bottoms that were desiccated by terrestrial vegetation that covered in some places up to 60% of the emerged terain.

5.2.4 Conservation of Wetland Biodiversity

The great extension of the Tubul-Raqui wetland, the most important one in the center and in the south of Chile; its high biodiversity and biological productivity, combined with a low degree of human disturbance, make this wetland one of the most important in Chile in terms of biodiversity conservation. Although severely affected by the February 2010 earthquake, it maintains properties that allows it to stay within the country's most important coastal wetlands. The wetland continues to provide nesting and shelter sites for numerous resident and migratory bird species, many of whom have conservation problems. This situation has been recognized at the regional level and has been identified as one of the six priority sites established in the Regional Strategy and Action Plan for the Conservation of Biodiversity of the Biobio Region.

The major anthropogenic threats to the conservation of the wetland and its environments have historically been bird hunting, and deforestation of the basins, which affects the sedimentation of the rivers that feed it. In relation to the above, the main measures adopted are, firstly, the hunting or capturing ban for amphibians, reptiles, birds and wild mammals, in a territory of 7822 ha. This ban is valid for 30 years from June 2006 and was established by the Supreme Decree No. 285 of the Agricultural and Livestock Service. The second measure of great importance was the declaration for conservation purposes of 350 ha of the Raqui island tax exemption estate, through the Supreme Decree No. 454 of the Ministry of National Assets, which aims to conserve habitats and their associated biota. A third measure that is currently being implemented, obviously the most important one because of its extension and ecosystem approach, corresponds to the wetland postulating as a Ramsar site, to form part of the network of wetlands of international importance. The total area requested to be declared as a Ramsar Site is 562 ha, of which 350 correspond to tax exemption land, and the other 212 are bodies of water in the rivers Tubul, Raqui and Las Peñas estuary, which correspond to the area of aquaculture concession owned by the Tubul Trade Association. This was granted in 1994 by the Directory of Maritime Territory and Merchant Marine, by the Supreme Decree No. 296. The lands surrounding the area being requested to be established as a Ramsar site are privately owned. It is clear that the designation of the wetland as a Ramsar site would be a major step forward for the conservation of this wetland, considering that their main objective is the conservation and wise use of wetlands through local and national actions, supported by international cooperation.

5.2.5 Conclusions

This chapter has presented a synthesis of the main ecosystem characteristics of the Tubul-Raqui wetland, as well as the most important changes in the wetland following the February 2010 earthquake.

Given the great extent of the Tubul-Raqui marsh, in addition to its high biodiversity and biological productivity, combined with a low degree of human disturbance, this wetland corresponds to one of the most important in Chile in terms of biodiversity conservation.

Although severely affected by the February 2010 earthquake, it maintains properties that allow it to be within the country's most important coastal wetlands. The wetland continues to provide nesting and shelter sites for numerous resident and migratory bird species, many of which have conservation problems.

The main anthropogenic threats to the conservation of the wetland and its surroundings have historically been the hunting of birds and deforestation of the basins, which affects the sedimentation of the rivers that feed it.

As for the structure of the physical habitat, water quality and aquatic biota of the wetland, from the February 27, 2010 earthquake, a series of relevant environmental changes resulting from the earthquake occurred. Some of them occurred immediately during the earthquake, while others still continue to manifest.

The major changes in the wetland caused by the earthquake have resulted from its rising at ca. 1.6 m above sea level, which has led to the total drying up of the network of internal channels that irrigate the wetland, and partial drying of the main channels of the rivers Tubul and Raqui. This has also limited the exchange with the sea, generating a decrease in the salinity of the waters to the interior of the wetland.

The desiccation of an important part of the wetland's bottoms produced the mortality of benthic invertebrates that inhabited them. Many of them survived in the shallow areas where water was conserved, and have shown a tendency to recover their populations over time. However, the two most important benthic species for the artisanal fishery, "Pelillo" (*Gracilaria* spp.) and "navajuela" bivalve (*Ensis macha*) were severely affected and there is no evidence of any degree of recolonization.

The extensive saline or "spartan" pastures dominated by *Spartina densiflora* have shown no signs of being affected by the coastal uprising which is important, considering that it is a species of great relevance in the wetland, its coverage and biomass.

Although the wetland was severely affected by the earthquake, it already shows signs of recovery. It is clear that these conditions will not return to what they were prior to the February 27, 2010 earthquake, however, it will continue to constitute the main coastal wetland with "Espartales" of Central Chile and probably the temperate Pacific coast of South America.

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5.2.6 References

Adam, P. 1990. Saltmarsh Ecology. Cambridge: Cambridge University Press.

Alveal, K. 1988. Gracilaria de Tubul. Historia y significado de un recurso. Gayana Botánica 45: 119–140.

Bayne, B.L., C.J. Bayne, T.C. Carefoot, and R.J. Thompson. 1976. The physiological ecology of Mytilus californianus Conrad. 1. Metabolism and energy balance. Oecologia 22: 211–228.

Begon, M., J.L. Harper, and C.R. Towsend. 1987. Ecología, individuos, poblaciones y comunidades. 2da ed. Barcelona: Omega.

Bertrán, C. 1989. Zonación I dinámica temporal de la macroinfauna intermareal en el estuario del río Lingue (Valdivia, Chile). Revista Chilena de Historia Natural. 62: 19–32.

Biró, L. 1979. Contribuciónal Conocimiento de la Formación Tubul, Plioceno Superior, Provincia de Arauco (37°14′ Lat. Sur), Chile. II Congreso Geológico Chileno 3: H33–H44.

Cabrera, A.L. 1970. Flora de la Provincia de Buenos Aires. Parte II. Ed. A.L. Cabrera, J.C. Hernández, and J.M. Caro. Buenos Aires: INTA.

Carrasco-lagos, P. 2003. Variaciones de la estructura de ensamble de aves a lo largo de un gradiente ambiental en el humedal Tubul-Raqui, VIII Región, Chile. Seminario de Investigación para optar al Grado de Licenciado en Biología, Facultad de Ciencias Naturales y Oceanográficas, 56, Universidad de Concepción.

———. 2004. Propuesta de manejo para la conservación del humedal Tubul-Raqui, VIII Región, Chile. Tesis para optar al título profesional de Biólogo, 76. Universidad de Concepción, Chile.

Carrasco-lagos, P., and M.C. Jiménez. 2009. Ficha Informativa de los Humedales de Ramsar

(FIR): Humedal Tubul-Raqui. Propuesta Unidad de Biodiversidad, 39, Departamento Protecciónde Recursos Naturales, CONAMA Regióndel Biobío.

Chapman, V.J. 1974. Salt marshes and salt desert of the world. 2da ed. Lehre: V von J Cramer.

———. 1977. In Introduction. En: Wet coastal ecosystems. Ecosystems of the world, ed. V.J. Chapman, 29. Amsterdam: Elsevier.

Chung, C.H. 1990. Twenty-five years of introduced Spartina anglica in China. In Spartina anglica – A research Rewiew, ed. A.J. Gray and P.E.M. Benham, 72–76. Institute of Terrestrial Ecology, Natural Environment research Council. China

Cisternas, M., A. Aranda, and I. Contreras. 2000. Reconocimiento y caracterización de la facies sedimentaria depositada por el Tsunami de 1960 en el estuario del río Maullín, Chile. Revista Geológica de Chile. 27: 3–11.

Clasing, E., T. Brey, R. Stead, J.M. Navarro, and G. Asencio. 1994. Population dynamics of Venus antiqua (Bivalvia: Veneracea) in the bahía de Yaldad, Isla de Chiloé, Southern Chile. Journal of Experimental Marine Biology and Ecology. 177: 171–186.

Conama. 2007. Solicitud de auto destinación de 350 hectáreas del Estuario Tubul- Raqui de propiedad del Ministerio de Bienes Nacionales, 22. Departamento de Recursos Naturales, CONAMA Región del Bío-Bío.

Constabel, S. 1993. Ambientes sedimentarios de los estuarios Tubul y Raqui, VIII Región, Chile. Tesis para optar al grado de Doctor en Ciencias Ambientales, 96, Universidad de Concepción.

Costa, C.S.B., and A.J. Davy. 1992. In Coastal saltmarsh communities of Latin America. En: Coastal Plant Communities of Latin America, ed. U. Seeliger, 179–199. Academic Press, Inc. USA

Cunha, M.R., J.C. Sorve, and M.H. Moreira. 1999. Spatial and seasonal changes of brackish peracaridan assemblages and their relation to some environmental Variables in two tidal channels of the Ria de Aveiro (NW Portugal). Marine Ecology Progress Series 190: 69–87.

Davenport, J., L.D. Gruffydd, and A.R. Beaumont. 1975. An apparatus to supply seawater of fluctuating salinity and its use in the study of the salinity tolerance of larvae of the scallop Pecten maximus L. Journal of the Marine Biological Association of the United Kingdom 55: 391–410.

Della-croce, N., and C. Valdovinos. 1994. Caracterización ambiental del área marina costera bajo la influencia de la cuenca hidrográfica del río Biobío, Chile central (1989–1992). En: El río Biobío y el área marina adyacente, ed. N. Della-Croce, 85–163. Italia: Univ. Di Genova.

Díaz-jaramillo, M., J.L. Ferreira, L.L. Amado, J. Ventura-lima, A. Martins, M.R. Retamal,

R. Urrutia, C. Bertrán, R. Barra, and J.M. Monserrat. 2010. Biomonitoring of antioxidant and oxidative stress responses in Perinereis gualpensis (Polychaeta: Nereididae) in Chilean estuarine regions under different anthropogenic pressure. Ecotoxicology and Environmental Safety 73: 515–523.

Eula. 2008. Guía de manejo para terreno fiscal con alto valor en biodiversidad en la Región del Bío-Bío. Sector humedal Tubul-Raqui. Informe técnico Centro de Ciencias Ambientales EULA, Universidad de Concepción. 143 pp.

Farías, M., G. Vargas, A. Tassara, S. Carrethier, S. Baize, D. Melnick, and K. Bataille. 2010. Land-Level Changes Produced by the Mw 8.8 2010 Chilean Earthquake. Science 329: 916. doi:10.1126/science.1192094.

Ferraris, F. 1981. Hoja Arauco– Lebu, Regióndel Biobío, escala 1: 250.000. Mapas Geológicos Preliminares de Chile, N° 5, 10, Instituto de Investigaciones Geológicas.

Figueroa, R., and C. Valdovinos. 1997. Productividad de pastizales salinos del estuario Lenga

(Chile) a escala de paisaje ecológico: análisis de imágenes Landsat TM y experimentos in situ. Boletin de la Sociedad de Biología de Concepción, Chile 68: 7–11.

Gallardo, C.S., M. Filún, and C. Manque. 2006. Kingiella chilenica (Bivalvia: Cyamiidae); populationdynamics, rates of survival, embryoproductionandannual recruitment of a semelparous brooding clam. Journal of the Marine Biological Association of the United Kingdom 86: 757–766.

Grandjean, M.M. 1985. Efecto de la temperatura sobre el balance energético y el crecimiento en Hemigrapsus crenulatus (Milne-Edwards, 1837) bajo condiciones de laboratorio. Tesis de magíster. Universidad Austral de Chile, Valdivia, Chile.

Habit, E., and P. Victoriano. 2005. Peces de agua dulce de la Cordillera de la Costa. En: Historia, Biodiversidad y Ecología de la Cordillera de la Costa de Chile, eds. C. Smith-Ramírez, J. Armesto and C. Valdovinos, 392–406. Santiago: Editorial Universitaria.

Jaramillo, E., H. Contreras, and C. Duarte. 2007. Community structure of the macroinfauna inhabiting tidal flats characterized by the presence of different species of burrowing bivalves in Southern Chile. Hydrobiology 580: 85–96.

Jiménez, J. 1996. Aspectos ecológicos en Spartina densiflora Brong. Memoria para optar al grado de doctor en Biología, Facultad de Biología, Universidad de Sevilla, España.

Kinne, O. 1966. Physiological aspects of animal life in estuaries with special reference to salinity. Netherlands Journal of Sea Research 3: 222–244.

Kinne o. 1971. Salinity, animals: invertebrates. Environmental factors. Part 2. In A comprehensive, integrated treatise on life in oceans and coastal waters. Volume I. Marine Ecology 1: 821–995.

Long, S.P., and C.F. Mason. 1983. Saltmarsh Ecology. Glasgow: Blackie.

Mardones, M. 1971. Contribución al estudio de la ganadería. Análisis del libro de cuentas de la feria agrícola-ganadera de Arauco, Concepción, Chile, 4-16. Universidad de Concepción.

Melnick, D., B. Bookhagen, H. Echtler, and M. Strecker. 2006. Coastal deformation and great subduction earthquakes, Isla Santa María, Chile (37°S). Geological Society of America Bulletin. 118: 1463–1480.

Mobberley. 1956. Taxonomy and distribution of the genus Spartina. Iowa State College journal of science 30: 471–574.

Navarro, J., E. Clasing, M. Lardies, and R. Stead. 2008. Feeding behavior of the infaunal bivalve *Tagelus dombeii* (Lamarck, 1818). Suspension vs. Deposit feeding. Revista de Biología Marina y Oceanografía. 43: 599–605.

Nielsen, S.N., and C. Valdovinos. 2008. Early Pleistocene Mollusks of the Tubul Formation, South-Central Chile. Nautilus 122: 201–216.

Parada, M. 2008. Proyecto Eólico Raqui – Quidico: Evaluación Ornitológica. Informe técnico de biornat Ltda., para Arauco Generación S. A, 54

Pérez-losada, M., C. Jara, G. Bound-backup, and K. Crandall. 2002. Conservation phylogenetics of Chilean freshwater crabs Aegla (Anomura Aeglidae): Assignig priorities for aquatic habitat protection. Biological Conservation 105: 345–353.

Pineda, V. 1985. Evolución Paleogeográfica de la Cuenca Sedimentaria Cretácico– Terciaria de Arauco. Geología y Recursos Minerales de Chile, 438 pp. Chile: Editorial de la Universidad de Concepción.

Ramsar. 2006. Manual de la Convención de Ramsar: Guía a la Convención sobre los Humedales (Ramsar, Irán, 1971), 4ª. Edición. Secretaría de la Convención de Ramsar, 124, Gland (Suiza).

Retamal, M.A. 1967. Estudios bionómicos en una población de Hemigrapsus crenulatus (H.

Milne Edwards), 1837, Lenga (36° Lat. S.). Informe de tesis para optar al título de Licenciado en Biología, 68. Instituto Central de Biología, Departamento de Zoología, Universidad de Concepción.

———. 1981. Catálogo ilustrado de los crustáceos de Chile. Gayana Zoológica. 44: 1–110.

Servicio agrícolayganadero (SAG). 2009. Ley de caza y su reglamento. Legislación de fauna silvestre. Ministerio de Agricultura. Servicio Agrícola y Ganadero. División de Protección de los Recursos Naturales Renovables, 10 Ed., Santiago.

Sanmartín, C., D. Contreras, J. Sanmartín, and C. Ramírez. 1992. Vegetacióndelasma- rismas del centro-sur de Chile. Revista Chilena de Historia Natural 65: 327–342.

Shuhong, Z. 2006. The influence of salinity, rhythm and day length on feeding behavior in Meretrix Linnaeus. Aquaculture 252: 584–590.

Spicer, J.I., and J.O. Stromberg. 2003. Metabolic responses to low salinity of the shipworm Teredo navalis (L.). Sarsia 88: 302–305.

Strahler, A.N. 1981. Geografía Física, 767. Barcelona: Editorial Omega S. A.

Stuardo, J., and C. Valdovinos. 1989. Estuarios y lagunas costeras: Ecosistemas importantes de Chile Central. Ambiente y Desarrollo. 5: 107–115.

Stuardo, J., C. Valdovinos, R. Figueroa, and A. Occhipinti. 1992. Ambientes costeros del Golfo de Arauco y áreas adyacentes. Publ. EULA-Chile. Ser. Mon. Cient. 9: 1–157.

Taylor, H., and D. Seneviratna. 2005. Ontogeny of salinity tolerance and hyper-osmoregulation in embryos of intertidal crabs *Hemigrapsus edwarsii* and *Hemigrapsus crenulatus* (Decapoda, Grapsidae): survival of acute hyposaline exposure. Comparative Biochemistry and Physiology. Part A 140:495–505.

Urbina, M., K. Paschke, P. Gebauer, and O. Chaparro. 2010. Physiological energetics of the estuarine crab *Hemigrapsus crenulatus* (Crustacea: Decapoda: Varunidae): responses to different salinity levels. Journal of the Marine Biological Association of the United Kingdom. 90: 267–273.

Valdovinos, C. 2001. Biodiversidad en fondos blandos sublitorales: Macroinvertebrados del Golfo de Arauco (Chile). En Sustentabilidad de la Biodiversidad: Bases científico-técnicas, teorizaciones y proyecciones, ed. K. Alveal and T. Antezana, Univ. De Concepción. 33:635–662.

———. 2004. Ecosistemas estuarinos. En Biología marina y oceanografía: Conceptos y procesos, ed. C. Werlinger, Trama Impresores S. A., Chile. 2:395–414.

———. 2006ª. Humedales dulceacuícolas y biodiversidad. En Atlas social y ambiental El Humedal costero Tubul-Raqui: un ecosistema chileno de alto valor de conservación • CAPÍTULO 10 Del área metropolitana de Concepción. Región del Bio-Bío, Chile, eds. J. Rojas, G. Azócar, M.D. Muñoz, C. Vega, A. Kindler and S. Kabisch, 104–124. Chile: Editorial Universidad de Concepción.

———. 2006b. Invertebrados dulceacuícolas. En Conama, eds. Biodiversidad de Chile, 204–225. Patrimonio y desafíos. Santiago de Chile: Ocho Libros Editores.

Valdovinos, C., and N. Sandoval. 2011. Cambios ambientales del humedal Tubul- Raqui derivado del alzamiento cosísmico y Tsunami, asociado al terremoto Mw 8,8. Informe técnico de la Unidad de Sistemas Acuáticos, del Centro de Ciencias Ambientales EULA, Universidad de Concepción, Chile.

Valiela, I., E. Kinney, J. Culberston, E. Peacock, and V.A. Smith. 2009. Global losses of mangroves and saltmarshes. En: Carlos M. Duarte, Ed. Global loss of coastal hábitats. Fundación BBVA, Bilbao, España. 4:107–138.

Vásquez, D. 2009. Delimitación y zonificación de los humedales costeros de Lenga y Tubul-Raqui: Orientaciones para el Ordenamiento Territorial de la Región del Bío – Bío, Tesis para optar al título de Geógrafo, Universidad de Concepción, 66–85.

Vergara, O., P. Carrasco-pagos, M.F. Saavedra, and J.C. Ortiz. 2008. Fauna del humedal Tubul- Raqui, Provincia de Arauco. Sitio Prioritario para la Conservación de la Biodiversidad, 72. Concepción: CONAMA Regióndel Biobío. Ed. Impresos del Sur.

Werlinger, C., and K. Alveal. 1988. Evaluación de algas en ambientes restringidos del Golfo de Arauco(Chile): Punta Fuerte Viejo a Río Tubul. Gayana Botánica. 45: 461–474.

CAPITULO 3:

EVALUACIÓN DE PERTURBACIÓN NATURAL MEDIANTE BIOINDICADORES BENTÓNICOS EN HUMEDALES COSTEROS

Basado en:

Impacts of coseismic uplift caused by the 2010 8.8 Mw earthquake on the macrobenthic community of the Tabul-Raqui Saltmarsh (central-south Chile). *Estuarine coastal and shelf science*. Doi.org/10.1016/j.ecss.2019.106278

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5.3 Capítulo 3: Impacts of coseismic uplift caused by the 2010 8.8 Mw earthquake on the macrobenthic community of the Tabul-Raqui Saltmarsh (central-south Chile)

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Abstract Coseismic uplift, as caused by high-magnitude earthquakes, can modify shoreline morphologies and the functioning of coastal wetlands. This phenomenon occurred with the 8.8-Richter scale earthquake that affected central-south Chile in 2010. The recorded coseismic uplift was 1.6 m.a.s.l. significantly changed the Tubul-Raqui Saltmarsh. The most important impact of this event was decreased marine intrusion, which, in turn, led to desiccation within the saltmarsh and, consequently, the death of aquatic organisms. This study recorded the effects that physical/chemical changes in water quality and the sedimentary environment had on the macrobenthic community (> 500 μm) 2, 6, and 10 months after the uplift event, with data compared against historical records. Non-metric multidimensional scaling evaluated changes in the biological community, while principal components analysis was used to assess environmental changes. Both matrices were adjusted through correlation. Significant pre- versus post-earthquake modifications were found at sites closest to the estuary inlet. The most significantly affected macroinvertebrate was *Paracorophium hartmannorum*. The most tolerant taxa to environmental perturbations (i.e., Diptera, Annelid, and Polychaeta) surpassed pre-earthquake abundance records after just ten months, whereas the most sensitive taxa were not found after the earthquake. Most (81.8%) variables of water quality (i.e., total suspended/inorganic/organic solids and chlorophyll-a), as well as the sedimentary environment (i.e., sediment redox potential, fine fraction, and area of emerged bed), were significantly correlated with the macrobenthic community. The results of this study show the resilience capacity of important components of a saltmarsh after a major natural disturbance.

Resumen El levantamiento cosísmico, como el causado por los terremotos de gran magnitud, pueden modificar la morfología litoral y el funcionamiento de los humedales costeros. Este fenómeno se produjo con el terremoto de 8,8 Richter que afectó al centro-sur de Chile en 2010. El levantamiento cosísmico registrado fue de 1,6 m.s.n.m. el cual cambió significativamente la marisma de Tubul-Raqui. El impacto más importante de este evento fue la disminución de la intrusión marina, que a su vez provocó la desecación dentro de la marisma y, en consecuencia, la muerte de organismos acuáticos. En este studio, se registraron los efectos que los cambios físico-químicos en la calidad del agua y el del sedimentario por medio de la comunidad macrobentónica (> 500 μm) a 2, 6 y 10 meses después del evento, los datos obtenidos fueron comparados con los registros históricos. El escalamiento multidimensional no métrico evaluó los cambios en la comunidad biológica, mientras que el análisis de los componentes principales se utilizó para evaluar los cambios ambientales. Ambas matrices se ajustaron mediante correlación. Se encontraron diferencias significativas entre los periodos pre y post terremoto en los sitios más cercanos a la entrada del estuario. Los macroinvertebrados más significativamente afectados fueron los anfípodos (*Paracorophium hartmannorum*), los taxones más tolerantes a las perturbaciones ambientales (e.g Dípteros, Anélidos y Poliquetos) superaron los registros de abundancia previos al terremoto después de diez meses de la perturbación, mientras que los taxones más sensibles no se encontraron después del terremoto. La mayoría (81,8%) de las variables de calidad del agua (sólidos suspendidos totales /inorgánicos/orgánicos y clorofila-a), así como los del sedimento (potencial redox, fracción fina y área del lecho emergido), se correlacionaron significativamente con la comunidad macrobentónica. Los resultados de este estudio muestran la capacidad de resistencia de importantes componentes de una marisma salina después de una perturbación natural de gran escala.

Keywords*:* Coseismic uplift, Macroinvertebrates, Sediment, Water quality, Perturbation, Wetland.

5.3.1 Introduction

Coastal countries close to active subduction zones of tectonic plates are frequently affected by earthquakes and tsunamis (Scholz, 1998; McCaffrey et al. 2007; Castaños and Lomnitz, 2012; Katsumata, 2017; McCaffrey et al. 2007; Scholz, 1998). These events can result in deformations of the continental shelf, such as coseismic uplift (Quezada et al. 2012), which consists in a lifting of the continent, sometimes up to 2 m in height. In the last 60 years, this phenomenon has been scarcely described, but records do exist for the following earthquakes: Chile in 1960 (Barrientos et al. 1992), 1985 (Castilla and Oliva, 1990), 1995 (Ortlieb et al. 1996), and 2010 (Melnick et al. 2012); Alaska, USA in 1964 (Cohen, 1996); Mexico in 1985 (Bodin and Klinger, 1986); Papua New Guinea in 1992 (Pandolfi et al. 1994); California, USA in 1992 (Carver et al. 1994); Algeria in 2003 (Meghraoui et al. 2004); Sumatra, Indonesia in 2004 and 2005 (Tobita et al. 2006); and Kaikoura, New Zealand in 2016 (Shi et al. 2017).

Along the western limit of South America, coseismic uplifting is caused by the Nazca Plate, which is subducting below the South America Plate (Briggs, 2016; Cahill and Isacks, 1992; Quezada et al. 2012). Following earthquakes with a greater than 7.5 moment magnitude (Mw), large variations have been recorded for the coastal morphology of this region, changes that consequently have significant impacts on coastal ecosystems such as estuaries, marshes, and coastal lagoons, among others (Castilla et al. 2010; Jaramillo et al. 2012).

On February 27th, 2010, south-central Chile was hit by an 8.8 Mw earthquake and subsequent tsunami (Vargas et al. 2011; Martínez et al. 2012; Quezada et al. 2012; Vargas et al. 2011). In areas close to the epicenter (Figura 5.3-1), the continental shelf uplifted more than 2 m, causing the death of nearly all intertidal organisms (Farías et al. 2010). Also affected was the Tubul-Raqui Saltmarsh, located 137.4 km from the rupture zone (Figura 5.3-1). This saltmarsh was uplifted 1.6 m above sea level (m.a.s.l.), and the soil shifts caused by the tsunami significantly decreased the pre-perturbation flow of water that existed between the Tubul-Raqui Rivers, i.e., the marsh, and the sea (Valdovinos et al. 2012) (Figura 5.3-2).

The coastal Tubul-Raqui Saltmarsh serves as a refuge, feeding, and nesting site for a wide diversity of birds (Valdovinos et al. 2010). Up to 2010, this saltmarsh was fished and harvested by locals for commercially valuable organisms (e.g. *Gracilaria spp*., *Tagelus dombeii*, *Ensis macha*). Following the decrease in marine intrusion, as caused by the 2010 coseismic uplift, the local community and scientists discovered that the abundance of these organisms significantly decreased (Valdovinos et al. 2012; Marín et al. 2014). Nevertheless, the possible effects of the uplifting event on benthic macrofauna (> 500 µm) present in the water and sediments of the saltmarsh were unknown.

Benthic macroinvertebrates are an important food source for the birds and fish of aquatic ecosystems (Allan and Castillo, 2007). Due to scarce vagility and reproductive cycles, these organisms additionally serve as a good indicator of environmental status (Resh et al. 1993; Fenoglio et al. 2002; Suriano and Fonseca-Gessner, 2013). Indeed, benthic macroinvertebrates have been widely used to evaluate the status of perturbed ecosystems (Moreno and Callisto, 2006; Batalla Salvarrey et al. 2014; Sukumaran et al. 2014). Therefore, this study assessed the abundance and richness of benthonic species to determine the degree to which ecosystem habitats were modified following the coseismic uplift of 2010. For this, multivariate analyses were conducted 2, 3, and 6 months after the event. The obtained results were then compared with records from up to one year prior to the coseismic uplift. To evaluate the influence of abiotic variables on the biological community, non-metric multidimensional scaling (NMDS) of biological matrix axes was performed between the water quality-habitat matrix.

5.3.2 Materials and methods

Study area

The Tabul-Raqui Saltmarsh is located in the Arauco Province of the Biobio Region (Figura 5.3-1), Chile (37°13´S; 73°26´W). The saltmarsh is comprised of the homonymous Tubul and Raqui Rivers, which are known for a pluvial regime and for jointly discharging into the southern part of the Gulf of Arauco, the dominant winds and tides of which originate from the northeast. Halophytes are the predominant vegetation of the saltmarsh, and 80% of vegetation is the species *Spartina densiflora*. The dense, wide coverage of this grass provides a complex channel network for the flow of brackish water, i.e., a fresh-saltwater mix of both rivers and marine intrusion. Prior to 2010, seawater advanced inland 8 to 10 km during high tide, depending on the season.

To evaluate the changes produced by coseismic uplifting of the coastal saltmarsh, physical, chemical, and biological analyses were conducted in April, August, and December 2010 (i.e., post-earthquake). Ten study sites were sampled at each time-point (Figura 5.3-1, Tabla 5.3-4). All of the established study sites had historical, pre-earthquake records for biological data and water quality. The data from 2008 and 2009 were used for comparative purposes.

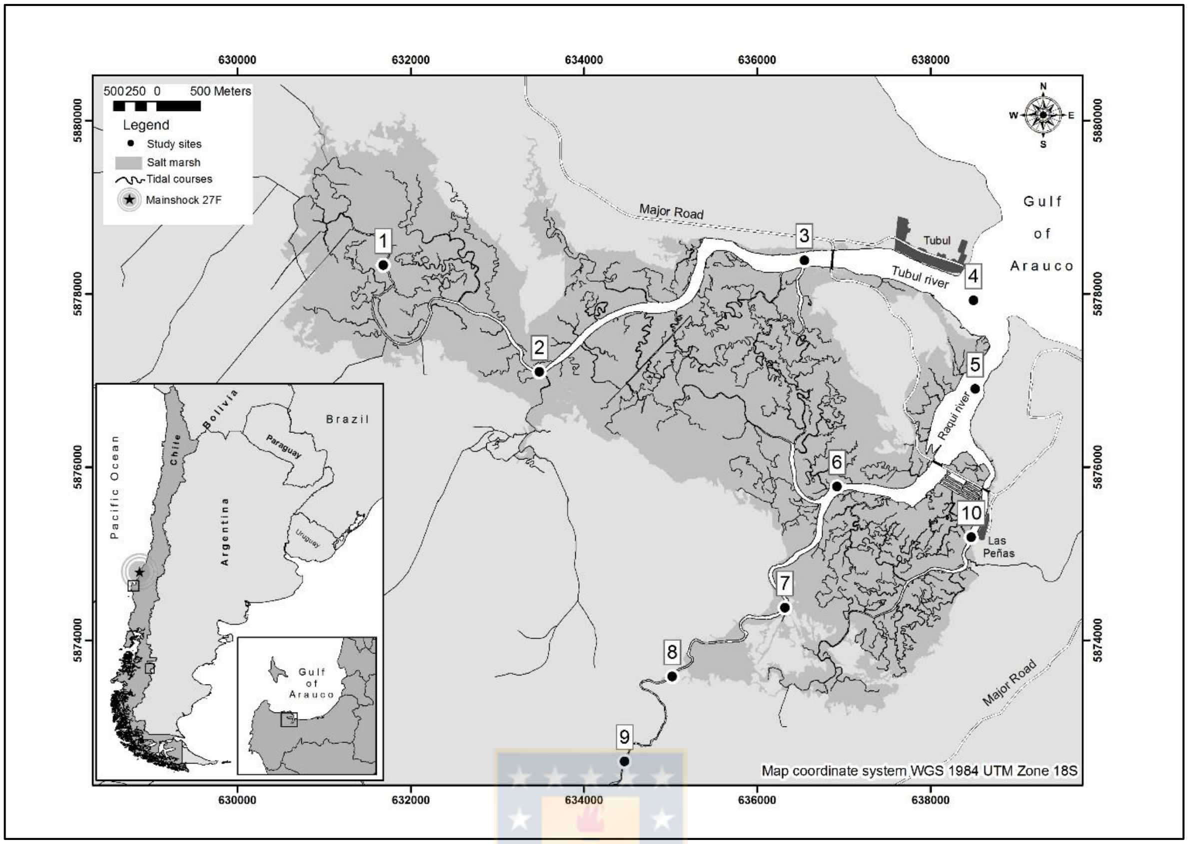

Figura 5.3-1 Sampling sites in the Tubul-Raqui Saltmarsh, proximal to the Gulf of Arauco, central-south Chile.

Sampling and analytical methods

Macrobenthic organisms (> 500 μm) were collected from each study site. On the first sampling date (i.e., April 2010, three months after the earthquake/tsunami), the study area was still unstable. Given this, 0.0084 m^2 core samples were collected along the shorelines of the Tubul and Raqui Rivers, with four replicates for each site. On posterior sampling dates, the study sites were sampled using a Van-Veen dredge (0.025 m^2 mouth opening). Four samples were collected per site, with a distance of 4 m between each replicate. The collected material was sieved *in situ* with a 0.5 mm mesh net, placed in labeled bags, and fixed with 70% ethanol.

Organisms within the collected material were identified hours later in the laboratory to the lowest possible taxonomic level, used literature of Fauchald (1977), Osorio (2002), Dominguez and Fernández (2009). Identifications were made using a stereomicroscope (Stremi SV8, Carl Zeiss) with cold light (KL1500-ZY, Schott). From this analysis, the richness and abundance of organisms, by study site, were determined. These data were standardized to individuals per square meter (N/m^2).

The physical habitat was characterized through fine fractions in sediment samples, which were collected using the same Van-Veen grab. The redox potential of the soil was measured *in situ* at each study site with a redox potential electrode submerged in the surface layer of sediment (20 mm depth). Maximum channel depth was estimated using metric tape measures. Three depth measurements were taken per site and averaged together to account for possible measurement error, specifically controlling for the possibility of the tape measure sinking into the channel bed, which was still unstable in the aftermath of the earthquake. In records available from 2008 and 2009, measurements of channel depth were also averaged. Finally, fully drained and emerged zones were measured during high tide with a metric tape measure or GPS, depending on the study site. Measurements were taken along one 15 m wide transect and considered the distances between (i) the exposed roots of S. densiflora and (ii) the upper limit of high tide. Emerged areas were expressed as a percentage of the total surface for the respective transect (Figura 5.3-4). To complement the recorded measurements, the April 2010 sampling time-point also included photographs taken using a remote-controlled drone. The photographs were used to verify the representativeness of the measurements taken along the transects. Prior to each drone flight, a 1 x 10 m rug was placed on nearby ground to serve as a reference for aerial photographs.

Chemical changes in water quality were determined during high tide using a multiparameter data sonde (Hydrolab DS5, OTT Hydromet) (Tabla 5.3-6). The following data were recorded: temperature, pH, salinity (measured in PSU), dissolved oxygen, and chlorophyll-a (Turner-Designs sensor). Furthermore, water samples were collected directly from the water surface in plastic containers, according to American Public Health Association standards - APHA (Eaton et al. 1998). Ammonium content was quantified within the first eight hours after water collection using the 4500-NH_3 F method, while parameters for total phosphorous, total nitrogen, and suspended solids (total, organic, and inorganic) were analyzed within the first

24 h after collection using the 4500-P, 4500-N, 2540 D, and 2540 E APHA methods, respectively.

Statistical análisis

All selected study sites (i.e., pre- and post-earthquake) were evaluated through biological, chemical, and physical variables. For better result interpretation, the sites were grouped into zones according to distance from the ocean inlet and historical traits of water quality (Valdovinos et al. 2012). The zone farthest from the ocean inlet grouped together sites 1, 8, and 9 and was termed the Freshwater Zone. The second zone, denominated the Mixed Zone, included sites 2, 6, 7, and 10, while sites 3, 4, and 5, all proximal to the ocean inlet, were grouped into the so-termed Estuary Zone (Figura 5.3-1).

Biological data were assessed through a square root-transformed abundance matrix. A Bray-Curtis similarity analysis was used to assess the transformed data, and pre- versus post-earthquake changes were evaluated through clustering analysis. The data were then ordered using NMDS in the PRIMER 6.0 program (Clarke and Gorley, 2006). Similarity profile analysis (5,000 permutations for the mean similarity profile and 999 permutations for the simulated profile) was used to detect significant differences ($p < 0.05$) between the pre- and post-earthquake groups. To evaluate the contribution of each species in the significantly different groups (represented in a cluster), similarity percentage analysis was conducted. An analysis of similarities test, i.e., a nonparametric permutation (randomization) procedure, was used to estimate any significant pre- versus post-earthquake variations between the benthic invertebrate groups found in the three zones. The R value was used to assess the direction of significant differences. Finally, significant changes among the most abundant species from the zones affected by seismic uplifting were subjected to permutated ANOVA in the R software (Oksanen et al. 2016).

Physical variables of the habitat and chemical variables of water quality were evaluated using principal components analysis (PCA) on a matrix that was previously $Log_{10}(x+1)$ transformed and normalized. Each principal component was correlated with the environmental variables, thereby establishing the relationship degree of each with the principal components. Variables with an $r \geq 0.8$ were selected. Finally, the abiotic matrices (i.e., physical variables and water quality) were correlated with the NMDS axes of the biological communities. The correlation was performed with the Vegan Packet in the R software (Oksanen et al. 2016).

5.3.3 Results

5.3.3.1 Abiotic conditions

Temporal variations in the physical and chemical parameters of water quality and in physical factors of the habitat over the course of the study period are shown in Figura 5.3-3. Temperatures ranged between 11.9-15.6 °C (pre-earthquake) and 11.2-18.5 °C (post-earthquake). The highest temperature was recorded in December 2010 in the Mixed Zone (18.5 °C; Fig. 3a). The salinity of the study area was influenced primarily by the coastal uplift, which decreased the inflow of seawater towards the continent. This was reflected by the salinity results, which varied from 0` to 0.1 PSU at all evaluated study sites in August 2010 (Figura 5.3-3b). Among all parameters, chlorophyll-a was one of the most variable, with a historic record of 15.32 µg/L recorded in December 2010 for study site 10 in the Mixed Zone. However, the Estuary Zone presented the highest average chlorophyll-a values in April 2010 (Fig. 3k). A similar trend was found for dissolved oxygen values in the Mixed and Estuary Zones. Namely, pre-earthquake values at all sites were ≥ 9.2 mg/L, but, following the seismic uplifting event, values sharply decreased (4.8-9.7 mg/L) in August 2010 before somewhat recovering in December 2010 (7.6-9.9 mg/L) (Fig. 3d). Pre-earthquake water pH was ≥ 7.0. In April 2010, the Freshwater and Mixed Zones presented minimum pH values of 6.1, but levels recovered by December 2010, with all study sites presenting pH ≥ 7.5 (Fig. 3c). Ammonium (NH_4^+) levels followed a pattern similar to chlorophyll-a. Specifically, ammonium considerable increased two months after the seismic uplift, with the obtained values (0.20-0.52 mg/L) contrasting with the pre-earthquake records (i.e., < 0.09 mg/L) (Figura 5.3-3h).

Historic measurements of suspended solids (total, inorganic, and organic) were recorded in April 2010 for all of the evaluated zones (Figura 5.3-3e-g). The highest values were 80.20 mg/L (total), 63.60 mg/L (inorganic), and 16.60 mg/L (organic) (Table S3). While these values did decrease by six months after the uplift event, the taken measurements were always greater than pre-earthquake records. Notably, suspended solids measurements were particularly elevated at ten months post-earthquake in the Estuary Zone. Nutrient values exhibit a trend similar to the parameters of water quality, i.e., a sharp increase in April 2010 before decreasing in August 2010 and increasing again in December 2010 (Figura 5.3-3h-j). Regarding total phosphorous, sites from the Mixed Zone showed the highest average increase (1.04 mg/L on average), with site 2 of this zone presenting the highest recorded total phosphorous levels in April 2010. In contrast, sites from the Freshwater Zone, sites farthest from the ocean inlet presented the lowest nutrient values. Nevertheless, total nitrogen levels only slightly varied between the Freshwater Zone and the Mixed/Estuary Zones, with the recorded ranges for the three zones being 0.30-0.92 mg/L pre-earthquake and 0.09-2.11(mg/L) post-earthquake.

Regarding habitat characteristics, the average area of emerged channel bed evidenced the most visually impactful change (Figura 5.3-2 and Figura 5.3-3l, Tabla 5.3-5). Prior to the coseismic uplift, saltwater intrusion reached approximately 10 km upriver for both the Tubul and Raqui Rivers. The post-earthquake coastal altitude and soil shifts caused by the tsunami impeded the inflow of saltwater to the saltmarsh, causing desiccation and, as such, channel bed emergence in the zones most influenced by marine intrusion (i.e., the Mixed and Estuary Zones). Specifically, emerged zones increased 0 m^2 to 3.128 m^2 on average in the Estuary Zone in April 2010, whereas the Freshwater Zone did not exhibit notable alterations in this variable. The effects of desiccation were also reflected in measurements of maximum channel depth during high tide (Fig. 3m). Prior to the earthquake, maximum depth in the Mixed Zone (site 2) was 2.3 m, but after the earthquake, the maximum recorded depth never surpassed 1.2 m. As with all measured habitat variables, the Freshwater Zone presented minimal changes in channel depth (Tabla 5.3-5). Regarding the fine fraction in sediment, variation was low (Figura 5.3-3n). The most notable change was found for the Estuary Zone, which had pre-earthquake fine fraction values of 3-96% and post-earthquake values of 5-99%. Finally, redox potential of the sediments showed historic lows in April 2010 for the Estuary and Mixed Zones (Figura 5.3-3o), with both zones having pre-earthquake values between -95 mV and -210 mV, but post-earthquake values between -95 mV and -285 mV.

Figura 5.3-2. Mouth of the Raqui River (A) in 2009, pre-earthquake (Courtesy Google Earth; 18/10/2009) and (B) in April 2010, post-earthquake.

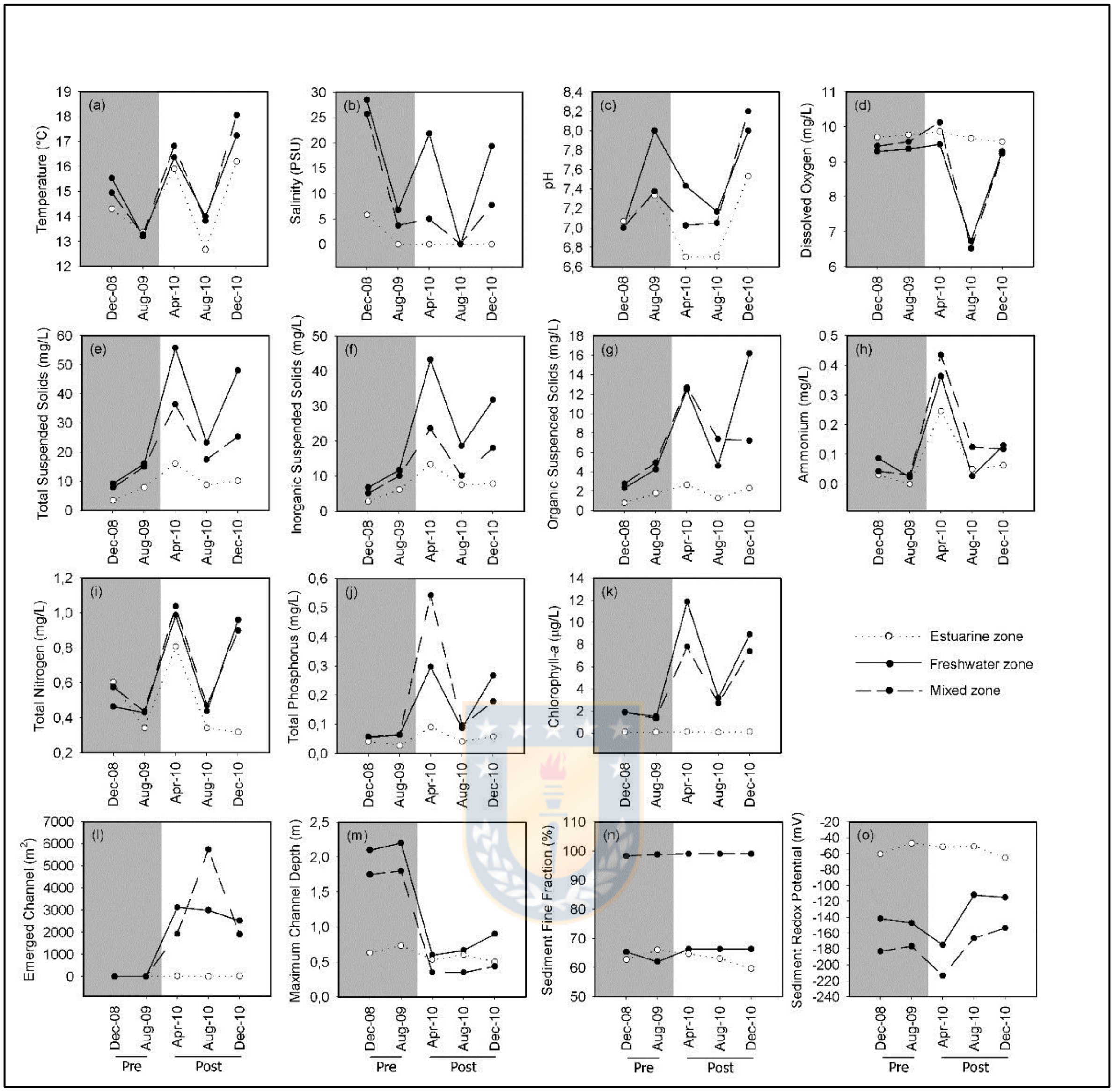

Figura 5.3-3 Temporal variations in parameters of water quality (a-k) and physical characteristics of the habitat (l-o), with pre-earthquake (August 2008 and December 2009) and post-earthquake (April, August, and December 2010). Each graph shows the average of data collected for sites within the Estuary, Mixed, and Freshwater Zones.

5.3.3.2 Macrobenthic community

Historically, 21 macrobenthic taxa have been identified in the Tubul-Raqui Saltmarsh. Maximum total richness pre-earthquake was 16 species (August 2008). Total richness post-earthquake averaged 9.3 taxa. The lowest richness values were recorded in April 2010 for all three zones (Figura 5.3-4, Figura 5.3-5), while maximum richness (i.e., 11 species) was recorded in December 2008, August 2009 and December 2008, 2009 and 2010 (Tabla 5.3-7). Pre-earthquake species abundance ranged, on average, from 1,105 ind./m^2 to 5,169 ind./m^2, a contrast to the post-earthquake average range of 912 ind./m^2 to 8,102 ind./m^2. Variations were similar across the three zones, and, as with richness, the lowest values were recorded in April 2010, just two months after the earthquake (Figura 5.3-3b). Regarding species dominance, the most abundance groups pre-earthquake were polychaetes (55.7% *Prionospio* (*Minuspio*) *patagonica*) and amphipods (29.5% *Paracorophium hartmannorum*). These values changed post-earthquake, with polychaetes dominating 42.7% *P*. (*M*) *patagonica* and 18.7% *Perinereis gualpensis*) (Tabla 5.3-1).

Evenness (J´) evidenced differences between the evaluated zones, as compared to the tendencies observed for the other indicators (i.e., richness and abundance). In April 2010, the Mixed Zone presented the maximum recorded value for evenness (0.89), whereas the Freshwater Zone presented a historic low (0.24). In turn, the Estuary Zone evidenced a gradual increase in evenness from December 2008 to December 2010 (Figura 5.3-4d). Diversity, as determined by the Shannon-Wiener Index (H´), showed similarities between three zones, most notably with a sharp decrease at two months post-earthquake (Figura 5.3-4c). The Estuary and Freshwater Zones decreased in richness when comparing pre-earthquake (average ranges of 0.87-0.95 and 0.95-1.21, respectively) and post-earthquake values (0.84 and 1.15 average maximums, respectively). Study site 1 (Freshwater Zone) presented the highest pre-earthquake diversity (August 2009), whereas the highest diversity post-earthquake was found at site 6 (Mixed Zone) (August 2010) (Figura 5.3-4 and Tabla 5.3-7).

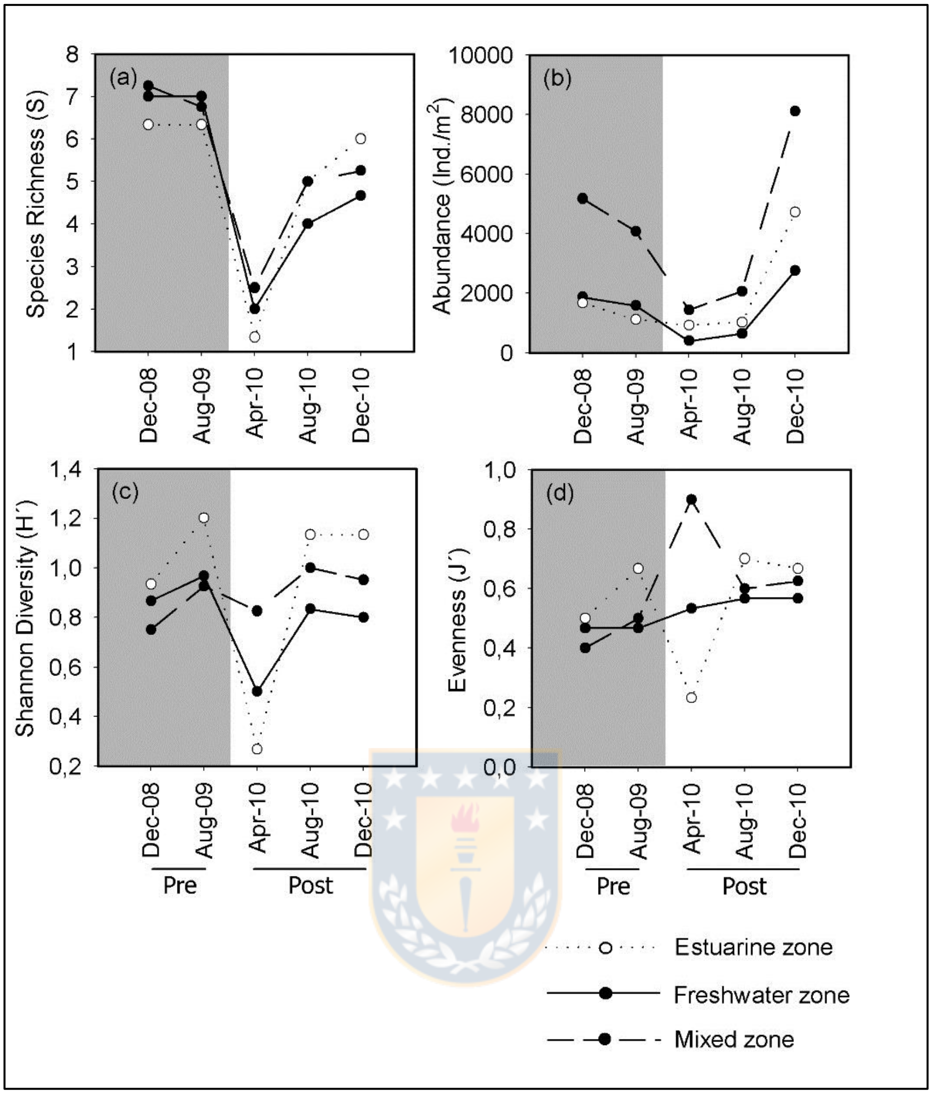

Figura 5.3-4. Temporal variations in (A) species richness, (B) macrobenthic abundance, (C) Shannon diversity (H'), and (D) evenness (J'). Each graph shows the average of data collected for sites within the Estuary (solid line), Mixed (dashed line), and Freshwater Zones (dotted line).

The one-way analysis of similarities evidenced significant differences between the Freshwater Zone and Estuary/Mixed Zones (global R = 0.531, $p = 0.001$). The same analysis underscored pre- versus post-earthquake differences for the Mixed and Estuary Zones (global R = 0.105, $p = 0.03$). Cluster analysis of the three zones revealed that macroinvertebrate community abundance did not significantly differ pre- versus post-earthquake for the Freshwater Zone (Group A, Figura 5.3-5), and, furthermore, the Freshwater Zone was dissimilar to the Estuary and Mixed Zones (Groups B-C, Figura 5.3-5). Group B in the cluster analysis principally grouped post-earthquake samplings, which were distanced from the primarily pre-earthquake samplings of Group C. The exceptions to these pre- versus post-earthquake groupings were: (i) Group B, pre-earthquake Estuary Zone site 4 (*), which was located at the estuary mouth; and (ii) Group C, post-earthquake Mixed Zone sites 6 (+) and 7 (*+) and post-earthquake Estuary Zone site 5 (++), which were sampled in December 2010.

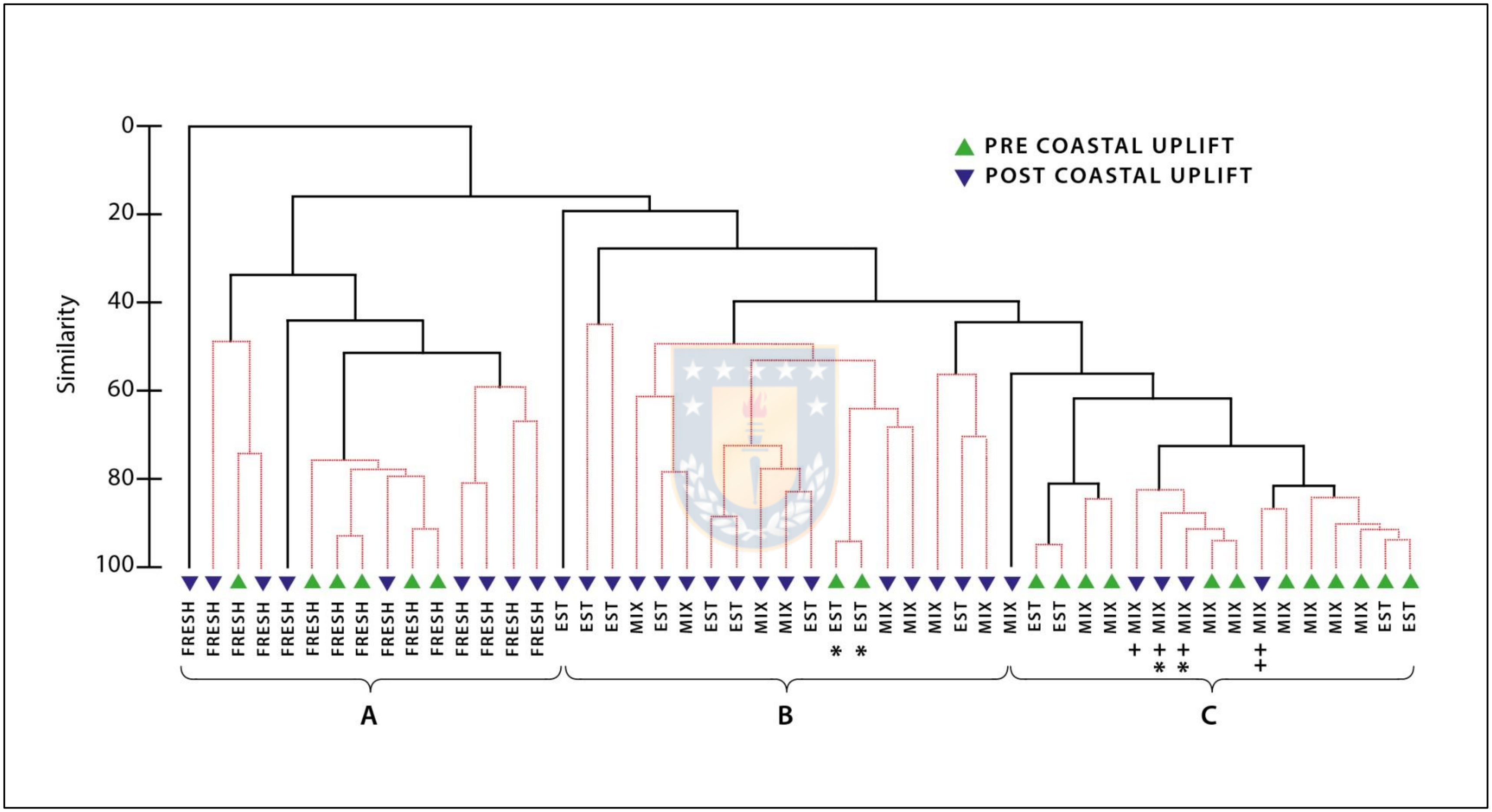

Figura 5.3-5. Spatial representation of richness (S) variations for benthic macroinvertebrates between the pre-earthquake (December 2008) and post-earthquake (April and December 2010) periods for each sampling site (1-10).

Regarding the contribution (%) of species to the macrobenthic assemblage (Figura 5.3-7, Tabla 5.3-1), the historically most abundant taxa had the highest contribution percentages. The similarity found between the pre-earthquake Group C and post-earthquake Group D was explained by the contributions of *P. (Minuspio) patagonica* (36.4% and 42.7%, respectively). Dissimilarity analysis between the pre- and post-earthquake periods revealed a 23.7% assemblage contribution from *P. hartmannorum*.

Other abundant species that were present in all pre- and post-earthquake samplings were *P. gualpensis*, *Chironomidae spp*., Oligochaeta indet., and Capitellidae indet. By contrast, species from the Tipulidae, Psychodidae, and Ceratopogonidae families, as well as *L. jaffueli*¸ were only found in August 2010. Similarly, the polycheate *Boccardia sp*. evidenced low abundance values and was absent in August 2009 and 2010. *Kingiella chilenica*, *T. dombeii*, *Neotrypaea uncinata*, and *Littoridina cumingii* were not recorded in for any post-earthquake sampling site. These findings are reflected by the post-earthquake decrease in richness, with most study sites evidencing a loss of 1, 2, or 3 species (Figura 5.3-6). The study sites that had the greatest absence of species were study site 3 (w/o *K. chilenica*) and study site 4 (w/o *N. uncinata*, *H. crenulatus*, or *T. dombeii*). In contrast, the Freshwater Zone site 8 increased in richness by two species.

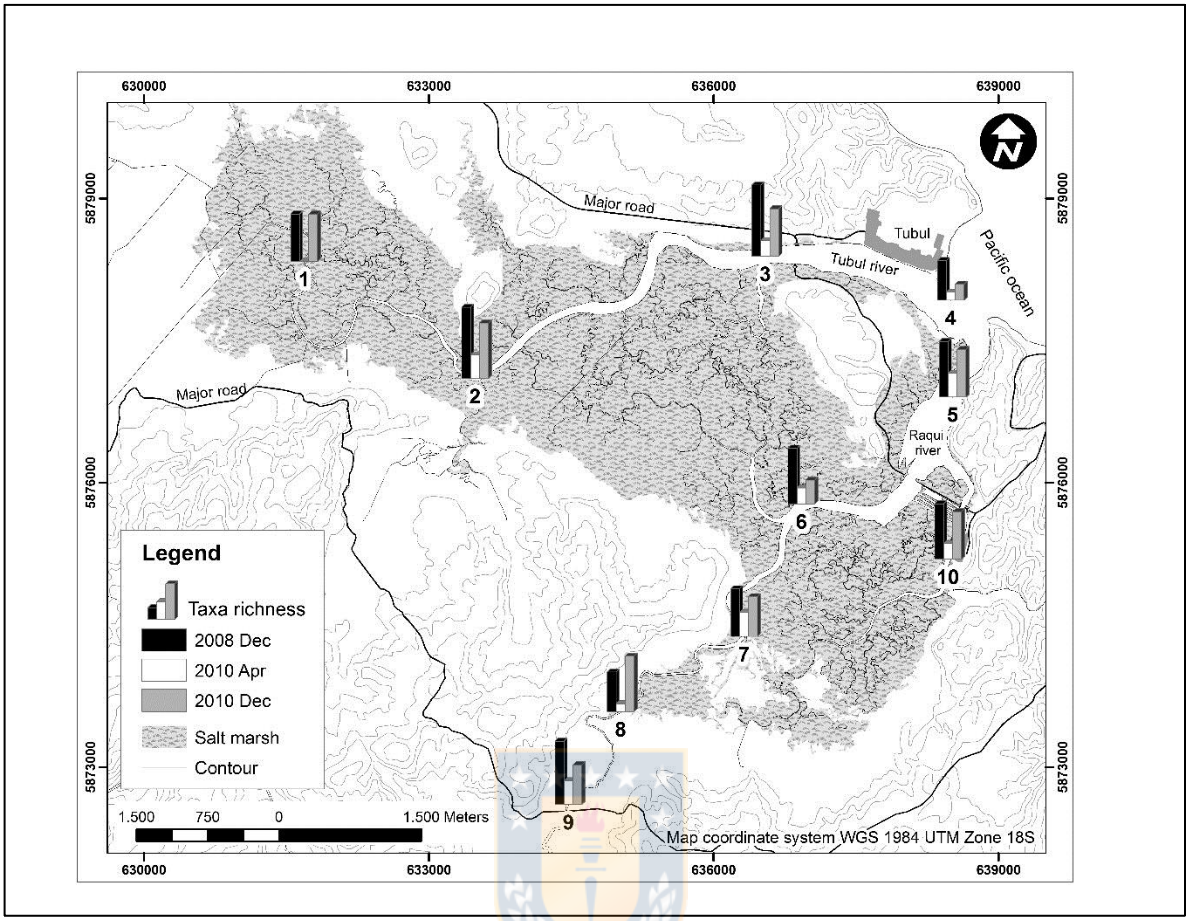

Figura 5.3-6. Cluster analysis of benthic macroinvertebrate abundances in the Freshwater (FRESH), Mixed (MIX), and Estuary (EST) Zones pre- and post-earthquake. Similarity profile analyses were used (p = 0.05). *, Pre-earthquake Estuary Zone site 4; +, Post-earthquake Mixed Zone site 6; *+, Post-earthquake Mixed Zone site 7; and ++, Post-earthquake Estuary Zone site 5.

Macroinfauna abundances were evaluated in the Mixed and Estuary Zones (i.e., those with significant pre- versus post-earthquake changes; (see Figura 5.3-4b and Figura 5.3-5 and Tabla 5.3-7, Tabla 5.3-8) for the most abundant species (i.e., *Paracorophium hartmannorum*, *Chironomidae* spp. *Perinereis gualpensis*, Capitellidae, *Prionospio (Minuspio) patagonica*, and Oligochaeta). Between periods, only the Mixed Zone showed a significant change in macroinfauna abundance, and this change was due to a single species, *Paracorophium hartmanorum* (p = 0.035) (Tabla 5.3-8). The abundance of this amphipod was zero in April 2010; nevertheless, the abundance of this species recovered and even surpassed historic records by ten months post-earthquake. A similar trend of recovery was observed for the other five macroinfauna species (Figura 5.3-7).

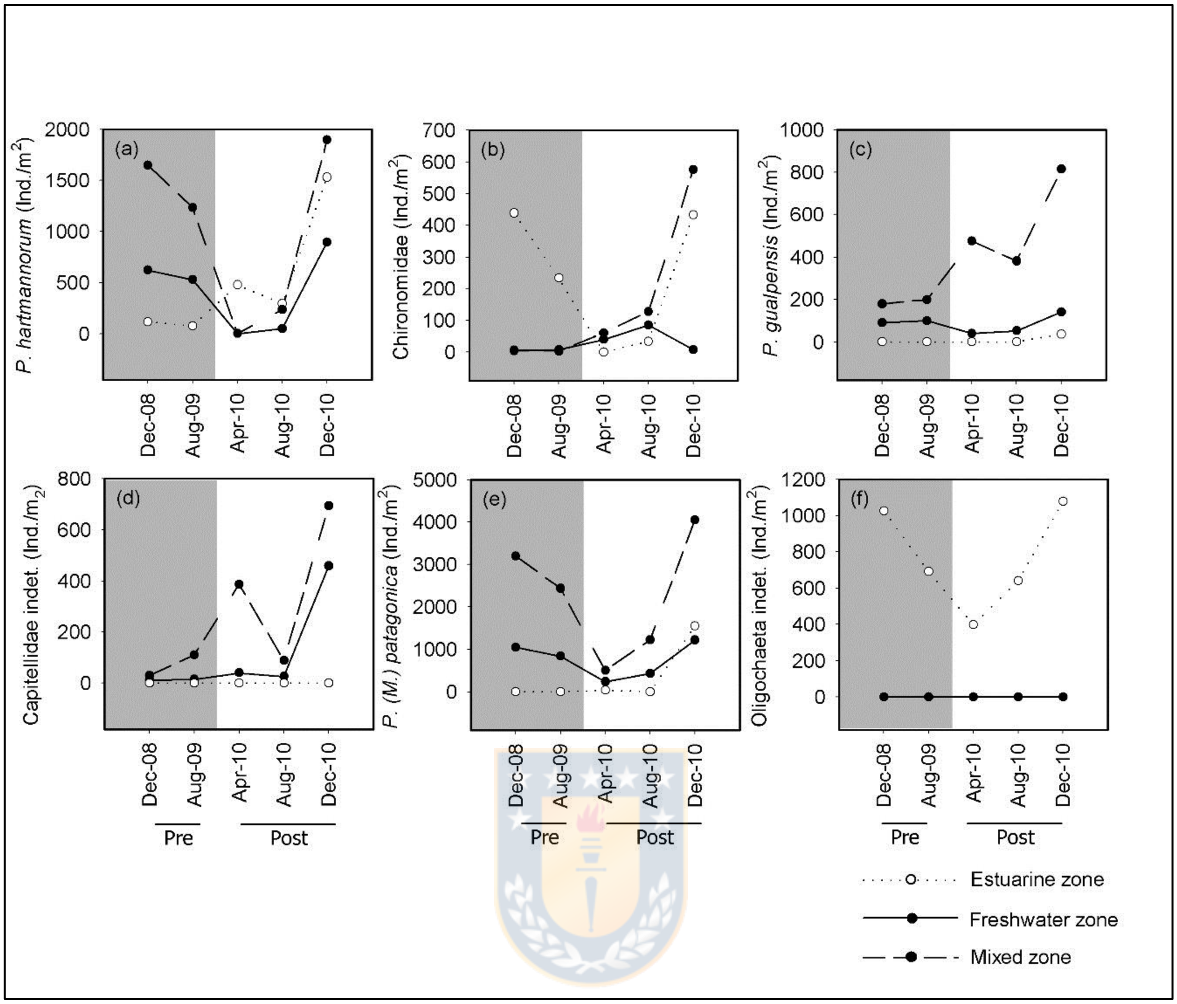

Figura 5.3-7. Changes in abundance for benthic macroinvertebrates between the pre- and post-earthquake periods. Each graph shows the average of data collected for sites within the Estuary (solid line), Mixed (dashed line), and Freshwater Zones (dotted line).

5.3.3.3 Interactions between macrobenthic community and environmental factors

PCA results for the water quality matrix revealed clear differences between the pre- and post-earthquake periods for the Mixed and Estuary, but not the Freshwater, Zones (Figura 5.3-8A). Of the evaluated variables, 5 of 11 best explained the assemblage, were total phosphorous, suspended solids (total, organic, and inorganic), and chlorophyll-a (Tabla 5.3-2). Correlations between the variables of water quality and NMDS of the biological matrix evidenced that 9 of the 11 evaluated parameters were significantly correlated ($p < 0.05$) with the assemblage of benthic species (Table 3). Excluded from this correlation were total nitrogen and dissolved oxygen (Figura 5.3-8B).

Regarding the examined habitat variables, two of the three zones aligned with the variance shown in the component 1 of the PCA. Specifically, the Mixed and Estuary Zones were grouped in the extreme opposite of the Freshwater Zone, which did not showed significant changes as a result of the uplift event (Figura 5.3-8C). The correlation between the NMDS-generated axes and the physical data (Figura 5.3-8D, Tabla 5.3-3) indicated that the variables with significant influence on the benthic species assemblage were sediment redox potential ($r^2 = 0.47$; $p = 0.001$), the silt-clay fraction ($r^2 = 0.22$; $p = 0.001$), and the area of emerged channel bed ($r^2 = 0.20$; $p = 0.001$) (Table 3).

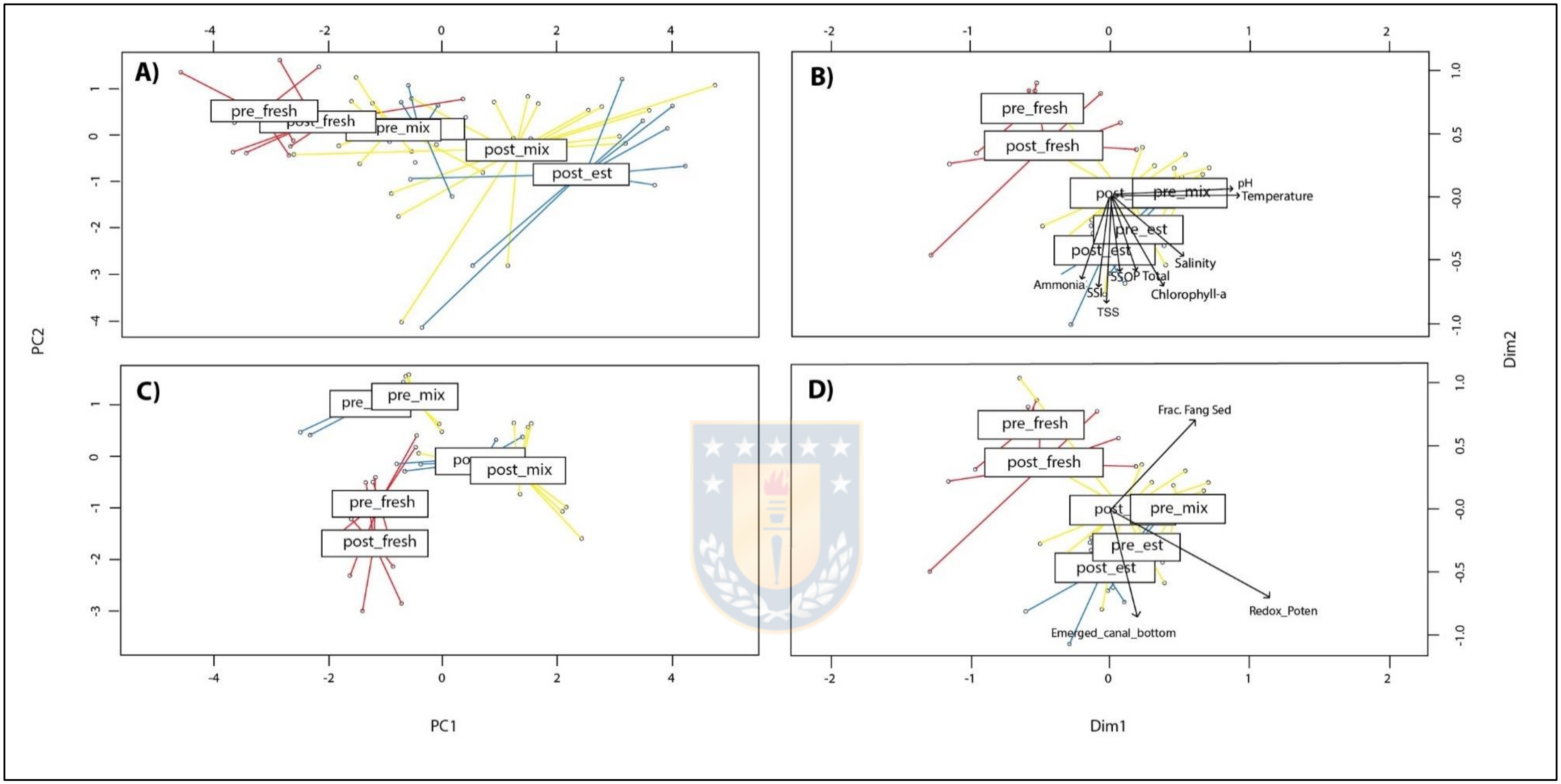

Figura 5.3-8. Multivariate analysis for the environmental and biological matrix. Left column: PCAs of (A) the matrix for variables of water quality and (C) habitat characteristics. Right column: NMDS of the sample sites as a function of biotic parameters (i.e., benthic macroinfauna abundance) and the correlation (indicated with arrows) of these parameters with (B) variables of water quality and (D) habitat characteristics. Pre-/Post-, periods prior to/after the coseismic uplift event for the Estuary (Est; Sites 3, 4, and 5), Mixed (Mix; Sites 2, 6, 7, and 10), and Freshwater (Fresh; Sites 1, 8, and 9) Zones.

5.3.4 Discussion

The Tubul-Raqui Saltmarsh, as with any other type of coastal wetland, has a close relationship with sea level (Valdovinos and Stuardo, 1989). Coastal wetlands are therefore particularly sensitive to movements of the earth's crust, such as occurs with uplifting or subsidence events, which can accompany or follow earthquakes (Cundy et al. 2000; Leonard et al. 2010). When such movements alter the connection between ocean and freshwater currents, macrobenthic dynamics can be affected (Currie and Small, 2005; Geddes, 1987). The macrobenthos is comprised of basal species within marine trophic food webs, meaning that changes to macrobenthic assemblage can have various ecological implications (Peterson and Heck, 1999; Zharikov and Skilleter, 2003).

The Tubul-Raqui Saltmarsh was impacted in February 2010 by an earthquake/coseismic uplifting event. The significant changes in abundance and diversity indicators in April 2010 could be interpreted as an inability of benthic organisms to survive the environmental modifications recorded post-earthquake. These modifications included the following: a) decreased marine intrusion of marine waters b) 100% desiccation of the channels providing water to halophyte vegetation and c) a decomposition of organic matter, resulting from the mass mortalities of larger aquatic organisms (e.g. bivalves, fish, and algae); Nevertheless, by six and ten months post-earthquake, the Tubul-Raqui Saltmarsh system evidenced signs of recovery (Valdovinos and Sandoval, 2011).

Regarding water quality, no pre- versus post-earthquake variations were found for the Freshwater Zone. However, differences in parameters were found for the Mixed and Estuary Zones, which grouped together sampling sites proximal to the ocean inlet and that, historically, were flooded by seawater (Stuardo et al. 1993). Eight of the evaluated parameters were considerably increased in April 2010 as compared to measurements taken before the earthquake. In August 2010, i.e., during the rainy season, water-quality parameters stabilized before once again increasing by December 2010, a month in which various values overtook historic records (Figura 5.3-3).

Principal components analysis of the Freshwater, Mixed, and Estuary Zones indicated that 45.4% of the measured variables significantly change pre- versus post-earthquake. These significantly modified variables included total phosphorous, chlorophyll-a, and total, organic, and inorganic suspended solids. A large amount of bed substrate was removed from the saltmarsh by the tsunami. This event, together with the desiccation brought on by the coastal uplift, favored substrate instability and the presence of poorly hydrodynamic waters at the majority of sampling sites, especially those within the Estuary Zone (i.e., sites 3, 4, and 5). Instability and poor hydrodynamism, in turn, likely increased sediment resuspension by wind, thereby increasing turbidity.

The augmented presence of nutrients recorded two months post-earthquake favored a flourishment of primary producers, as reflected by the significant increase in chlorophyll-a. The high concentrations of total phosphorous and total nitrogen in the Freshwater Zone could be related to the runoff of sediments and water from sectors neighboring the saltmarsh, sectors commonly used for livestock (Valdovinos et al. 2010). Also, worth considering, domestic wastewaters were dumped into the Tubul River, Raqui River, and Las Peñas Estuary (in the Mixed/Estuary Zones) as a result of earthquake -damaged sewers in the nearby Tubul Cove, home to roughly 2,200 inhabitants.

Regarding salinity, which is described as a structuring factor for the macrobenthic community in saltmarsh ecosystems (Nebra et al. 2016; Telesh and Khlebovich, 2010), one could presume that decreased marine intrusion following the coastal uplift event would translate into significant pre- versus post-earthquake variances. Nevertheless, no significant changes were found for salinity. Indeed, historic records for the Tubul-Raqui Saltmarsh evidence that salinity is a highly variable component (Figura 5.3-3). For example, Estuary Zone sites sampled in December 2008 (austral summer) presented between 25.1 and 32.2 PSU, whereas in August 2009 (austral winter), values ranged between 6.0 and 7.2 PSU. These data underscore the impact of the pluvial regimes for the Tubul and Raqui Rivers, which are located in a temperate rainy climate with maritime influence (average precipitation > 1,000 mm/year). During the winter (i.e., July-September), the diluting capacity of the rivers increases, thereby decreasing the concentration of salts in the water (Acevedo-Merino et al. 2005). Nevertheless, historically low salinity values (i.e., 0) were recorded in August 2010 for all sites within the Estuary Zone. The increase of this and other parameters for water quality in December 2010 can be explained by the extraction of sediment by heavy machinery work near the ocean inlet of the saltmarsh. This work, together with topographical conditions, permitted seawater advancement up the Tubul River, whereas the Raqui River was scarcely intruded by seawater.

Regarding habitat variables, the area of emerged channel bed showed significant changes ($p < 0.001$). Prior to the earthquake, the saltmarsh extended approximately 2,238 ha and was flooded by the overtopping of both rivers. The resulting brackish water served to submerge an extensive reach of *S. densiflora*, a grass fundamental to the saltmarsh structure (Valdovinos et al. 2017). Overall, the saltmarsh served as a navigable ecosystem that had a wide extension of habitats for diverse aquatic and semi-aquatic species. The channels of the saltmarsh, however, were desiccated following the coseismic uplift event.

The benthic macroinvertebrate community underwent significant pre- versus post-earthquake differences for the Mixed and Estuary Zones, similar to observations for abiotic variables. Among the represented clusters, the cluster grouping the post-earthquake sites (Figura 5.3-6, group B) also included two pre-earthquake sampling time-points for site 4 (Estuary Zone). This sampling site, located in front of the estuary mouth, is a "high-energy" area where the Tubul River, Raqui River, and ocean converge. Due to this convergence, site 4 has been characterized for poor richness (i.e., max 5 species). This specific cluster grouped together high-vigility invertebrate decapods (*Hemigrapsus crenulatus* and *N. uncinata*), highly saline-resistant polychaetes (*P. gualpensis* and *P. (Minuspio) patagonica*), and the commercially important bivalve *T. dombeii.* Although the convergence zone (i.e., site 4) was strongly impacted by the coastal uplift and tsunami, the community structure did not present significant changes. Indeed, species that were not recorded post-earthquake (*H. crenulatus* and *N. uncinata*) had low abundances pre-earthquake (Table S4). Exceptions in the pre-earthquake cluster (Figura 5.3-6, group C) included sites 6 and 7 (Mixed Zone), as well as site 5 (Estuary Zone), from the August and December 2010 sampling time-points. These sites were sampled ten and six months after the uplift event and evidenced signs of recovery for the biological community. Recovery was also reflected in diversity, evenness, and abundance indicators for all evaluated zones. Nevertheless, the recorded richness values were consistently less than those registered in 2008 and 2009.

Specific richness, an indicator of change in biological communities, considers the least and most frequent species (Batalla-Salvarrey et al. 2014). Therefore, the recorded decrease in specific richness post-earthquake could be explained by the least common species that were not found in 2010, i.e., *T. dombeii*, *K. chilenica*, *N. uncinata*, and *L. cumingii*. Regarding *T. dombeii*, although the dispersal and settlement processes of this bivalve are poorly understood (Hernández et al. 2011). Pineda et al. (2007) did report that connectivity processes between subpopulations are important for larval dispersion. This might explain the post-earthquake lack of this species in the saltmarsh, specifically as a consequence of becoming disconnected from the ocean, where this highly valuable bivalve can be readily found. As with *T. dombeii, K. chilenica* primarily inhabits sandy beds. The reproductive success of this semelparous species in saltmarshes is linked to body size (Gallardo, 1993). Therefore, the mortality of larger-sized *K. chilenica* individuals following the earthquake might have played a role in the reproductive failure of this species during 2010. Indeed, Valdovinos and Sandoval (2011) reported that 100% of larger-sized bivalves died due to desiccation after the 2010 earthquake. In turn, while the gastropod *L. cumingii* and crustacean *N. uncinata* are adapted to survive the variations present in wetland ecosystems, these species have poor survival rates in turbid, low-oxygen water. Recent studies support that crustaceans, as compared to mollusks and polychaetes, are the most hypoxia-sensitive invertebrate group (Dean, 2008; Vaquer-Sunyer and Duarte, 2010). A high amount of organic matter and stagnant pools of water after the earthquake could explain the disappearance of these groups within the Tubul-Raqui Saltmarsh.

The results obtained for macrobenthic community abundances three months after the coseismic uplift event contrasted with the results obtained six and ten months after the February 27th earthquake. Specifically, populations of the most abundant species within the saltmarsh increased in direct relation to habitats that became available after the earthquake (Figura 5.3-4, Figura 5.3-5, Tabla 5.3-7). The low abundances recorded in April 2010 could be explained by the status of the substrate, i.e., irregular proportions of sand, organic material, and a mixed fine fraction. This may have influenced the colonization of organisms that typically develop within the first few centimeters of sandy-silt/clay beds in species-fixed proportions (Quijón and Jaramillo, 1993).

Changes in dominance within the macrobenthic community were also found. Species that were more tolerant to environmental variations (Dean, 2008; Diaz and Rosenberg, 1995) did not significantly vary between the compared periods. However, *P. hartmannorum*, of the Amphipoda order, registered zero in abundance at the April 2010 sampling time-point. The significant drop in dominance for this species was probably associated with the high sensitivity of this order to changes in water and sediment qualities (Marsden et al. 2000). The species with the greatest abundance and contribution values within the macrobenthic community was *P. (M) patagonica*. This taxa is characteristically resistant in environments rich with organic material (Elías et al. 2005), a point that coincides with the general status of the saltmarsh system after the earthquake.

The conducted correlation analysis established that 81.8% of water quality parameters were significantly related to the macrobenthic community. These significant variables included suspended solids (organic, inorganic, and total) and chlorophyll-a, which scored the greatest significance among all parameters ($p < 0.001$; $r^2 > 0.23$). In turn, redox potential of the sediments was significantly higher than the other habitat variables. Substrate status, together with water quality, highly influence benthic species (Von Bertrab et al. 2013). Therefore, the richness and abundance of benthic species can be modified in relation to the frequency of flooding, bed composition, pH, and habitat structure, among others (Hellawell, 1986; Yozzo and Smith, 1995; Peeters and Gardeniers, 1998; Steinman et al. 2003). In line with this, Yozzo and Osgood (2013) indicated that the zonation of the Tubul-Raqui Saltmarsh gradually transitions from the Estuary to the Freshwater Zones. The benthic species across this zonation are characterized for being resistant to different perturbations, even despite evidencing poor richness values. The macrobenthos is one of the most important resident animal groups for coastal wetlands (Bao-Ming et al. 2011), and the permanence of the Tubul-Raqui macrobenthos after the highly disruptive 2010 earthquake indicates that this saltmarsh was able to maintain a highly diverse food web, as described in prior years for this ecosystem.

5.3.5 Conclusion

The most important modification caused by the cosismic uplift on the benthic community was caused by desiccation and decomposition of organic matter, which resulted in significant physical-chemical changes in the wetland, leading to a decrease in benthic diversity and a significant loss of aquatic habitat. Benthic species are presented as good indicators of the environmental condition of a naturally disturbed wetland. The results of this study show the resilience capacity of important components of a saltmarsh after a major natural disturbance. These results have important implications for understanding the time scales at which conservation and management efforts of should be considered.

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5.3.6 References

Acevedo-Merino, A., Garrido-Pérez, C., Nebot-Sanz, E., Sales-Márquez, D., 2005. Fenómenos de dilución y autodepuración de un vertido de aguas residuales urbanas en un ecosistema litoral: el caso del estuario del Río Iro. Cienc. Mar. 31, 221–230.

Allan, J.D., Castillo, M.M., 2007. Stream ecology: Structure and function of running waters. 2nd Edition, Chapman and Hall, New York. 436 pp. http://dx.doi.org/10.1007/978-1-4020-5583-6

Eaton, A. D., Clesceri, L. S., Greenberg, A. E., Franson, M. A. H., 1998. Standard methods for the examination of water and wastewater. 20th ed. Washington, DC: American Public Health Association.

Barrientos, S.E., Plafker, G., Lorca, E., 1992. Postseismic coastal uplift in southern Chile. Geophys. Res. Lett. 19, 701–704. https://doi.org/10.1029/92GL00210

Batalla-Salvarrey, A.V., Kotzian, C.B., Spies, M.R., Braun, B., 2014. The influence of natural and anthropic environmental variables on the structure and spatial distribution along longitudinal gradient of macroinvertebrate communities in southern Brazilian streams. J. Insect Sci. 14, 1-23. https://doi.org/10.1093/jis/14.1.13

Bodin, P., Klinger, T., 1986. Coastal uplift and mortality of intertidal organisms caused by the September 1985 Mexico earthquakes. Science. 233. 1071–1073. https://doi.org/1 10.1126/science.233.4768.1071

Briggs, R., 2016. Earthquakes: Megathrusts and mountain building. Nat. Geosci. 9, 346–348.https://doi.org/10.1126/science.233.4768.1071

Cahill, T., Isacks, B.L., 1992. Seismicity and shape of the subducted Nazca plate. J. Geophys. Res. Solid Earth.97, 17503–17529. https://doi.org/10.1029/92JB00493

Carver, G.A., Jayko, A.S., Valentine, D.W., Li, W.H., 1994. Coastal uplift associated with the 1992 Cape Mendocino earthquake, northern California. Geology. 22. 195–198.

https://doi.org/10.1130/0091-7613(1994)022<0195

Castaños, H., Lomnitz, C., 2012. Darwin and Plate Tectonics, in: Earthquake disasters in Latin America. Springer Briefs in Earth Sciences. https://doi.org/10.1007/978-94-007-2810-3_1

Castilla, J., Oliva, D., 1990. Ecological consequences of coseismic uplift on the intertidal kelp belts of Lessonia nigrescens in central Chile. Estuar. Coast. Shelf Sci. 31, 45–56. https://doi.org/10.1016/0272-7714(90)90027

Castilla, J.C., Manríquez, P.H., Camaño, A., 2010. Effects of rocky shore coseismic uplift and the 2010 Chilean mega-earthquake on intertidal biomarker species. Mar. Ecol. Prog. Ser. 418, 17–23. https://doi.org/10.3354/meps08830

Clarke, K.R., Gorley, R.N., 2006. PRIMER v6: User manual/tutorial. Prim. Plymouth Marine Laboratory, U. K. 190 pp.

Cohen, S.C., 1996. Time dependent uplift of the Kenai Peninsula and adjacent regions of south central Alaska since the 1964 Prince William Sound earthquake. J. Geophys. Res. Solid Earth. 101, 8595–8604. https://doi.org/10.1029/96JB00175

Cundy, A.B., Kortekaas, S., Dewez, T., Stewart, I.S., Collins, P.E.F., Croudace, I.W. Maroukian, H., Papanastassiou, D., Gaki-Papanastassiou, P., Pavlopoulos, K., 2000. Coastal wetlands as recorders of earthquake subsidence in the Aegean: a case study of the 1894 Gulf of Atalanti arthquakes, central Greece. Mar. Geol. 170, 3–26. https://doi.org/10.1016 /S0025-3227(00)00062-1

Currie, D.R., Small, K.J., 2005. Macrobenthic community responses to long-term environmental change in an east Australian sub-tropical estuary. Estuar. Coast. Shelf Sci. 63, 315–331. https://doi.org/10.1016/j.ecss.2004.11.023

Dean, H.K., 2008. The use of polychaetes (Annelida) as indicator species of marine pollution: a review. Rev. Biol. Trop. 56, 11-38. https://doi.org/10.15517/ RBT.V56I4.27162

Diaz, R.J., Rosenberg, R., 1995. Marine benthic hypoxia: a review of its ecological effects and the behavioural responses of benthic macrofauna. Oceanogr. Mar. Biol. An Annu. Rev. 33, 203–245.

Domínguez E., Fernández, H.R, 2009. Macroinvertebrados Bentónicos Sudamericanos. Sistemática y Biología. Fundación Miguel Lillo, Tucumán, Argentina, 656 pp. https://doi.org/10.1603/008.103.0401

Elías, R., Palacios, J.R., Rivero, M.S., Vallarino, E.A., 2005. Short-term responses to sewage discharge and storms of subtidal sand-bottom macrozoobenthic assemblages off Mar del Plata City, Argentina (SW Atlantic). J. Sea Res. 53, 231–242. https://doi.org/10.1016/j.seares.2004.08.001

Farías, M., Vargas, G., Tassara, A., Carretier, S., Baize, S., Melnick, D., Bataille, K., 2010. Land-level changes produced by the Mw 8.8 2010 Chilean earthquake. Science. 329, 916. https://doi.org/10.1126/science.1192094

Fauchald, K., 1977. The polychaete worms. Definitions and keys to the orders, families and genera. Natural History Museum of Los Angeles County, Science Series. 28, 1–188.

Fenoglio, S., Badino, G., Bona, F., 2002. Benthic macroinvertebrate communities as indicators of river environment quality: an experience in Nicaragua. Rev. Biol. Trop. 50, 1125–1131

Gallardo, C.S., 1993. Reproductive habits and life cycle of the small clam Kingiella chilenica (Bivalvia: Cyamiidae) in an estuarine sand flat from the South of Chile. Mar. Biol. 115, 595–603. https://doi.org/10.1007/BF00349367

Geddes, M.C., 1987. Changes in salinity and in the distribution of macrophytes, macrobenthos and fish in the Coorong Lagoons, South Australia, following a period of River Murray flow. Trans. R. Soc. South Aust. 111, 173-182.

Hellawell, J.M., 1986. Field assessments of environmental quality. In: Biological Indicators of Freshwater Pollution and Environmental Management. Springer. 398–434.

Hernández, A.F., Cubillos, L.A., Quiñones, R.A., 2011. Evaluación talla estructurada de los stocks de *Ensis macha* y *Tagelus dombeii* en el Golfo de Arauco, Chile. Rev. Biol. Mar. Oceanogr. 46, 157–176. http://dx.doi.org/10.4067/S0718-19572011000200006

Jaramillo, E., Dugan, J.E., Hubbard, D.M., Melnick, D., Manzano, M., Duarte, C., Campos, C., Sanchez, R., 2012. Ecological implications of extreme events: footprints of the 2010 earthquake along the Chilean coast. PLoS One. 7, e35348. https://doi.org/10.1371/journal.pone.0035348

Katsumata, K., 2017. Long-Term Seismic Quiescences and Great Earthquakes in and Around the Japan Subduction Zone Between 1975 and 2012. Pure Appl. Geophys. 174, 2427–2442. http://doi.org/10.1007/s00024-016-1415-8

Leonard, L.J., Currie, C.A., Mazzotti, S., Hyndman, R.D., 2010. Rupture area and displacement of past Cascadia great earthquakes from coastal coseismic subsidence. Geol. Soc. Am. Bull. 122, 2079–2096. https://doi.org/10.1130/B30108.1

Marín, A., Gelcich, S., Castilla, J.C., 2014. Ecosystem services and abrupt transformations in a coastal wetland social-ecological system: Tubul-Raqui after the 2010 earthquake in Chile. Ecol. Soc. 19. 22-34. http://dx.doi.org/10.5751/ES-05633-190122

Marsden, I.D., Wong, C.H.T., Al-Mudaffar, N., 2000. Assessment of an estuarine amphipod (Paracorophium excavatum) as a bioindicator of contaminated sediment. Australas. J. Ecotoxicol. 6, 21–30.

Martínez, C., Rojas, O., Aránguiz, R., Belmonte, A., Altamirano, Á., Flores, P., 2012. Riesgo de tsunami en caleta Tubul, Región del Biobío: escenarios extremos y transformaciones territoriales posterremoto. Rev. Geogr. Norte Gd. 53, 85–106. http://dx.doi.org/10.4067/S0718-34022012000300006

McCaffrey, R., Qamar, A.I., King, R.W., Wells, R., Khazaradze, G., Williams, C.A., Stevens, C.W., Vollick, J.J., Zwick, P.C., 2007.

Fault locking, block rotation and crustal deformation in the Pacific Northwest.Geophys. J. Int. 169, 1315–1340. https://doi.org/10.1111/j.1365-246X.2007.03371.x

Meghraoui, M., Maouche, S., Chemaa, B., Cakir, Z., Aoudia, A., Harbi, A., Alasset, P., Ayadi, A., Bouhadad, Y., Benhamouda, F., 2004. Coastal uplift and thrust faulting associated with the Mw= 6.8 Zemmouri (Algeria) earthquake of 21 May, 2003. Geophys. Res. Lett. 31, 1-4. http://doi.org/10.1029/2004GL020586

Melnick, D., Cisternas, M., Moreno, M., Norambuena, R., 2012. Estimating coseismic coastal uplift with an intertidal mussel: calibration for the 2010 Maule Chile earthquake (M w= 8.8). Quat. Sci. Rev. 42, 29–42. http://doi.org/10.1016/ j.quascirev.2012.03.012

Moreno, P., Callisto, M., 2006. Benthic macroinvertebrates in the watershed of an urban reservoir in southeastern Brazil. Hydrobiologia. 560, 311–321. https://doi.org/10.1007/s10750-005-0869-y

Nebra, A., Alcaraz, C., Caiola, N., Muñoz-Camarillo, G., Ibáñez, C., 2016. Benthic macrofaunal dynamics and environmental stress across a salt wedge Mediterranean estuary. Mar. Environ. Res. 117, 21–31. https://doi.org/10.1016/j.marenvres.2016.03.009

Oksanen J., Kindt R., Legendre P., O'Hara B., Simpson G.L., Solymos P., Stevens M.H.H., Wagner H., 2016. The vegan package (Community ecology package) Version 2.4-1 https://github.com/vegandevs/vegan R-Forge.

Ortlieb, L., Barrientos, S., Guzman, N., 1996. Coseismic coastal uplift and coralline algae record in northern Chile: the 1995 Antofagasta earthquake case. Quat. Sci. Rev. 15, 949–960. https://doi.org/10.1016/S0277-3791(96)00056-X

Osorio, C., 2002. Moluscos marinos de Chile: especies de importancia económica. Ed. Universidad de Chile Santiago 211 pp. https://doi.org/10.5354/ 0365-7779.2005.899

Pandolfi, J.M., Best, M.M.R., Murray, S.P., 1994. Coseismic event of May 15, 1992, Huon Peninsula, Papua New Guinea: Comparison with Quaternary tectonic history. Geology. 22, 239–242. https://doi.org/10.1130/0091-7613(1994)022<0239:CEOMHP>2.3.CO;2

Peeters, E., Gardeniers, J., 1998. Relative effect of light intensity and size of organic matter on decomposition and macroinvertebrates in microcosms. Int. Vereinigung für Theor. und

Angew. Limnol. Verhandlungen. 27, 1326–1330. https://doi.org/10.1080 / 03680770.1998.11901451

Peterson, B.J., Heck, K.L., 1999. The potential for suspension feeding bivalves to increase seagrass productivity. J. Exp. Mar. Bio. Ecol. 240, 37–52. https://doi.org/10.1016/S0022-0981(99)00040-4

Pineda, J., Hare, J.A., Sponaugle, S.U., 2007. Larval transport and dispersal in the coastal ocean and consequences for population connectivity. Oceanography. 20, 22–39. https://doi.org/10.5670/oceanog.2007.27

Quezada, J., Jaque, E., Fernandez, A., Vasquez, D., 2012. Relief changes generated by the 2010 Mw= 8, 8 February 27th earthquake in south-central Chile. Rev. Geogr. Norte Gd. 53, 35–55. http://dx.doi.org/10.4067/S0718-34022012000300003

Quijón, P., Jaramillo, E., 1993. Temporal variability in the intertidal macroinfauna in the Queule river estuary, south-central Chile. Estuar. Coast. Shelf Sci. 37, 655–667. https://doi.org/10.1006

Resh, V.H.R., David, M., VH, R., 1993. Freshwater biomonitoring and benthic macroinvertebrates. Chapman and Hall, New York. 488 pp. https://doi.org/10.1002/aqc.3270040110

Scholz, C.H., 1998. Earthquakes and friction laws. Nature. 391, 37–42. https://doi.org/10.1038/34097

Shi, X., Wang, Y., Liu-Zeng, J., Weldon, R., Wei, S., Wang, T., Sieh, K., 2017. How complex is the 2016 M w 7.8 Kaikoura earthquake, South Island, New Zealand? Sci. Bull.62, 309-311. http://dx.doi.org/10.1016/j.scib.2017.01.033

Steinman, A.D., Conklin, J., Bohlen, P.J., Uzarski, D.G., 2003. Influence of cattle grazing and pasture land use on macroinvertebrate communities in freshwater wetlands. Wetlands. 23, 877–889. https://doi.org/10.1672/0277-5212(2003)023[0877:IOCGAP

Stuardo, J., Valdovinos, C., Figueroa, R., Ochipinti, A., 1993. Los ambientes costeros del Golfo de

Arauco y áreas adyacentes. Serie Monografías Científicas, EULA, Universidad de Concepción, Chile. 9, 157 pp.

Sukumaran, S., Mulik, J., Rokade, M.A., Kamble, A., 2014. Impact of "Chitra" oil spill on tidal pool macrobenthic communities of a tropical rocky shore (Mumbai, India). Estuaries and coasts. 37, 1415–1431. https://doi.org/10.1007/s12237-014-9791-8

Suriano, M.T., Fonseca-Gessner, A.A., 2013. Structure of benthic macroinvertebrate assemblages on a gradient of environmental integrity in Neotropical streams. Acta Limnol. Bras. 25, 418–428. https://dx.doi.org/10.1590/S2179-975X2013000400007

Telesh, I. V, Khlebovich, V. V, 2010. Principal processes within the estuarine salinity gradient: a review. Mar. Pollut. Bull. 61, 149–155. https://doi.org/10.1016/j.marpolbul.2010.02.008

Tobita, M., Suito, H., Imakiire, T., Kato, M., Fujiwara, S., Murakami, M., 2006. Earth, planets Sp. 58, e1–e4. https://doi.org/10.1186/BF03351906

Valdovinos, C., Muñoz, M.D., Sandoval, N., Vásquez, D., Olmos, V., 2010. Natural disasters and biodiversity: the case of Tubul-Raqui coastal wetland. Soc. Hoy. 19, 33–51.

Valdovinos, C., Sandoval, N., 2011. Cambios ambientales del humedal Tubul-Raqui derivado del alzamiento cosísmico y tsunami, asociado al terremoto Mw 8, 8. Inf. técnico la Unidad Sist. Acuáticos, del Cent. Ciencias Ambient. EULA, Universidad de Concepción, Chile. 55 pp.

Valdovinos, C., Sandoval, N., Vasquez, D., Olmos, V., 2017. The Tubul-Raqui Coastal Wetland: A Chilean Ecosystem of High Conservation Value Severely Disturbed by the 2010 Earthquake. In: The Ecology and Natural History of Chilean Saltmarshes. Springer, pp. 293–327. https://doi.org/10.1007/978-3-319-63877-5_10

Valdovinos, C., Sandoval, N., Vásquez, D., Olmos, V., 2012. El humedal costero Tubul-Raqui: un ecosistema chileno de alto valor de conservación severamente perturbado por el terremoto del 2010. In: Humedales Costeros de Chile. Ediciones UC, Santiago Chile. 391–437.

Valdovinos, J., Stuardo, C., 1989. Estuarios y lagunas costeras: ecosistemas importantes del Chile central. Ambiente y Desarrollo. 5, 107-115.

Vaquer-Sunyer, R., Duarte, C.M., 2010. Sulfide exposure accelerates hypoxia driven mortality. Limnol. Oceanogr. 55, 1075–1082. https://doi.org/10.4319/lo.2010.55.3.1075

Vargas, G., Farías, M., Carretier, S., Tassara, A., Baize, S., Melnick, D., 2011. Coastal uplift and tsunami effects associated to the 2010 Mw8. 8 Maule earthquake in Central Chile. Andean Geol. 38, 219-238. http://dx.doi.org/10.5027/andgeoV38n1-a12]

Von Bertrab, M.G., Krein, A., Stendera, S., Thielen, F., Hering, D., 2013. Is fine sediment deposition a main driver for the composition of benthic macroinvertebrate assemblages? Ecol. Indic. 24, 589–598. https://doi.org/10.1016/j.ecolind.2012.08.001

Yozzo, D.J., Osgood, D.T., 2013. Invertebrate communities of low-salinity wetlands: overview and comparison between Phragmites and Typha marshes within the Hudson River Estuary. Estuaries and coasts. 36, 575–584. https://doi.org/10.1007/s12237-012-9543-6

Yozzo, D.J., Smith, D.E., 1995. Seasonality, abundance, and microhabitat distribution of meiofauna from a Chickahominy River, Virginia tidal freshwater marsh. Hydrobiologia. 310, 197–206. https://doi.org/10.1007/BF00006831

Zharikov, Y., Skilleter, G.A., 2003. Depletion of benthic invertebrates by bar-tailed godwits Limosa lapponica in a subtropical estuary. Mar. Ecol. Prog. Ser. 254, 151–162. https://doi.org/10.3354/meps254151

5.3.7 Tables

Tabla 5.3-1 Similarity percentage analysis results for the pre- and post-earthquake groups. Values are given for average similarity and dissimilarity (~ 40%), for the contribution of those species that mostly explained the formation of each cluster-analysis group, and for the accumulated contribution of said species.

Group		Average Similarity (± SD)	Contribution (%)	Cumulative (%)
Pre-earthquake	Average similarity = 69.34			
	Prionospio (*M*) *patagonica*	25.25 ± 1.6	**36.42**	36.42
	Paracorophium hartmannorum	11.06 ± 0.88	15.95	52.37
	Oligochaeta indet.	8.15 ± 0.54	11.75	64.12
Post-earthquake	Average similarity = 40.15			
	Prionospio (*M*) *patagonica*	17.14 ± 1.1	**42.69**	42.69
	Perinereis gualpensis	7.5 ± 0.74	18.67	61.36
	Oligochaeta indet.	4.72 ± 0.43	11.74	73.11
Pre- and post-earthquake	Average dissimilarity = 53.73			
	Paracorophium hartmannorum	12.76 ± 1.26	**23.74**	23.74
	Prionospio (*M*) *patagonica*	11.98 ± 1.24	22.3	46.05
	Chironomidae spp.	5.73 ± 0.89	10.67	56.71

Tabla 5.3-2 PCA results for the matrix of chemical variables of water quality (WQ) and characteristics of the physical habitat (PH). * $p < 0.05$.

Importance of components		PC1		PC2		PC3	
WQ	Standard deviation	2.4262		1.2468		1.0701	
	Proportion of variance	0.5351		0.1413		0.1041	
	Cumulative proportion	0.5351		0.6764		0.7805	
PH	Standard deviation	1.2688		1.1161		0.9543	
	Proportion of variance	0.4025		0.3114		0.2277	
	Cumulative proportion	0.4025		0.7139		0.9416	
WQ		r^2	*p*	r^2	*p*	r^2	*p*
	Total phosphorus	0.92	<0.001*	0.0009	0.9	0.23	0.1
	Total suspended solids	0.91	<0.001*	0.29	0.03	0.01	0.9
	Organic suspended solids	0.88	<0.001*	0.27	0.05	0.08	0.54
	Chlorophyll-*a*	0.86	<0.001*	0.21	0.12	-0.11	0.42
	Inorganic suspended solids	0.85	<0.001*	0.24	0.08	0.01	0.9
	Temperature	0.69	<0.001	0.48	<0.001	-0.25	0.85
	Salinity	0.54	<0.001	0.35	0.01	-0.34	0.01
	Ammonium	0.74	<0.001	0.31	0.02	0.46	<0.001
	Total nitrogen	0.70	<0.001	0.26	0.06	0.26	0.06
	Dissolved oxygen	-0.35	0.8	0.87	<0.001*	-0.11	0.40
	pH	0.42	0.2	0.04	0.7	-0.81	<0.001*
PH	Average area of emerged channel	0.85	<0.001*	-0.09	0.5	-	-
	Maximum channel depth	-0.55	<0.001	0.78	<0.01*	-	-
	Fine fraction of sediments	0.53	<0.001	0.16	0.25	-	-
	Redox potential of sediments	0.55	<0.001	0.76	<0.01*	-	-

Tabla 5.3-3 Correlation results between abiotic variables of water quality (WQ) and the physical habitat (PH), with biotic variables represented through the two-dimensional vectors of NMDS. * p < 0.05.

Vectors		Dim1	Dim2	r^2	*p*
WQ	Total suspended solids	-0.06616	-0.99781	0.3419	0.001*
	Inorganic suspended solids	-0.11625	-0.99322	0.3210	0.001*
	Chlorophyll-a	0.36421	-0.93132	0.2696	0.001*
	Organic suspended solids	0.06647	-0.99779	0.2377	0.001*
	Ammonium	-0.17809	-0.98401	0.2087	0.001*
	pH	0.99957	0.02935	0.1974	0.001*
	Temperature	0.99999	-0.00380	0.1703	0.01*
	Salinity	0.61189	-0.79094	0.1649	0.01*
	Total phosphorus	0.25502	-0.96694	0.1637	0.01*
	Dissolved oxygen	0.44197	0.89703	0.0660	1
	Total nitrogen	0.78792	-0.61578	0.0622	1
FH	Redox potential of sediment	0.85556	-0.51771	0.4737	0.001*
	Fine fraction of sediment (silt + clay)	0.66013	0.75115	0.2274	0.001*
	Average area of emerged channel	0.22969	-0.97326	0.2020	0.001*
	Maximum channel depth	0.98550	-0.16966	0.0974	0.05

5.3.8 Suplementary information

Tabla 5.3-4. **Geographical coordinates (UTM) of the sampling sites (zone 18).**

Sampling sites	UTM coordinates (m)	
	E	S
1	631748.26	5878215.87
2	633482.70	5877100.24
3	636545.22	5878360.24
4	638776.81	5877888.32
5	638458.97	5876863.19
6	636953.12	5875788.15
7	636331.71	5874420.54
8	635101.19	5873648.86
9	634463.21	5872602.47
10	638425.90	5875092.16

Tabla 5.3-5. **Characterization of the physical habitat along the Tubul (sampling sites 1-4) and Raqui (sampling sites 5-10) Rivers. Data are show for the pre-earthquake (December 2008 and August 2009) and post-earthquake (April, August, and December 2010) periods.**

Parameter	Date	1	2	3	4	5	6	7	8	9	10
Average area (m^2) of emerged channel bed during high tide	Dec-08	0	0	0	0	0	0	0	0	0	0
	Aug-09	0	0	0	0	0	0	0	0	0	0
	Apr-10	0	1890±55	2383±20	1076±18	5925±89	2404±34	2373±43	54±2	0	1038±32
	Aug-10	0	1764±49	2284±12	1060±28	5636±72	2254±45	2051±51	0	0	1002±44
	Dec-10	0	1512±39	1821±25	682±22	5058±91	2494±39	2491±39	54±3	0	1120±39
Proportion (%) of emerged channel bed during high tide	Dec-08	0	0	0	0	0	0	0	0	0	0
	Aug-09	0	0	0	0	0	0	0	0	0	0
	Apr-10	0	75±2	72±1	71±1	82±1	80±2	81±1	20±2	0	88±2
	Aug-10	0	70±2	69±1	70±1	78±2	75±2	70±1	0	0	85±1
	Dec-10	0	60±2	55±1	45±1	70±1	83±1	85±2	20±3	0	95±2
Maximum channel depth (m) during high tide	Dec-08	0.3±0.1	2.3±0.1	2.2±0.1	2.1±0.1	2.0±0.1	2.3±0.1	1.8±0.1	0.8±0.1	0.8±0.1	0.6±0.1
	Aug-09	0.4±0.1	2.3±0.1	2.3±0.1	2.2±0.1	2.1±0.1	2.3±0.1	1.9±0.1	0.9±0.1	0.9±0.1	0.7±0.1
	Apr-10	0.2±0.1	0.6±0.1	0.6±0.1	0.8±0.1	0.4±0.1	0.4±0.1	0.3±0.1	0.6±0.1	0.8±0.1	0.1±0.1
	Aug-10	0.2±0.1	0.6±0.1	0.6±0.1	1.0±0.1	0.4±0.1	0.4±0.1	0.3±0.1	0.7±0.1	0.9±0.1	0.1±0.1
	Dec-10	0.1±0.1	0.8±0.1	0.9±0.1	1.2±0.1	0.6±0.1	0.5±0.1	0.4±0.1	0.6±0.1	0.8±0.1	0.05±0.0
Fine fraction (%) in sediments	Dec-08	47	99	95	5	96	99	99	99	42	96
	Aug-09	52	98	91	3	92	99	99	98	48	99
	Apr-10	45	99	95	5	99	99	99	99	50	99
	Aug-10	50	99	95	5	99	99	99	99	40	99
	Dec-10	40	99	95	5	99	99	99	99	40	99
Redox potential (mV) in sediments at 20 mm depth	Dec-08	-32	-210	-148	-95	-183	-175	-152	-100	-50	-195
	Aug-09	-10	-198	-165	-110	-167	-165	-145	-121	-10	-198
	Apr-10	-25	-285	-210	-145	-170	-184	-176	-110	-20	-210
	Aug-10	-8	-270	-129	-98	-109	-106	-102	-100	-45	-187
	Dec-10	-20	-220	-134	-100	-111	-95	-110	-120	-56	-190

Tabla 5.3-6. Water quality pre-earthquake (December 2008 and August 2009) and post-earthquake (April, August, and December 2010). N-total, total nitrogen; DO, dissolved oxygen; P-total, total phosphorous; ISS, inorganic suspended solids; OSS, organic suspended solids; TSS, total suspended solids; Temp, temperature.

Sampling Site	Date	Temp (°C)	Salinity (PSU)	pH	DO (mg/L)	Chlorophyll (ug/L)	Ammonium (mg/L)	P-total (mg/L)	N-total (mg/L)	TSS (mg/L)	ISS (mg/L)	OSS (mg/L)
1	Dec-08	14.5	0	7.1	9.8	0.05	0.03	0.02	0.35	2.10	1.79	0.32
	Aug-09	13.4	0	7.7	9.7	0.04	<0.02	0.01	0.40	5.50	4.51	0.99
	Apr-10	14.0	0	6.2	9.8	0.08	0.20	0.09	0.80	3.20	2.80	0.40
	Aug-10	11.2	0	6.1	9.6	0.05	0.05	0.03	0.43	6.70	5.49	1.21
	Dec-10	14.2	0	7.5	9.7	0.09	0.02	0.03	0.09	6.40	4.50	1.90
2	Dec-08	14.7	31.0	7.0	9.5	0.12	0.03	0.04	0.39	8.20	4.67	3.53
	Aug-09	12.9	1.2	7.6	9.6	0.09	0.02	0.05	0.40	10.10	6.16	3.94
	Apr-10	16.1	3.5	6.7	9.7	6.31	0.26	0.51	0.80	39.30	20.70	18.60
	Aug-10	12.9	0	6.7	5.0	2.68	<0.02	0.09	0.41	17.60	12.67	4.93
	Dec-10	18.3	16.1	8.0	9.6	7.58	0.14	0.23	0.99	39.00	23.80	15.20
3	Dec-08	15.4	32.2	7.0	9.2	1.45	0.09	0.03	0.41	9.30	6.70	2.60
	Aug-09	14.1	7.2	7.6	9.3	1.31	0.02	0.05	0.40	10.20	6.94	3.26
	Apr-10	17.2	28.0	7.6	9.5	13.10	0.28	0.28	1.48	40.60	29.20	11.40
	Aug-10	13.1	0	7.1	4.8	3.45	0.02	0.08	0.42	19.40	13.39	6.01
	Dec-10	18.6	21.0	8.1	9.3	15.32	0.07	0.24	0.99	46.00	26.60	19.40
4	Dec-08	15.6	25.1	7.0	8.9	3.00	0.09	0.07	0.55	9.80	7.84	1.96
	Aug-09	11.9	7.2	8.2	8.8	2.10	0.02	0.09	0.49	20.50	15.99	4.51
	Apr-10	15.6	31.5	7.4	8.9	10.20	0.44	0.31	0.64	80.20	63.60	16.60
	Aug-10	13.8	0	7.1	6.6	3.12	0.02	0.12	0.59	30.40	24.02	6.38
	Dec-10	14.6	26.5	7.7	8.7	6.10	0.21	0.28	0.62	74.20	56.60	17.60
5	Dec-08	15.6	28.1	7.0	9.8	1.20	0.08	0.06	0.43	8.30	5.81	2.49
	Aug-09	13.6	6.0	8.2	10.0	1.10	0.03	0.05	0.40	17.20	12.21	4.99
	Apr-10	16.3	6.0	7.3	10.1	12.30	0.37	0.30	0.84	46.40	37.00	9.40
	Aug-10	15.1	0	7.3	8.8	2.95	0.04	0.06	0.30	19.90	18.40	1.50
	Dec-10	18.5	10.5	8.2	9.9	5.30	0.11	0.28	1.27	23.80	12.20	11.60
6	Dec-08	15.1	27.2	7.0	9.7	1.32	0.04	0.04	0.32	7.90	5.61	2.29
	Aug-09	13.7	6.3	7.3	9.9	1.12	0.03	0.05	0.32	16.60	12.12	4.48
	Apr-10	17.1	2.0	7.2	10.3	6.25	0.47	0.30	0.46	30.40	23.40	7.00
	Aug-10	14.2	0	7.2	7.2	2.72	0.07	0.06	0.31	13.60	10.88	2.72
	Dec-10	17.8	1.1	8.1	9.8	4.80	0.13	0.12	0.64	16.40	12.60	3.80
7	Dec-08	15.1	17.3	7.0	9.9	1.01	0.02	0.06	0.67	5.20	3.80	1.40
	Aug-09	13.0	0	7.3	9.9	0.91	0.03	0.05	0.41	12.20	9.52	2.68
	Apr-10	17.0	1.2	7.0	10.3	3.45	0.49	0.28	0.78	36.80	30.00	6.80
	Aug-10	13.9	0	7.1	8.4	1.25	<0.02	0.09	0.48	14.20	11.36	2.84
	Dec-10	17.8	0.6	8.3	9.9	4.70	0.14	0.11	0.60	18.80	14.20	4.60
8	Dec-08	14.8	17.2	7.0	9.8	0.09	<0.02	0.05	0.71	4.80	3.79	1.01
	Aug-09	13.8	0	7.2	9.9	0.07	<0.02	0.03	0.32	9.00	6.93	2.07
	Apr-10	16.9	0	7.0	10.0	0.15	0.30	0.10	0.80	25.30	21.10	4.20
	Aug-10	13.4	0	7.0	9.7	0.09	<0.02	0.04	0.27	9.40	7.61	1.79
	Dec-10	17.3	0	7.6	9.9	0.20	0.13	0.06	0.37	11.80	9.20	2.60
9	Dec-08	13.6	0.1	7.1	9.5	0.09	<0.02	0.05	0.75	3.60	2.56	1.04
	Aug-09	12.9	0	7.1	9.7	0.08	<0.02	0.04	0.30	9.10	6.83	2.28
	Apr-10	16.8	0	6.9	9.8	0.10	0.24	0.08	0.82	19.60	16.20	3.40
	Aug-10	13.4	0	7.0	9.7	0.08	<0.02	0.05	0.32	10.20	9.38	0.82
	Dec-10	17.1	0	7.5	9.1	0.10	0.04	0.08	0.49	12.20	9.80	2.40
10	Dec-08	14.9	27.2	7.0	8.7	5.12	0.08	0.09	0.92	10.10	6.16	3.94
	Aug-09	13.5	7.3	7.3	8.9	3.12	0.04	0.10	0.61	21.00	12.39	8.61
	Apr-10	17.1	13.1	7.2	10.2	15.20	0.52	1.08	2.11	38.80	20.40	18.40
	Aug-10	14.3	0.1	7.2	5.5	4.14	0.18	0.14	0.68	24.20	5.49	19.01
	Dec-10	18.3	13.0	8.4	7.6	12.40	0.06	0.25	1.36	26.80	21.60	5.20

Tabla 5.3-7. Abundances and diversity indicators for benthic macroinvertebrates (> 500 µm), with values expressed as ind./m2, for the pre-earthquake (December 2008 and August 2009) and post-earthquake (April, August, and December 2010) periods. Amp, Amphipod; Biv, Bivalve; Dec, Decapod; Gas, Gastropod; Ins, Insect; Oli, Oligochaete; and Pol, Polychaete.

Taxa	Sampling Site 1					Sampling Site 2					Sampling Site 3					Sampling Site 4					Sampling Site 5				
	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10
Paracorophium hartmannorum (Amp)	0	0	0	0	11	56	89	0	0	78	98	131	0	11	122	0	0	0	0	0	1765	1452	0	133	2567
Hyalella curvispina (Amp)	22	11	0	0	67	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Hemigrapsus crenulatus (Dec)	0	0	0	0	0	185	123	0	0	256	98	114	0	0	0	2	3	0	0	0	87	56	0	0	78
Neotrypaea uncinata (Dec)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	0	0	0	0	0	0
Chironomidae spp. Indet. (Ins)	188	45	0	22	278	22	11	238	344	2278	11	22	119	178	11	0	0	0	22	0	0	0	0	56	11
Tipulidae indet. (Ins)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Psychodidae indet. (Ins)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Ceratopogonidae indet. (Ins)	11	22	0	22	33	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oniscigrastridae indet. (Ins)	0	0	0	0	22	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Limnoperla jaffueli (Ins)	22	11	0	11	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Perinereis gualpensis (Pol)	0	0	0	0	0	123	98	119	11	11	88	75	0	56	11	86	102	119	0	0	98	123	0	100	411
Capitellidae indet. (Pol)	0	0	0	0	0	22	323	0	0	2011	11	22	0	56	1333	0	0	0	0	11	22	22	119	22	33
Prionospio (Minuspio) patagonica (Pol)	0	0	0	0	0	2343	1823	476	711	1767	1011	898	476	522	689	345	284	0	456	56	1780	1340	238	322	2911
Boccardia sp. (Pol)	0	0	0	0	0	11	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	119	0	0
Polydora sp. (Pol)	0	0	0	0	0	0	0	0	0	0	11	11	0	0	44	0	0	0	0	0	0	0	0	0	0
Oligochaeta indet. (Oli)	856	65	0	22	1133	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Nucula sp. (Biv)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kingiella chilenica (Biv)	0	0	0	0	0	22	11	0	0	0	11	11	0	0	0	0	0	0	0	0	22	11	0	0	0
Tagelus dombeii (Biv)	0	0	0	0	0	28	19	0	0	0	31	25	0	0	0	3	2	0	0	0	26	33	0	0	0
Littoridina cumingii (Gas)	22	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chilina dombeyana (Gas)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Taxa richness (S)	6	6	0	4	6	9	8	3	4	7	9	9	2	5	6	5	5	1	2	2	7	7	3	5	6
Total abundance (N/m^2)	1120	165	0	77	1544	2812	2497	833	1077	6412	1370	1309	595	823	2210	438	392	119	478	67	3800	3037	476	633	6011
Evenness (J´)	0.4	0.9	0	1	0.5	0.3	0.5	0.9	0.5	0.7	0.5	0.5	0.7	0.6	0.5	0.4	0.4	0	0.3	0.6	0.5	0.5	0.9	0.8	0.6

Taxa	Sampling Site 1					Sampling Site 2					Sampling Site 3					Sampling Site 4					Sampling Site 5				
	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10
Shannon diversity (H´)	0.8	1.5	0	1.4	0.8	0.7	1	1	0.7	1.3	1	1.2	0.5	1	1	0.6	0.7	0	0.2	0.4	1	1	1	1.3	1

(continued)

Taxa	Sampling Site 6					Sampling Site 7					Sampling Site 8					Sampling Site 9					Sampling Site 10				
	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10
Paracorophium hartmannorum (Amp)	2310	1867	0	67	3100	978	1091	0	822	1378	0	0	0	189	2111	343	234	1429	689	2467	3245	1876	0	56	3033
Hyalella curvispina (Amp)	0	0	0	0	0	0	0	0	0	0	56	89	0	0	78	22	44	0	78	0	0	0	0	0	0
Hemigrapsus crenulatus (Dec)	34	18	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	34	56	0	0	33
Neotrypaea uncinata (Dec)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Chironomidae spp. Indet. (Ins)	0	0	0	56	0	0	0	0	0	22	562	345	0	56	411	567	311	0	22	611	0	0	0	111	0
Tipulidae indet. (Ins)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	22	0
Psychodidae indet. (Ins)	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	0	0	0	0	0	0	0	0	0	0
Ceratopogonidae indet. (Ins)	0	0	0	0	0	0	0	0	0	0	0	0	0	11	0	22	22	0	11	33	0	0	0	0	0
Oniscigrastridae indet. (Ins)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Limnoperla jaffueli (Ins)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Perinereis gualpensis (Pol)	231	256	357	67	333	298	321	714	356	244	0	0	0	0	111	0	0	0	0	0	65	121	714	1089	2667
Capitellidae indet. (Pol)	0	0	0	122	0	89	110	1548	111	122	0	0	0	0	0	0	0	0	0	0	9	9	0	122	644
Prionospio (Minuspio) patagonica (Pol)	3453	1802	119	122	7000	5760	4565	476	4033	6900	0	0	0	0	2911	11	22	119	11	1744	1231	1565	952	33	511
Boccardia sp. (Pol)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Polydora sp. (Pol)	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Oligochaeta indet. (Oli)	0	0	0	0	0	0	0	0	0	0	1231	987	595	122	1433	989	1020	595	1778	667	0	0	0	0	0
Nucula sp. (Biv)	11	0	0	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Kingiella chilenica (Biv)	44	11	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Tagelus dombeii (Biv)	12	18	0	0	0	15	21	0	0	0	0	0	0	0	0	0	0	0	0	0	10	14	0	0	0

Taxa	Sampling Site 6					Sampling Site 7					Sampling Site 8					Sampling Site 9					Sampling Site 10				
	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10	Dec-08	Aug-09	Apr-10	Aug-10	Dec-10
Littoridina cumingii (Gas)	0	0	0	0	0	11	44	0	0	0	22	11	0	0	0	22	22	0	0	0	0	0	0	0	0
Chilina dombeyana (Gas)	0	0	0	0	0	0	0	0	0	0	22	22	0	0	22	22	22	0	0	0	22	11	0	0	11
Taxa richness (S)	7	6	2	6	3	6	6	3	4	5	5	5	1	5	7	8	8	3	6	5	7	7	2	6	6
Total abundance (N/m^2)	6095	3972	476	445	10433	7151	6152	2738	5322	8666	1893	1454	595	389	7077	1998	1697	2143	2589	5522	4616	3652	1666	1433	6899
Evenness (J´)	0.5	0.5	0.8	0.9	0.7	0.4	0.5	0.9	0.5	0.4	0.5	0.5	0	0.7	0.7	0.6	0.6	0.7	0.4	0.8	0.4	0.5	1	0.5	0.7
Shannon diversity (H´)	0.9	1	0.6	1.6	0.7	0.7	0.8	1	0.8	0.6	0.8	0.9	0	1.2	1.3	1.2	1.2	0.8	0.8	1.3	0.7	0.9	0.7	0.9	1.2

Tabla 5.3-8. ANOVA results between species pre- and post-earthquake. Significance established at p < 0.05.

Taxa	ZONE									
	Mixed					Estuary				
	Df	**Sum Sq**	**Mean Sq**	**F value**	***p***	**Df**	**Sum Sq**	**Mean Sq**	**F value**	***p***
AMPHIPOD										
Paracorophium hartmannorum	1	15.014	15.014	5.928	**0.035**	1	3.692	3.692	1.091	0.288
	18	45.584	2.532	NA	NA	13	43.979	3.383	NA	NA
POLYCHAETE										
Perinereis gualpensis	1	0.082	0.082	0.229	0.637	1	6.709	6.709	4.367	0.061
	18	6.481	0.36	NA	NA	13	19.972	1.536	NA	NA
Capitellidae indet.	1	0.032	0.032	0.011	0.915	1	0.468	0.468	0.24	0.632
	18	50.352	2.797	NA	NA	13	25.393	1.953	NA	NA
Prionospio (*M*) *patagonica*	1	1.444	1.444	4.231	0.056	1	1.6	1.6	1.508	0.246
	18	6.142	0.341	NA	NA	13	13.795	1.061	NA	NA
INSECT										
Chironomidae ssp.	1	5.487	5.487	2.404	0.13	1	3.539	3.539	2.174	0.138
	18	41.077	2.282	NA	NA	13	21.157	1.627	NA	NA

CAPITULO 4:

EVALUACIÓN DE PERTURBACIÓN NATURAL MEDIANTE CAMBIOS MORFOLÓGICOS EN HUMEDALES COSTEROS

Basado en:

Morphological impacts of the Chilean megathrust earthquake Mw 8.8 on 2 coastal wetlands of high conservation value.

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5.4 Capítulo 4: Morphological impacts of the Chilean megathrust earthquake Mw 8.8 on coastal wetlands of high conservation value

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Abstract The subduction earthquake Mw = 8.8 on February 27th, 2010 which affected Chile's south-central coast (37ºS) produced a co-seismic uplift of ~ 1.4 m in coastal Tubul-Raqui wetland area, with abrupt morphological changes. In order to determine the magnitude of the changes, in this area of high conservation value, salt marsh morphological features were identified and quantified by mapping the changing extent of the coverage of morphological features before (2009) and after (2011-2012) the tectonic disturbance. Rectified satellite images of seven study sites were created for the three years using Google Earth images and processed in ArcGIS. The results indicate a total decline of 31.7% in the area of the morphological features and the emergence of 1.25 km^2 of dried area; salt pans and tidal creeks were severely affected, with more than 90% loss. In contrast, there was a slight recovery of the Tubul and Raqui main river channel (12%) and the tidal channels (8.5%) between 2011 and 2012, mainly in the area near the river mouth. The salt marsh (cover by *Spartina densiflora*) showed slight variation after the co-seismic uplift (14.6%), demonstrating high tolerance in the face of high-impact natural disturbances. The changes and later evolution may be explained mostly by the action of the seismic cycle in subduction zones. Continuing to monitor state of the recovery of the salt marsh and other similar

environments may help to understand the true role that the seismic cycle plays in the dynamics of coastal ecosystems, as well as its incidence in the recovery process.

Resumen El terremoto de subducción 8,8 Richter del 27 de febrero de 2010 que afectó a la costa centro-sur de Chile (37ºS) produjo un levantamiento co-sísmico de ~ 1,4 m en la zona costera del humedal de Tubul-Raqui, con cambios morfológicos abruptos. A fin de determinar la magnitud de los cambios, en esta zona de alto valor de conservación, se identificaron y cuantificaron los rasgos morfológicos del humedal costero mediante cartografía en period pre-terremoto (2009) y post-terremoto (2011-2012), de este modo se describe la morfología cambiante en el humedal a través de la cobertura vegetacional. Se crearon imágenes satelitales rectificadas de siete sitios de estudio para los tres años utilizando imágenes de Google Earth y se procesaron en ArcGIS. Los resultados indican una disminución total del 31,7% en la superficie de los rasgos morfológicos y la aparición de 1,25 km^2 de zona seca; las lagunas salinas y los canales de marea se vieron gravemente afectados, con una pérdida de más del 90%. En cambio, entre 2011 y 2012 se produjo una ligera recuperación del cauce principal del río Tubul y Raqui (12%) y de los cauces de las mareas (8,5%), principalmente en la zona cercana a la desembocadura del río. La marisma (cubierta por *Spartina densiflora*) mostró una ligera variación tras el levantamiento cosísmico (14,6%), demostrando una alta tolerancia frente a las perturbaciones naturales de alto impacto. Los cambios y la evolución posterior pueden explicarse principalmente por la acción del ciclo sísmico en las zonas de subducción. Seguir vigilando el estado de la recuperación de la marisma y otros entornos similares puede ayudar a comprender el verdadero papel que desempeña el ciclo sísmico en la dinámica de los ecosistemas costeros, así como su incidencia en el proceso de recuperación.

Keywords*:* Coseismic uplift, Geomorphology, Megathrust Earthquake, Salt marsh, South America.

5.4.1 Introduction

Salt marshes in South America have been described on the Atlantic coast in Argentina, Uruguay and southern Brazil (Chapman, 1960; Costa and Davy, 1992; Cagnoni and Faggi, 1993; Isacch et al. 2006); however, salt marshes of the southern Pacific coast are rarely documented, especially in Chile (e.g. San Martín et al. 1992; Ramírez et al. 1988, 2002, 2014; Valdovinos, 2004; Valdovinos et al. 2017; Sandoval et al. 2019), and even less on marsh morphological features of the landscape (e.g. Among coastal ecosystems, salt marshes provide a high number of valuable benefits to humans, including raw materials and food, coastal protection, erosion control, water purification, maintenance, carbon sequestration, tourism, recreation, education and research (Barbier et al. 2011).

The west coast of South America is a tectonically active margin influenced by the dynamics imposed by the seismic cycle of large subduction earthquakes that has affected the area in the last centuries (Kelleher, 1972; Silgado, 1985). The subduction zone of Chile is between the most active convergent margins on Earth, producing a high-magnitude earthquake (Mw > 8.0) every 10-20 years (Moscoso et al. 2011; Udías et al. 2012). The records indicate that at least nine earthquakes with magnitude greater than Mw = 8.0 have affected the coast of the south-central region of Chile since 1562 (Lomnitz, 1970; Urrutia and Lanza, 1993; Cisternas et al. 2005).

Major earthquakes in the west coast of South America causing tragic loss, economic devastation and destruction during the last few years, emphasize the high vulnerability of the world's heavily populated and ecologically critical coasts (Jaramillo et al. 2012; Jorat et al. 2015). Due to this, neotectonics is an important factor to consider in the geological formation and evolution of its salt marshes of the Chilean coast, which must be capable of resisting to the land level changes produced by earthquakes, expressed in subsidence or uplift, which depends on their position with respect to these areas of high slip release (Jaramillo et al. 2012; Quezada et al. 2012). The effect caused by a co-seismic uplift on a coastal ecosystem is an aspect less known in the literature, mainly referring to coastal wetlands of the Copper River

Delta in Alaska (e.g. Thilenius, 1990, 1995; Boggs and Shephard, 1999; Christensen et al. 2000).

On February 27, 2010 (27/F) a Mw=8.8 earthquake affected the south-central Pacific coast, generating an uplift of ~ 1.4 m in Tubul (Farías et al. 2010; Quezada et al. 2010), where the Tubul-Raqui salt marsh is located. This is the coastal wetland with the highest conservation value in central Chile, providing important ecosystem services to the local community (Marin et al. 2014; Valdovinos et al. 2017; Sandoval et al. 2019). Drastic morphological changes occurred, which generated changes in the base level of the main rivers, altered the hydrological balance, drying most channels, reducing salt-freshwater interaction, as well as generating strong modifications in the aquatic components and macroinvertebrate communities (Valdovinos et al. 2010, 2017; Quezada et al. 2012; Marín et al. 2014; Martínez et al. 2015). This study took the opportunity to document for the first time the morphological responses of an important and widespread coastal ecosystem, the Tubul-Raqui salt marsh, to a major earthquake.

The Arauco Peninsula was uplifted in the earthquakes of 1835, 1960 and 2010 (Jaramillo et al. 2012; Quezada et al. 2012). The higher contribution was due to the 1960 earthquake (Quezada et al. 2012). The pioneering observations of co-seismic uplift during the 1835 Chile earthquake by Fitz-Roy in Tubul are considered the first empirical evidence of the influence of co-seismic uplift on the salt marsh dynamics (Fitz-Roy, 1839). The 1960 earthquake in Valdivia generated a new uplift of about one meter in the Arauco Peninsula (Lomnitz, 1970; Martínez et al. 2011, 2012, 2015). Although the effects in the area of Tubul were not described specifically, the massive wetland created by land subsidence on the Río Cruces (Figure 1a) after the 1960 (Mw = 9.5) Chilean earthquake (Reinhardt et al. 2010; Jaramillo et al. 2012) is another example of the effects of subduction earthquakes on Chilean coastal ecosystems, with totally opposite results to those observed in Tubul-Raqui. Recently, the earthquake on 27 February 2010 had similar effects to the 1835 earthquake in the area of

Tubul, such as causing a profound change in the base level of the river system and widening of the beach.

Geomorphological analysis of natural or anthropic perturbations may be applied to understand the extension and magnitude of the changes, since the landforms are extremely sensitive units. A better understanding of marsh morphology is required to provide a foundation for protection and restoration of threatened salt marshes in the face of sea level rise and other challenges, as well as a co-seismic uplift (e.g. Zeff, 1999; Fagherazzi et al. 2004; Wallace et al. 2005; Goudie, 2013).

The purpose of this study is to analyze the morphological changes in a salt marsh in central-southern Chile which has been abruptly affected by co-seismic uplift at different time periods asking the following research questions: 1. What is the geomorphology of the Tubul-Raqui salt marsh? 2. How much did the morphology of the salt marsh change after the co-seismic uplift and what has been the evolution of these changes? 3. Was there a homogeneous or differentiated response to the co-seismic uplift within the salt marsh?

This research will provide a better understanding of the role that the co-seismic cycle plays in coastal wetlands, which can be applied to coastal management, and could have methodological application aimed at developing integrative evaluation tools together with the published available data (e.g. Valdovinos et al. 2010, 2017; Marín et al. 2014).

5.4.2 Study area

The Tubul-Raqui salt marsh is located in south-central Chile (37°14' S; 73°26' W) on the coast of the southern Pacific Ocean (Figura 5.4-1 a-c). According to the genetic classification of Guilcher (1957), it is an estuarine-type salt marsh associated with the shallow estuary system (Daniel et al. 2013), which begins in the mouth of the interconnected watersheds of the Tubul and Raqui Rivers. The estuary zone has seasonal inputs of fresh water and a marked marine influence in the Tubul River during the summer season, as a consequence of the decrease of rainfall and evapotranspiration (Stuardo et al. 1993). Both coastal watersheds are pluvial and originate north of the Arauco Peninsula, an uplifted block of continental shelf that forms the largest anomaly on the Pacific margin of South America (Melnick et al. 2009). The area has a wide continental platform of low slope, with a tectonic tendency to upthrust (Araya-Vergara, 1985) and a high rate of uplift in the Quaternary (Melnick et al. 2009; Nielsen and Valdovinos, 2008). The records of the co-seismic tectonics of the area indicate that there have been numerous subduction earthquakes; the largest recorded ones were in 1835, 1960 and 2010 (Fitz-Roy, 1839; Farías et al. 2010). In the events of 1835 and 2010 the salt marsh area had co-seismic uplifts of ~1.8 and ~1.4 m, respectively (Fitz-Roy, 1839; Farías et al. 2010; Quezada et al. 2012). In the inter-seismic period there has been a tendency to subsidence as part of the dynamics of the co-seismic cycle (Kaizuka et al. 1973; Quezada et al. 2012; Wesson et al. 2015).

The area has been modified by epirogenetic movements from the Upper Cretaceous to the Plio-Pleistocene in the Arauco Peninsula, producing a complex sedimentary cycle with alternation of marine and continental sedimentary sequences (Pineda, 1986). The current salt marsh plain is a remnant of the Holocene lowlands of marine and alluvial origin (Kaizuka et al. 1973); its genesis is due to the slow sedimentary filling during the episodes of marine transgressions and regressions that have affected the Gulf of Arauco during the Holocene as a consequence of glacial eustatics. The geology of the area, including the location of the Quaternary terraces and the main active faults, has been described by Pineda (1986).

Valdovinos (2007) recognized a sequence of four Holocene marine transgressions in the Tubul-Raqui area; the last regression is dated at 810±100 BP, which is concordant with the Flandrian regression that occurred from 1000 to 600 BP (Martínez, 1968). The final stage in the evolution of this plain has been the establishment of the Tubul-Raqui salt marsh (Valdovinos, 2007), whose present morphology is due to the colonization of *S. densiflora* from the east coast of South America; it was first recorded in Chile in 1822-1825 by Brongniart (1829) in Concepción (Bortolus, 2006). The salt marsh has a surface area of about 22.38 km^2; it is dominated by *S. densiflora*, which is the most important species in terms of cover and biomass (Valdovinos et al. 2010). This species occupied an empty niche or displaced the non-aggressive native halophytes (Ramírez et al. 1988; 2002); it has been called a bio-engineering organism (Bortolus, 2006) which favors the development of winding dentritic canals (Valdovinos et al. 2017).

According to Hayes' classification (1975), the Tubul-Raqui estuary is influenced by a microtidal regime (tidal range <2 m), with an average of amplitude of 1.1 m (Stuardo et al.1993).

5.4.3 Materials and methods

5.4.3.1 Sampling area

In total, seven study sites were selected within Tubul-Raqui salt marsh (Figura 5.4-1c). The study sites were concordant with sites described in the literature (Stuardo et al. 1993; Valdovinos et al. 2010), uniformly distributed in the Tubul-Raqui estuary system, from upper to lower salt marsh land. Sites 1, 2 and 3 are in the Tubul salt marsh, from the high part of the middle marsh to the low zone near the mouth (Figura 5.4-1). Study sites 4, 5 and 6 are in the Raqui salt marsh; site 4 is the lowest and 6 is the highest. Study site 7 is located in Las Peñas stream, an affluent of the Raqui River, also in the Raqui salt marsh.

To identify and map the salt marsh morphological features one uniform sized frame was used for each study site. Each frame was 800 x 800 m created with the ArcGIS tool. This size was chosen because it shows a sufficiently large enough area of the marsh that the general appearance can be seen. Within each frame, the sampling station was located in the center of the river channel.

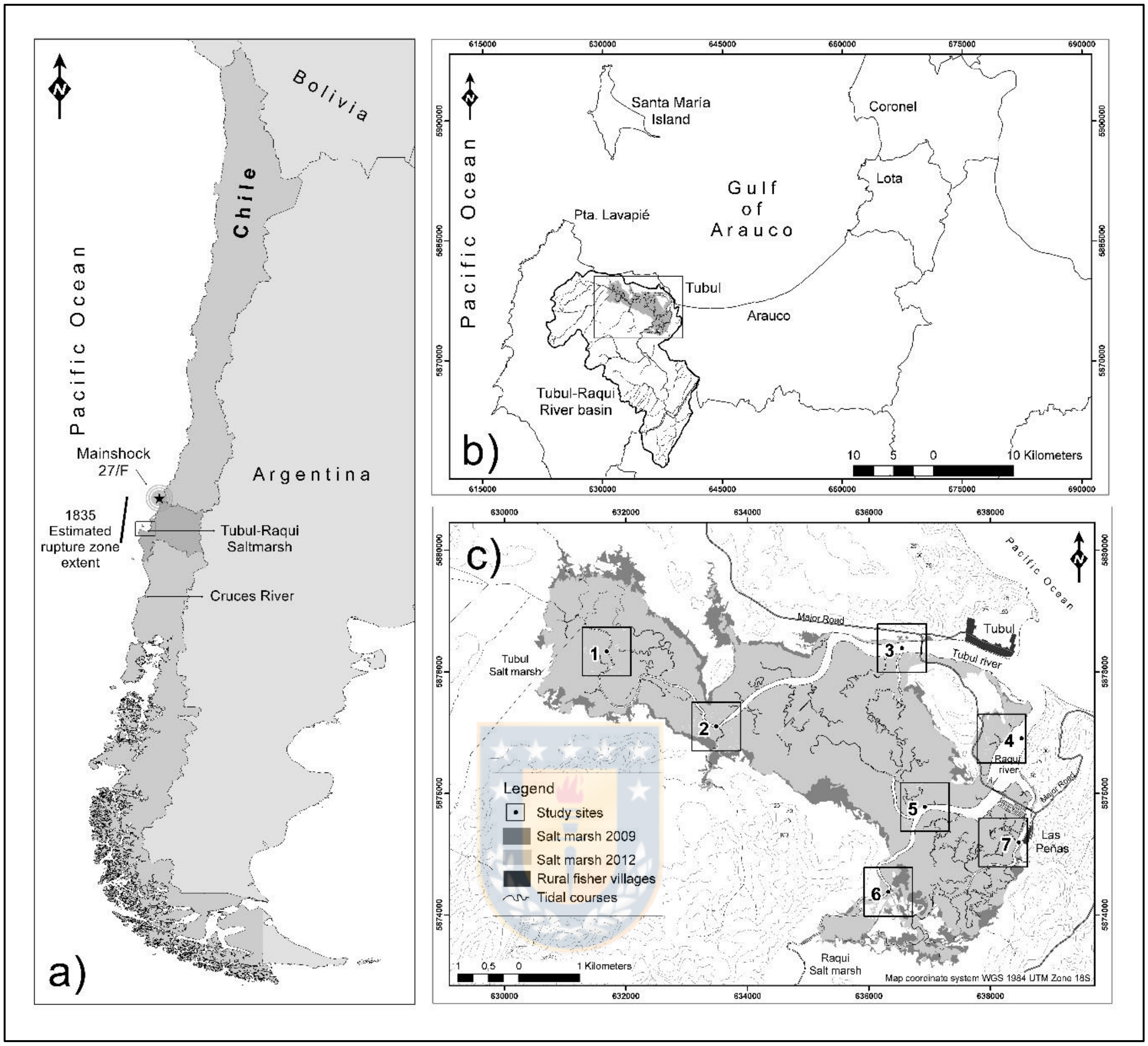

Figura 5.4-1. Study area and sampling design. (a) Location of the Tubul-Raqui salt marsh in the Pacific coast of South America. (b) Regional context with the watersheds of the Tubul and Raqui Rivers. (c) study site locations in the Tubul-Raqui 1, 2 and 3 are placed in the Tubul salt marsh, 4, 5 and 6 in the Raqui salt marsh and 7 in Las Peñas stream, also Raqui salt marsh (salt marsh area for 2009 and 2012 was obtained by analysis of Google Earth images).

5.4.3.2 Data sources

This study was based on morphological data of the Tubul-Raqui marsh acquired from Google Earth. Digital Globes (e.g. Google Earth) have become an increasingly important tool in Earth Science research (Tooth, 2006; Friess et al. 2011; Yu and Gong, 2012; Goudie, 2013) and have been successfully used to investigate the key morphological characteristics of salt marshes (Goudie, 2013).

Detailed marsh morphological data were acquired from Google Earth and analyzed for the seven study sites. The frame file was converted and exported from ArcGIS to Google Earth and used as a guide in lining up the view. An image of 4800 x 3128 pixels resolution for each study site was exported from Google Earth with a zoom level of 1.24 km. The image pixel resolution for different dates of imagery was checked using ArcGIS to ensure that the images were comparable.

The years chosen for analysis were in part dictated by the image availability on Google Earth, especially after the co-seismic uplift. After searching the historical records of comparable images available on Google Earth, three years were selected: a) 18 October 2009 – Pre-uplift, spring (GeoEye 1; Image ID 10504100019D5700; Pixel resolution 0.46 m; Max. GDS 0.51 m; b) 19 August 2011 – Post-uplift, Winter (WorldView-2, Image ID 103001000C7FFB00; Pixel resolution 0.52 m; Max. GDS 0.56 m); c) 24 January 2012 – Post-uplift, summer (WorldView-2; Image ID 1030010010916100; Pixel resolution 0.52 m; Max. GDS 0.60 m) (Supplementary material S1 a and b). All the satellite images analyzed were acquired at high tide in the daytime. The tidal ranges and maximum and minimum tidal levels during the day of the three satellite images acquisition are included in Supplementary material S1(b).

The typical morphology of the Tubul-Raqui salt marsh before the 2010 earthquake was defined by an analysis of 2009 image, together with the support of historical panchromatic aerial photographs taken in 1990 (nominal scale 1:10,000), provided by the Geomatics Laboratory of Environmental Sciences Center (EULA-Chile). Over a period of 19 years (1990-2009), the marshes presented no relevant changes due to the low degree of human intervention, until the 2010 earthquake.

The bathymetric profile of site 4 (Figura 5.4-6 A-B), was carried out in the years 2011 (August 27) and 2012 (January 10), by wading the channel at low tide. The marsh elevations along the A-B transect were determined with a differential-corrected GPS (TRIMBLE GPS RTK GNSS R8), with measurements at 10 m intervals. The mean high tide level (MHTL) elevation was measured with in situ GPS, considering the tide tables for the area available on the Servicio Hidrográfico y Oceanográfico de la Armada de Chile (SHOA) website: https://www.shoa.cl/php/mareas.php.

5.4.3.3 Characterization of geomorphological zones and salt marsh morphological features

The geomorphology of the salt marsh was characterized using the classification of Paskoff (1985), identifying two geomorphological zones, tidal flat or *slikke* and salt marsh (middle or upper zone) or *schorre*. Salt marsh area and edge limits were determined according to the methodology proposed by Vásquez (2013) utilizing a combined geomorphology and floristic criteria using the dominant species *S. densiflora.* For the purposes of this study, tidal courses were divided into tidal channels and tidal creeks (Perillo, 2009). Within tidal courses, tidal channels and tidal creeks have been distinguished only on the basis of their width (maximum creek width of 10 m, which corresponds to the minimum channel width). The main channel of Tubul and Raqui River systems and Las Peñas stream were considered as an individual morphological feature, since they are the main sources of the water which enters the rest of the system and they underwent considerable changes after the 27/F co-seismic uplift. Except for the morphological zones which were defined by the presence of *S. densiflora*, the criteria to define the extent of morphological features were the presence or absence of water. For this reason, after 2009 many morphological features became dried areas as a consequence of the post-earthquake drying, which added a new morphological feature to the analysis.

5.4.3.4 Processing and analysis of satellite images

The satellite image sets were georeferenced and rectified in ArcGIS using control points previously geo-positioned in the field using a GPS device with dual frequency (Trimble, model R-4) together with the support of topographical IGM maps (G-002, G-013, 1:50.000). The mean square error (RMSE) was calculated to minimize errors in the georeferencing process according to the criteria of Araujo et al. (2009), giving values of less than 1 m. Recognition of morphological features was defined by interpretation of the Google Earth satellite images, as well as in situ observations in April, August and December 2010. Details of these field observations were published by Valdovinos et al. (2017) and Sandoval et al. (2019). Supplementary material (S2) includes photographs obtained in the field. The appearance of the morphological features in satellite images of the three years of analysis may be observed in Figura 5.4-2A, C and D. All morphological features and zones were drawn with polygons, except for tidal creeks which were drawn with lines (Figura 5.4-2 B); then to calculate the tidal creek area, first it was converted to raster and then to a vector/polygon format. The total area was calculated using the 800 x 800 frame as reference area in ArcGIS. A comparison map was produced in order to analyze the changes produced in the salt marsh by the co-seismic uplift of 27/F.

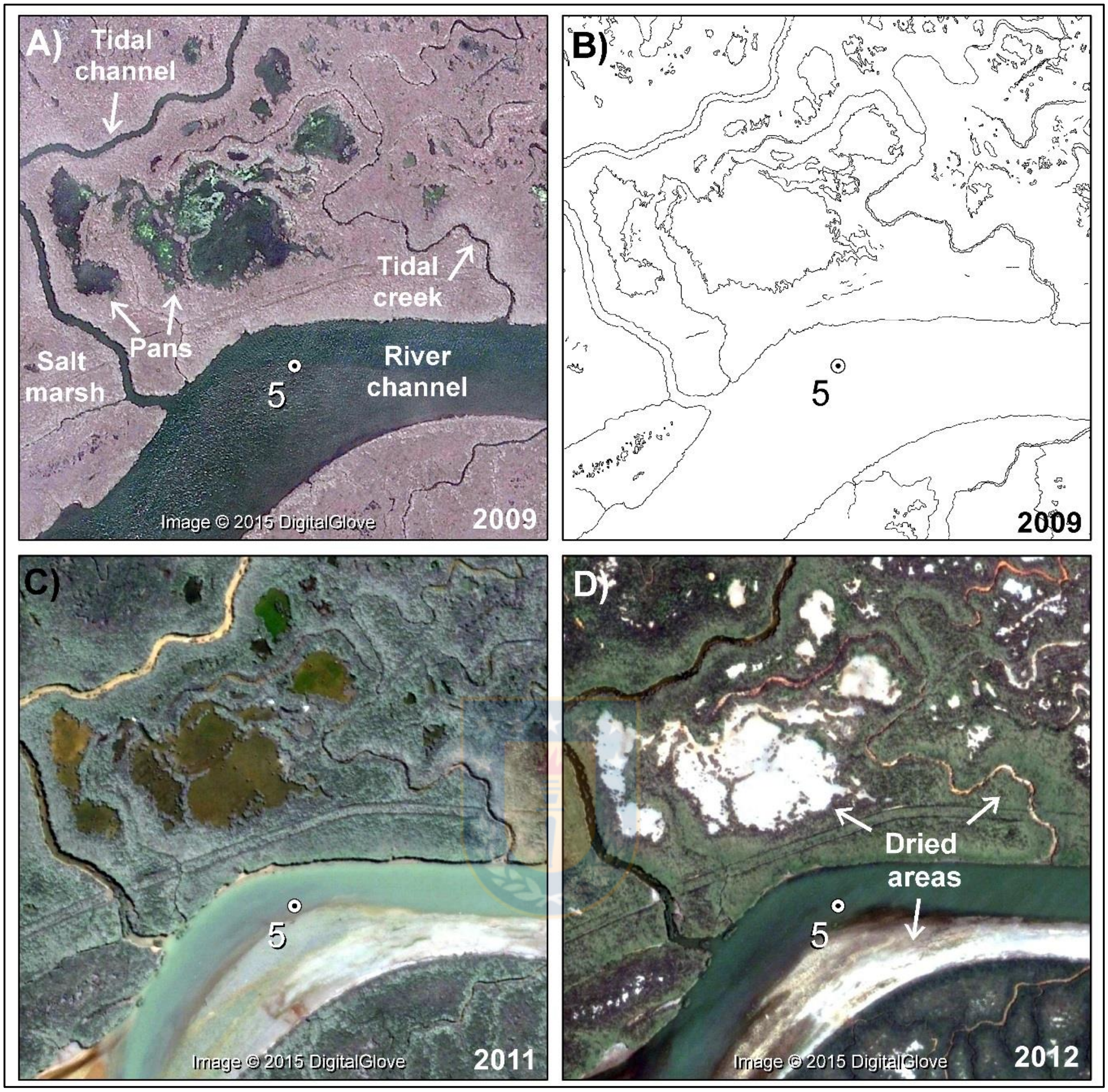

Figura 5.4-2 . A) Example of Google Earth image showing morphological features on October 18, 2009, the reference condition. B) Example of vectorized image interpretation in ArcGIS©. C) Example of Google Earth image showing morphological features on August 19, 2011. D) Example of Google Earth image showing morphological features on January 24, 2012, where salt pans and tidal creeks are dried. Courtesy of Google Earth ©Google Earth 2015.

5.4.3.5 Statistical analysis

The study sites and periods (i.e., pre- and post-earthquake) were evaluated on the basis of changes in the cover (km^2) of their morphological features (river channel, tidal channel, tidal creeks, salt pans, salt marsh, dried areas). The data were first squareroot transformed and then normalized. A Euclidean distance score analysis was used to assess the normalized data, and pre-versus post-earthquake changes were evaluated through clustering analysis. The data were then ordered using non-metric multidimensional scaling (NMDS) in PRIMER 6.0 (Clarke and Gorley, 2006). Similarity profile analysis (5000 permutations for the mean similarity profile and 999 permutations for the simulated profile) was used to detect significant differences ($p < 0.05$) between the pre- and post- uplift groups. An analysis of similarities test, i.e., a nonparametric permutation (randomization) procedure (Sandoval et al. 2019), was used to estimate any significant pre-versus post-earthquake variations between the morphological features of the seven study sites.

5.4.4 Results

5.4.4.1 Morphological features

Analysis of the 2009 set of satellite images enabled the definition of the following morphological features inside the Tubul-Raqui salt marsh, before the co-seismic uplift of 27/F (Figura 5.4-3):

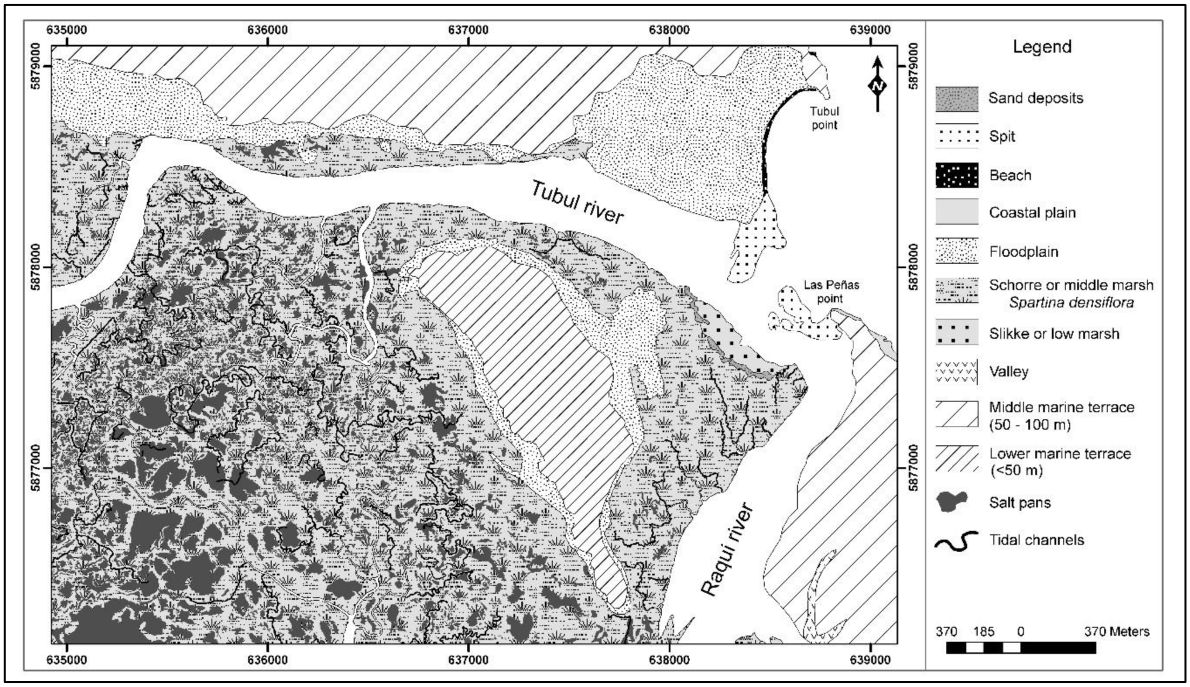

Figura 5.4-3. Distribution of geomorphological characteristics of the marsh prior to the earthquake (2009), using the Paskoff (1985) classification system (based on the GeoEye 1 Pre-uplift image, 18 October 2009).

(a) **Tidal flat or *Slikke*.** This small zone (0.0724 km^2) is located in the middle of the river mouth, protected by two mobile spits. The low marsh had no emergent vegetation; it is composed of fine materials (Stuardo et al. 1993), and is almost completely submerged at high tide, although some algae are visible at low tide. It is furrowed by some dendritic channels and separated from the salt marsh or *schorre* by the accumulation of a discontinuous strip of deposited sand, also without vegetation, which is not covered by high tide. Due to their small area, none of the study sites were included in this geomorphological zone.

(b) **Salt marsh or *Schorre***. It is widely extended (22.38 km^2), colonized by the *Sacocornio-Spartinentum densiflorae* association described by San Martín et al. (1992). The Tubul salt marsh is notably developed inland; it reaches up to 10 km from the coast mainly due to the wide, flat morphology of this area, together with a marked saline influence

(Valdovinos et al. 2017). In the westernmost part a small freshwater salt marsh occurs (1.7 km^2). The Raqui salt marsh reaches 6 km upstream, limited by a major fluvial influence (Valdovinos et al. 2017) and by the presence of marine terraces that limit the salt marsh to the east. The salt marsh has the role of the matrix in the marsh landscape. Before the 2010 earthquake (see Stuardo et al. 1993), the boundary between the "middle salt marsh" and the "main channel of the Tubul and Raqui Rivers and Las Peñas stream", was clearly limited by the zone of influence of the "ean high tide level" (year 2009 in Figura 5.4-6 A).

(c) **Main channel of the Tubul and Raqui Rivers and Las Peñas stream.** The main river channel is of variable width (10 – 300 m), usually less than 40 m upstream and over 300 m near the river mouth, thus the sites show differences in the percentage areas (Tabla 5.4-1). It is sinuous in the high part; however, as the river approaches the mouth and the slope decreases, the width of the channel increases and sinuosity decreases. Before the earthquake, the channels were used for intensive cultivation of *Gracilaria chilensis* (Marín et al. 2014). All study sites are located in this morphological zone.

(d) **Tidal courses**. Tidal channels and tidal creeks form a complex and intricate dendritic network, with a representative density in most of the study sites (Tabla 5.4-1), which is connected to the main channel of the Tubul and Raqui Rivers and Las Peñas stream. Tidal channels have widths of around 10 to 50 m, and tidal creeks range from 0.5 to 10 m. They form the connection of the Tubul and Raqui Rivers before reaching the mouth. Some anthropic alterations to the channel morphology were observed, such as their channeling for irrigation in the high part of the salt marsh near site 1, and the creation of artificial pools for aquaculture (cultivation of *Gracilaria*) in the middle part of site 7 in Las Peñas stream.

(e) **Salt pans**. Mostly secondary pools, according to the typology proposed by Yapp et al. (1977), are observed in Tubul-Raqui salt marsh. Morphologically they are elongated, sinuous and in a number of cases are observed as branches of tidal courses. The area is variable (0.0001 to 28.543 m^2), however more than 90% have a surface area of less than

100 m^2 and only 1.5% is greater than 1000 m^2. Size and coverage percentage increased as the salt marsh penetrated inland (Tabla 5.4-1).

Tabla 5.4-1 Salt marsh morphological features areas for reference condition (2009). All areas are given in percentages.

Study site	River	Salt marsh (%)	Main river channel (%)	Tidal channels (%)	Tidal creeks (%)	Salt pans (%)
1	Tubul	79.4	3.2	1.7	1.3	16.6
2	Tubul	72.5	8.1	2.5	0.9	11.7
3	Tubul	34.2	24.4	3.3	0.6	1.5
4	Raqui	54.5	35.9	1.6	1.0	1.4
5	Raqui	75.9	12.4	5.0	2.7	6.9
6	Raqui	45.1	5.2	0.4	0.8	7.1
7	Las Peñas	67.7	8.5	3.6	1.5	12.7

5.4.4.2 Broad changes in morphological features area

Changes identified through comparison of pre-uplift (2009) and post-uplift (2011, 2012) maps, demonstrate a significant decline in the total area of salt marsh morphological features for the study sites (Tabla 5.4-2, Figura 5.4-4 and Figura 5.4-5). During 2009, the total area of all morphological features of the landscape covered 3.91 km^2 (river channel, tidal channel, tidal creeks, salt pans and salt marsh), while for the year 2012 this area declined to 2.67 km^2 by desiccation of a significant portion of the area. This represents an overall reduction of over 31.7% in the total inundated area for the study sites mapped. There are some marked contrasts within these morphological features. The main channel of the Tubul and Raqui

Rivers, for example, experienced a decline of 65.4% in 2011; while Las Peñas stream declined around 63%. Site 4 was the most critical, with a decrease of 85.4%; the tidal courses dried abruptly as a result of the co-seismic uplift and consequent change in the base level of the river (Figura 5.4-6 A and B). However, during 2012, this was slightly countered by an increase of 12% in the area inundated of the main river channel (Figura 5.4-7a), mainly in the study sites near to the mouth of the river (3 and 4) and site 5 in the Raqui salt marsh. Due to uplift, the main river channel had an overall reduction of 53.4% by 2012; the greatest decline was found in site 1 of 69.3%, located in the highest part of the Tubul salt marsh, followed by site 4 of 67%, located near the Raqui River mouth (Figura 5.4-7a).

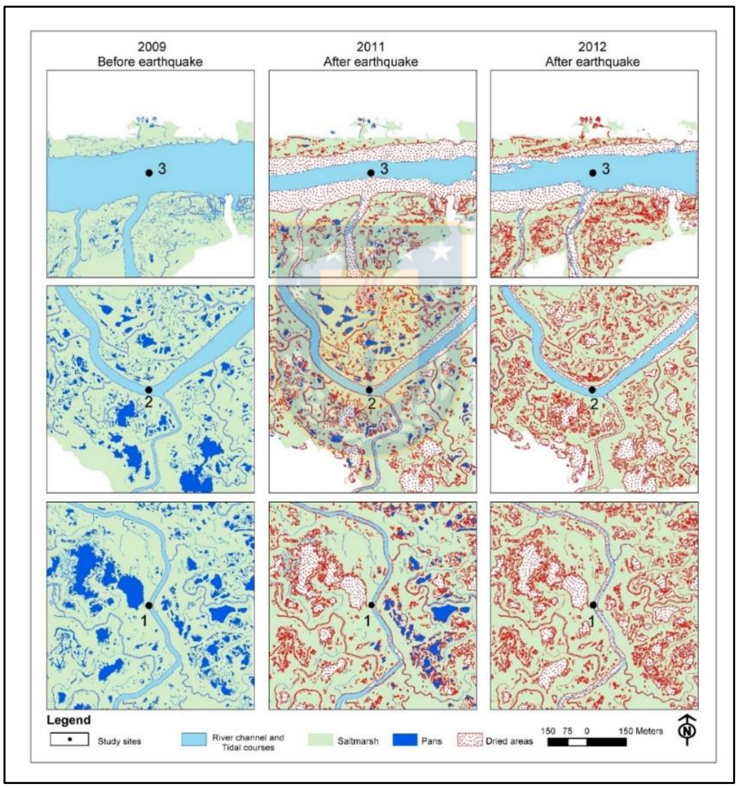

Figura 5.4-4 Morphological changes in the Tubul salt marsh. Study sites are ordered by distance from the mouth of the river. Dried areas are indicated in striped fill. The first column shows the reference condition, observed in Google Earth satellite images of 2009, before the co-seismic uplift, in spring. The second column shows the beginning of drying out of morphological features, 18 months after the earthquake, in winter. The third column gives the observations in 2012, 23 months after the earthquake, in summer. There is an evident progressive drying of channels and salt pans produced by the uplift, while the main channel of the rivers shows a tendency to recovery.

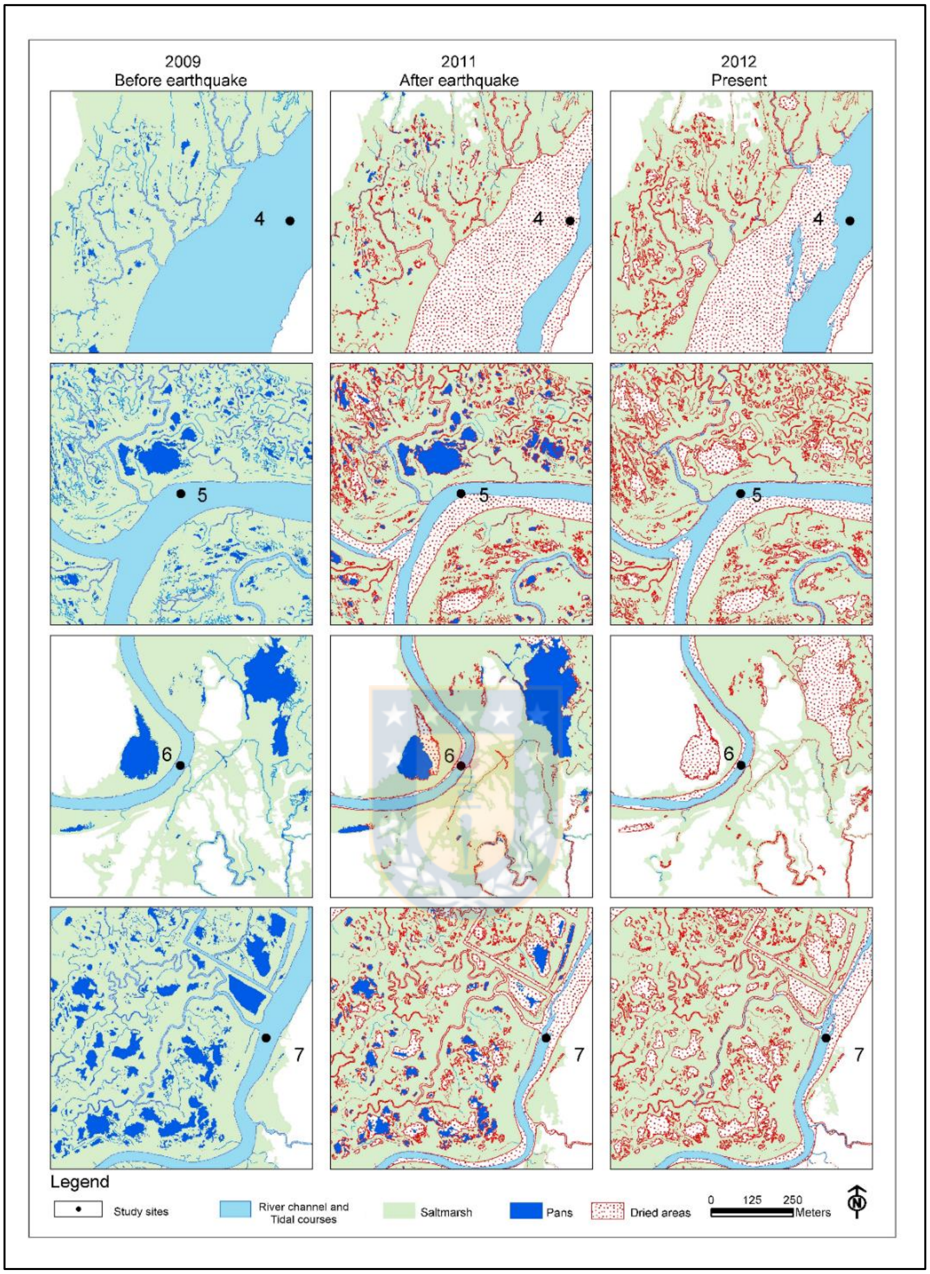

Figura 5.4-5. Morphological changes in the Raqui salt marsh. Study sites are ordered by distance from the mouth of the river. Dried areas are indicated in striped fill. The scheme follows the same order as in Figure 5.4-4.

Most of the channels were disconnected from the main flow of the rivers, which thus broke the existing connection between the Tubul and Raqui Rivers in the central zone of middle salt marsh. Tidal channels registered a decline of 87.1% in 2011; more than 70% decrease was observed in all sites. Study site 6 lost 100% of the tidal channel area (Figura 5.4-7 b). However, like the main river channel, tidal channels had an increase of 8.5% in 2012 near the mouth of the river and in the middle Raqui salt marsh area.

Tidal creeks declined by 56.4% in 2011 (Tabla 5.4-2); the greatest loss was observed in site 7, which declined about 73.7% (Figura 5.4-7 c). In 2012, all tidal creeks disappeared in site 3; while most of the study sites presented a decline of more than 80%. No recovery signal was observed for tidal creeks in any of the study sites, recording a total loss of 92.4% of loss (Figura 5.4-7 d), which produced the total functional loss of this morphological feature. In 2011, site 1 showed the greatest decrease of 76%; however, site 6 had an atypical behavior with a 10% increase in the inundated area compared to 2009 (Figura 5.4-7 d).

Tabla 5.4-2 Surface area changes of salt marsh morphological features in the different time periods. The reference base is the morphological area extent of 2009 (negative values indicate a loss of area compared to 2009).

Geomorphic feature	Area 2009 (km^2)	Area 2011 (km^2)	Area 2012 (km^2)	Change 2009-2011		Change 2011-2012		Change 2009-2012	
				Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)	Area (km^2)	Proportion (%)
Main river channel	0.630	0.220	0.290	-0.41	-65.4	0.08	12.0	-0.33	-53.4
Tidal channel	0.120	0.010	0.020	-0.10	-87.1	0.01	8.5	-0.09	-78.6
Tidal creeks	0.060	0.020	0.004	-0.03	-56.4	-0.02	-36.1	-0.05	-92.4
Salt pans	0.370	0.170	0	-0.20	-55.3	-0.17	-44.7	-0.37	-100
Salt marsh	2.730	2.560	2.350	-0.18	-6.7	-0.22	-7.9	-0.40	-14.6
Dried areas	0	0.930	1.250	0.93	74.5	0.32	25.5	1.25	100

The salt pans gradually declined until disappearing completely in 2012 with a 100%

The total area of the *S. densiflora* salt marsh was not severely affected, it declined by 6.7% in 2011; sites 6 and 3 had the largest losses of 14-15% (Figura 5.4-7 e). The salt marsh area, concentrated mainly at the border with the flood plains with more freshwater influence, declined by 14.6% in 2012. Site 6 showed the greatest decline of 31.9%, while the other sites lost less than 20%.

The loss of water originally retained in these morphological features produced the appearance of 0.93 km^2 of dried areas in 2011, given mainly by the emergence of the salt marsh mud flat. In 2012 the dried areas increased by nearly 25.5%, with a total area of 1.248 km^2 (Tabla 5.4-2).

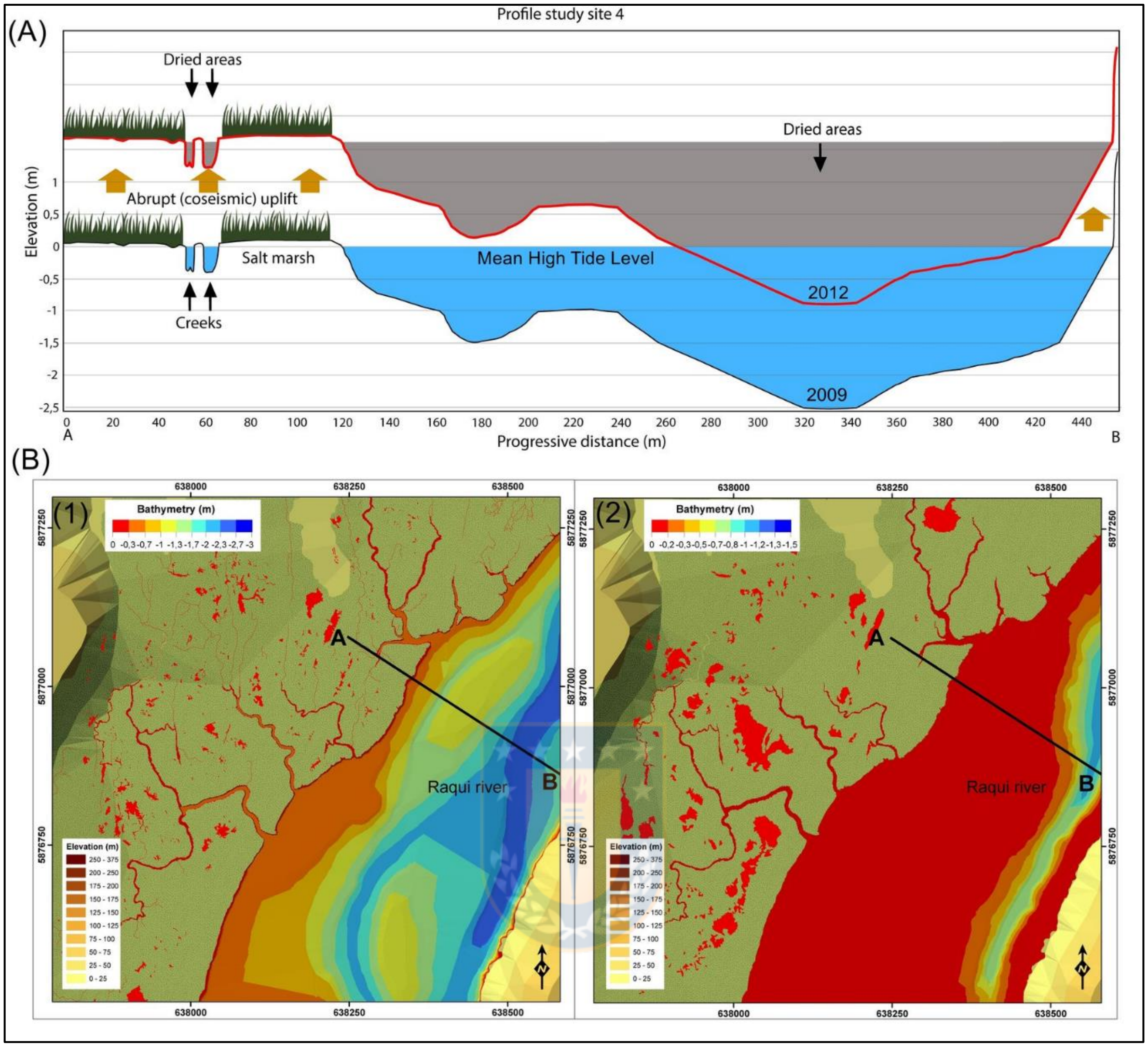

Figura 5.4-6. A) Study site 4 bathymetric profile, located near the mouth of the Raqui River, comparing the situation before (2009) and after (2012) co-seismic uplift. B) Digital elevation model (DEM) shows bathymetry changes 2009 – 2012. Pre-uplift data for DEM were taken from Stuardo et al. (1993) at high tide; these were contrasted with the post-uplift measurements of Valdovinos et al. (2010) using GPS with differential correction (± 2 cm) in all sampling sites at high tide. The light-grey area shows the level of water lost due to co-seismic uplift. DEM was produced using ArcGIS version 9.2.

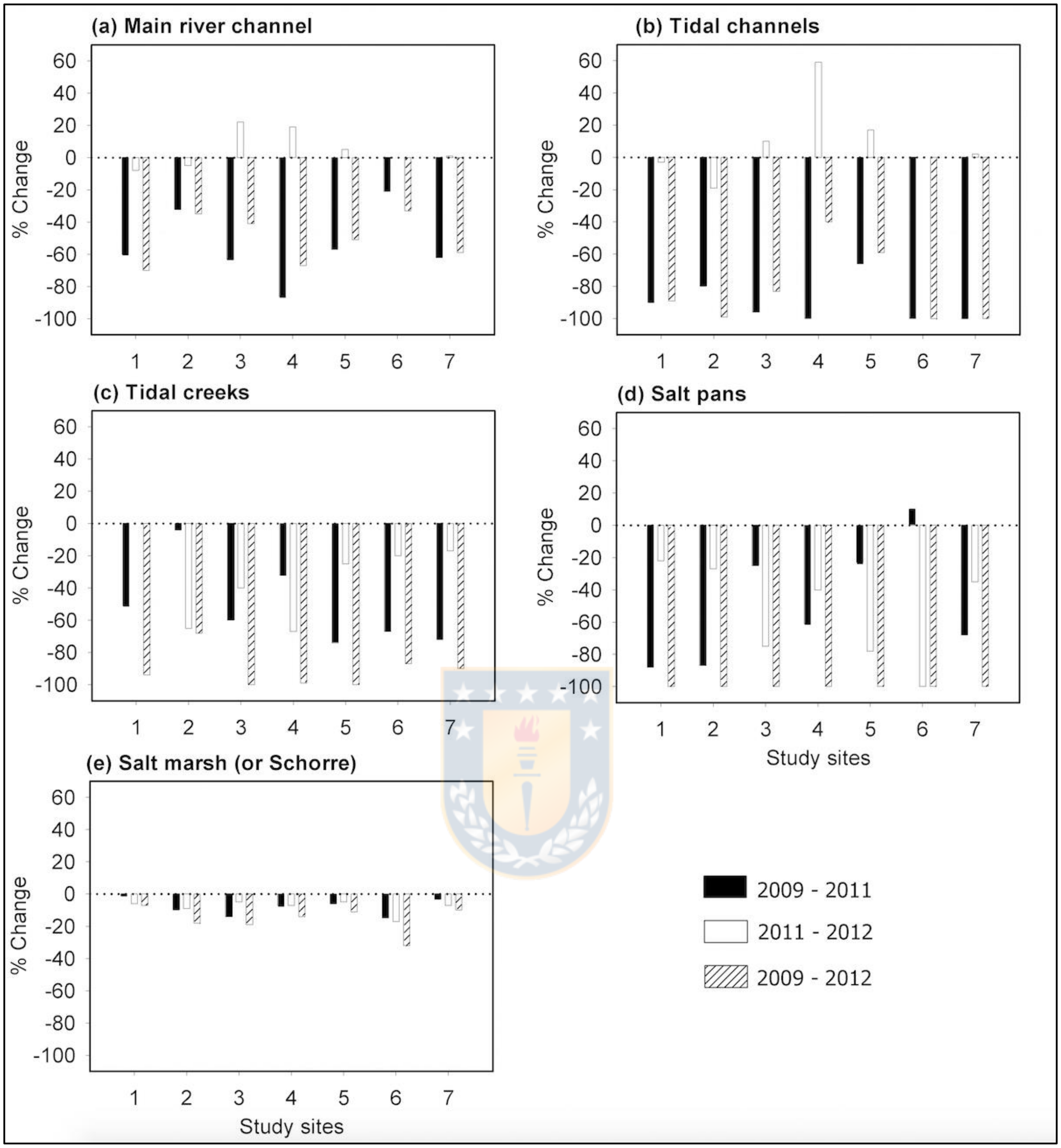

Figura 5.4-7 . Changes in area (km2) of the Tubul-Raqui marsh between the post-uplift periods (2011 and 2012) with respect to the pre-uplift period (2019), expressed as a percentage (%) of change. (a) Main river channel, (b) tidal channels, (c) tidal creeks, (d) salt pans, (e) salt marsh (or schorre).

5.4.4.3 Statistical analysis of measured changes

The ordination of sampling sites using NMDS, considering the areas occupied by the different geomorphological types (Figura 5.4-8), allowed us to recognize three groups (stress = 0.12). First, based on their condition before or after the earthquake, and second, their location with respect to the mouth. The differences between these three groups were statistically significant ($p<0.05$). The arrows for each sampling site in Figura 5.4-8 show the temporal changes that occurred at each site from 2009 to 2012.

All site measurements after the earthquake formed one group (1), while those made before the earthquake formed two groups (2 and 3) differentiated by a different morphological behavior of the sites near the mouth of the estuary (sites 3 and 4).

Figure 8 shows that before the earthquake (pre-uplift), there were two clearly differentiated groups of stations in the area due to their location within the marsh (groups 2 and 3). However, after the earthquake (Post-uplift), a homogenization of the area was observed, forming only one group (1), which remained unchanged in 2011 and 2012.

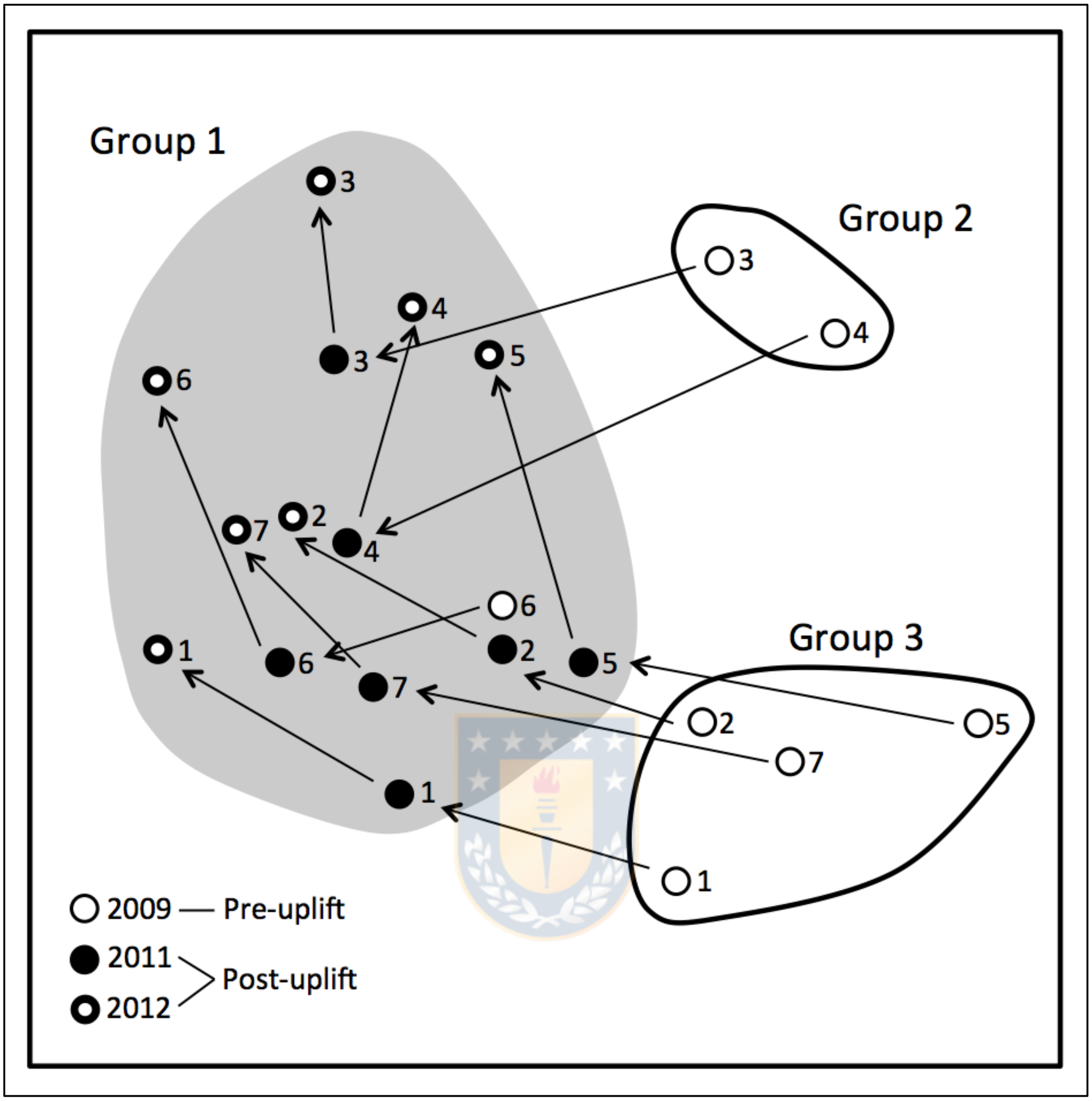

Figura 5.4-8. Ordination of all study sites (1 - 7) in the three years analyzed (2009, 2011, 2012) using the data of morphological features area with multidimensional metric scaling (NMDS). The lines delimit the statistically significant ($p<0.05$) groups 1-3 (stress = 0.12). The arrows show the temporal changes of each site studied, from 2009 to 2012.

This similarity was the result of a reduction in the area of salt pans, which was less than 100 m^2 in both sites. Another factor in this differentiation was the widening of the river channel typical of river mouths. Only site 6, located in the high part of the Raqui salt marsh, did not fit the observed model, grouping in group 1. It has reduced *S. densiflora* cover, and thus limited presence of sea channels or salt pans. In spite of these specific differences, the typical landscape elements in a coastal salt marsh were quite homogeneously and uniformly distributed in the entire study area. The analysis shows that there were no significant differences in unit distribution among the sites in the two years after the earthquake (2011 and 2012); the changes appear to be homogeneous from the mouth to the high part of the salt marsh. However, the analysis above indicated that there are subtle differences in the behavior of the sites which was revealed in the detailed analysis of each morphological unit by station.

5.4.5 Discussion

Projected global sea level rises for the 21st century are expected to be a critical issue for humanity (Nicholls and Cazenave 2010). Sea level rise is estimated to directly affect people and infrastructure by causing flooding and coastal erosion, and indirectly by influencing the world's coastal ecosystems (Albert et al. 2017). Understanding how coastal ecosystems respond to sea level changes in general is fundamental to the development of predictive models and adaptation initiatives in coastal zones (Bell et al. 2014). In general, with rising sea levels, the seaward margin of intertidal and shallow subtidal ecosystems is expected to contract, and the landward margin is expected to expand (Short et al. 2016). The results we obtained in the Tubul-Raqui salt marsh demonstrate the importance of considering tectonic factors such as coastal uplift, which occurs periodically in some areas of the world (Quezada et al. 2012) in these predictions. Few studies have examined in situ the impacts of decreases in relative water depth on modern coastal ecosystems. For example, some authors have studied the impacts of coastal uplift on coastal wetlands of the Copper River Delta in Alaska (Thilenius, 1990, 1995; Boggs and Shephard, 1999; Christensen et al. 2000), sandy beach ecosystems (Jaramillo et al. 2012; Brante et al. 2019) and rocky intertidal communities

(Bodin and Klinger, 1986; Castilla, 1988). The results obtained in Tubul-Raqui, correspond to the main quantitative antecedents of the effects of the raising of a marsh caused by an earthquake at ecological landscape scale.

Using the classification of Paskoff (1985), two main geomorphological zones were identified: tidal flat or *slikke* and salt marsh or *schorre*. Two morphological features were identified in these zones: salt pans and tidal courses, concordant with those described in the literature for coastal salt marshes (e.g. Yapp et al. 1917; Chapman, 1960; Pestrong, 1965; Pethick, 1974; Paskoff, 1985; Mitsch and Gosselink, 1993, 2000; Perillo, 2009; Perillo et al. 1996; Packham and Willis 1997; Goudie 2013).

The analysis of the morphological responses after the vertical uplift of ~ 1.4 m (Quezada et al. 2010; Farías et al. 2010) revealed abrupt transformations experimented on the salt marsh landscape of the Tubul area, which were strongly affected by the magnitude of land-level change. The morphological changes observed in the Tubul-Raqui salt marsh may be explained by the action of two important processes of the seismic cycle: co-seismic uplift and post-seismic subsidence (e.g. Kaizuka, 1973; Quezada et al. 2012; Wesson et al. 2015). For example, during the period of greatest frequency of aftershocks there was a recovery of part of the co-seismic uplift, ~20-30 cm of post-seismic subsidence in Santa María Island (Figura 5.4-1 b) and the western border of the Arauco Peninsula (Quezada et al. 2012). Aftershocks in the rupture area were concentrated between March and May 2010, progressively decreasing (Quezada et al. 2012).

The severe uplift of the salt marsh is the main causal factor of the changes observed in the seven sites of this study. It caused a significant decrease in the total surface area of the morphological characteristics of the Tubul-Raqui salt marsh. This generated an overall reduction of more than 31.7% of the total flooded area for the mapped study sites. However, within each site, local differences induce slightly different responses, as shown in Figura 5.4-7. Site 4 was the most affected by the uplift, with a decrease of 85.4% of its surface area due to desiccation. But then, during 2012, this was partially offset by a 12% increase in the area flooded by the main river channel (mainly sites 3, 4 and 5 near the mouth of the estuary). This partial recovery could have been mainly due to the post-seismic subsidence processes described for the area by Quezada et al. (2012). The results obtained in our study show that this same post-seismic subsidence process was observed in the salt marsh (sites 3, 4 and 5; an increase in the flooded area).

After the earthquake, most of the tidal courses (tidal channels and tidal creeks) were disconnected from the main river channels. Tidal channels showed a decrease of more than 70% in all study sites. The most extreme condition was observed at site 6, which lost 100% of the tidal channel area (Figura 5.4-7 b), this could be associated with local conditions at this site, its geomorphology and slightly higher elevation above sea level. The tidal creeks decreased in 2011 by almost half over the entire study area, with the largest loss at site 7 (73.7%). This site is the farthest from the mouth of the river, and it is located near the edge of the marsh, where the terrestrial ecosystems begins.

The salt pans of all stations gradually decreased until they completely disappeared in 2012 with a 100% loss, which produced the total functional reduction of this morphological characteristic. Historical records indicate a high marine influence in Tubul estuary (Stuardo et al. 1993), with freshwater intakes highly dependent on seasonal precipitation. After the 27/F co-seismic uplift the main entrance of water to the Tubul River system was highly impeded, and this could explain why the upstream study sites (sites 1 and 2) showed a tendency to decline, in contrast to the study site near the river mouth (site 3). This can also be observed in the records of the salt pans area mapped in 2011, where at least 40% of the flooded area is conserved (see example in Figura 5.4-2 C, the flooded salt pans from site 5 in August 2011). Google Earth image 2011 of this study corresponds to August, the rainy season during which 75% of the rainfall is concentrated (Stuardo et al. 1993), which is in agreement with the records of the nearby station of the river Carampangue, with amounts of 216 to 230 mm of precipitation between June and September of 2011 (Valdovinos et al.

2017). Thus, it is important to consider the effect of the seasonal precipitations on the dynamics of salt pans, which are flooded by winter rains and then dry up in dry season.

The dominant vegetation in the salt marsh or *schorre* showed a low percentage of loss (14.6%) compared to the rest of the morphological elements. Sites 6 and 3 had the highest losses (14-15%), which could be associated with their elevations and local geomorphology. The high resistance shown by the saline grasslands dominated by this plant association agrees with the descriptions of Nordby and Zedler (1991), Cagnoni (1999), Castillo et al. (2005), Maricle et al. (2007), and Vásquez (2013), who noted a great tolerance of this genus to extreme conditions. This may well be an example of a tolerant coastal system, in which the dominant vegetation is highly resistant, which allows it to support large natural perturbations. This high resistance makes it possible for the salt marsh to continue to provide ecosystem services, which are highly important to consider this wetland as a priority site for conservation (Marín et al. 2014), especially for bird fauna diversity (Vergara et al. 2008; Valdovinos et al. 2017).

The duration of environmental changes depends on the type of ecosystem affected and its inherent dynamics. For example, the River Copper Delta in Alaska, whose morphology is influenced by co-seismic dynamics of similar characteristics, adjusted rapidly to co-seismic uplift of 1.8 to 3.4 m in 1964. Within 15 years, the newly cut channels were filled and the river was once again flooding vegetated islands (Christensen et al. 2000). Drainage conditions on the delta fluctuate wildly because of large and seasonally varying tides, heavy summer rainfall, and the seasonal melt of upstream glaciers and snowfields. The results obtained in the Tubul-Raqui salt marsh indicate a gradual recovery of the tidal courses. However, it is very probable that the Tubul-Raqui salt marsh will respond much more slowly to the uplift, since there is an important difference in the hydrological regimen of the two systems (there are also differences in slope, geomorphological/sedimentological characteristics and vegetation cover). The marsh in this area was completely dry due to an uplift of ~1.4 m above the "mean high tide level" (MHTL). However, during 2012, this was slightly countered by an increase of 12% in the area inundated of the main river channel, mainly in the study sites near to the mouth of the river (3 and 4) and site 5 in the Raqui salt marsh. In addition, while the uplift in Copper River Delta created new pools (Van Duzor, 2011), in Tubul-Raqui the 27/F co-seismic uplift produced the drying and total loss of the saline pools in 2012. Thus, ecological impacts of co-seismic uplifts on coastal ecosystems appear to vary strongly across ecosystem types and with hydrological regime.

Salt marshes are ephemeral systems with a very short life cycle (Fagherazzi, 2013). This is the reason why the effects caused by tectonic uplifts before 2010 on the biota of the Tubul-Raqui salt marsh are mostly unknown. Also, there is a marked youth of the flora and vegetation of Chilean salt marshes or in one generation of them, after the recurrent tsunamis that have devastated the Chilean coast, periodically changing the littoral landscape (Ramírez et al. 2014).

5.4.6 Conclusions

This study shows that seismotectonics plays an important role in controlling the dynamics of morphological features in Tubul-Raqui salt marsh. The effects of major natural disturbances are strong and severe, meaning a decline of 31.7% of the total area of morphological features after 27/F, 2010 co-seismic uplift. The results demonstrated high sensitivity and fragility of two morphological features, salt pans and tidal creeks, with a loss of more than 90% and no signs of recovery. Only the main channel of the rivers and tidal channels showed signs of recovery (12% and 8.5%); nevertheless, the signs of recovery are low and differentiated in the salt marsh area, concentrated in the study sites near the river's mouth and the middle part of Raqui salt marsh. The results obtained related to the descriptions of the co-seismic cycle in the area (Kaizuka et al. 1973; Quezada et al. 2012; Wesson et al. 2015) suggest that these are influenced by the process of post-seismic subsidence. Also, the salt marsh or *schorre* was the morphological feature that less varied in the period analyzed, with a total reduction of 14.6% in 2012, demonstrating high tolerance to major disturbances. Continuing to monitor the state of recovery of the salt marsh and other similar areas may help to establish the true role that the seismic cycle plays in the dynamics of Chilean coastal ecosystems, as well as its incidence in the recovery process. Incorporating these effects in the policies and planning programs of the coastal zone will help to guarantee the conservation of its resources and the well-being of the populations that depend upon them.

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5.4.7 References

Albert, S., Saunders, M., Roelfsema, C., Leon, J., Johnstone, E., Mackenzie, J., Hoegh-Guldberg, O., Grinham, A., Phinn, S., Duke, N., Mumby, P., Kovacs, E., Woodroffe, C., 2017. Winners and losers as mangrove, coral and seagrass ecosystems respond to sea-level rise in Solomon Islands. Environ. Res. Lett. 12, 1-11 DOI: 10.1088/1748-9326/aa7e68

Araujo, R., Silva, G., Freitas, D., Klein, A., 2009. Georreferenciamiento de fotografías aéreas e análise da variação da linha de costa. In: Alcántara-Carrió, J., Correa, I., Isla, F., Alvarado, M., Klein, A., Cabrera, J., Barlow, R. (Eds.), Métodos en teledetección aplicada a la prevención de riesgos naturales en el Litoral. Programa Iberoamericano de Ciencia y Tecnología para el Desarrollo (CYTED), Manuales Cyted, pp. 123-138.

Araya-Vergara, J.F., 1985. Trend analysis of shoreline changes and coastal management in Central Chile (33-34.5°S). Actes Excursion-Symposium No. 9: La Cote Atlantique. Union Géographique Internationale, Commission sur 1' Environnement Cótier, Paaris, pp. 99-110.

Barbier, E.B., Hacker, S.D., Kennedy, C., Koch, E.W., Stier, A.C., Silliman, R., 2011. The value of estuarine and coastal ecosystem services. Ecol. Monographs 81, 169–193 https://doi.org/10.1890/10-1510.1

Bell, J., Saunders, M., Leon, J., Mills, M., Kythreotis, A., Phinn, S., Mumby, P., Lovelock C., Hoegh-Guldberg, O., Morrison, T., 2014. Maps, laws and planning policy: working with biophysical and spatial uncertainty in the case of sea level rise Environ. Sci. Policy 44, 247–257 DOI: 10.1016/j.envsci.2014.07.018

Bodin, P., Klinger, T., 1986. Coastal Uplift and Mortality of Intertidal Organisms Caused by the September 1985 Mexico Earthquakes. Science 233, 1071-1073 DOI: 10.1126/science.233.4768.1071

Boggs, K., Shephard, M., 1999. Response of marine deltaic surfaces to major earthquake uplifts in southcentral Alaska. Wetlands 19, 13-27.

Bortolus, A., 2006. The austral cordgrass *Spartina densiflora* Brong.: its taxonomy, biogeography and natural history. J. Biogeography 33, 158-168 https://doi.org/10.1111/j.1365-2699.2005.01380.x

Brante, A., Guzmán-Rendón, G., Barría, E., Guillemin, M., Vera-Escalona, I., Hernández, C., 2019. Post-Disturbance Genetic Changes: The Impact of the 2010 Mega-Earthquake and Tsunami on Chilean Sandy Beach Fauna. Sci. Rep. 14239, 1-12 DOI: 10.1038/s41598-019-50525-1.

Brongniart, M.A., 1829. Phanerogamie. In: Voyage autour du monde sur la corvette La Coquille, pendant les ane´es 1822–1825, M.L.I. Duperrey, Paris, pp. 232.

Cagnoni, M., 1999. Espartillares de la costa bonaerense de la República Argentina. Un caso de humedales costeros. In: Malvárez, A. (ed.), Tópicos sobre humedales subtropicales y templados de Sudamérica. ORCYT, Montevideo Uruguay, pp. 55-69.

Cagnoni, M., Faggi, A.M., 1993. La vegetación de la Reserva de Vida Silvestre Campos del Tuyú. Parodiana 8, 101-111.

Castilla, J.C., 1988. Earthquake-caused coastal uplift and its effects on rocky intertidal kelp communities. Science 242, 440-443 DOI: 10.1126/science.242.4877.440

Castillo, J.M., Rubio-Casal, A.E., Redondo, S., Álvarez-López, A.A., Luque, T., Luque, C., Nieva, F.J., Castellanos, E.M., Figueroa, M.E., 2005. Short-term responses to salinity of an invasive cordgrass. In: Capdevila-Argüelles, L., Zilletti, B. (Eds.), Issues in Bioinvasion Science. The Springer, pp. 29–35.

Chapman, V.J., 1960. Salt marshes and salt deserts of the world. Interscience, New York, pp. 1-392.

Christensen, H.H., Mastrantonio, L., Gordon, J.C., Bormann, B.T., 2000. Alaska's Copper River: humankind in a changing world. U.S. Department of Agriculture, Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-480, Portland USA, pp. 1-20.

Cisternas, M., Atwater, B., Torrejón, F., Sawai, Y., Machuca, G., Lagos, M., Eipert, A., Youlton, C., Salgado, I., Kamataki, T. Shishikura, M., Rajendran, C., Malik, J., Rizal, Y., Husni, M., 2005. Predecessors of the giant 1960 Chile earthquake. Nature 437, 404–407 https://doi.org/10.1038/nature03943

Clarke, K.R., Gorley, R.N., 2006. PRIMER V6: User Manual/tutorial. Prim. Plymouth Marine Laboratory, U.K, pp. 190.

Costa, C.S.B., Davy, A.J., 1992. Coastal salt marshes of Latin America. In: Coastal Plant Communities of Latin America. Academic Press Inc., San Diego, USA. pp. 179– 199.

Daniel, I., De Grandpre, M., Farías, L., 2013. Greenhouse gas emissions from the Tubul-Raqui estuary (central Chile 36°S). Estuar. Coast. Shelf Sci. 134, 31-44 DOI: 10.1016/j.ecss.2013.09.019

Fagherazzi, S., 2013. The ephemeral life of a salt marsh. Geology 41, 943-944 doi: 10.1130/focus082013.1.

Fagherazzi, S., Howard, A.D., Wiberg, P.L., 2004. Modeling fluvial erosion and deposition on continental shelves during sea level cycles. J. Geophys. Res. Surf. 109, 1-16 doi: 10.1029/2003JF000091

Farías, M., Vargas, G., Tassara, A., Carretier, S., Baize, S., Melnick, D., Bataille, K., 2010. Land-Level Changes Produced by the Mw 8.8 2010 Chilean Earthquake. Science 329, 916-916. DOI: 10.1126/science.1192094

FitzRoy, R. 1839. Narrative of the surveying voyages of His Majesty's Ships Adventure and Beagle between the years 1826 and 1836, describing their examination of the southern shores of South America, and the Beagle's circumnavigation of the globe. Proceedings of the second expedition, 1831-36, under the command of Captain Robert Fitz-Roy, 3, R.N., Henry Colburn 3, pp. 402-425.

Friess, D.A., Kudavidanage, E.P., Webb, E.L. 2011. The digital globe is our oyster. Front. Ecol. Environ. 9, 542. https://doi.org/10.1890/11.WB.029

Goudie, A., 2013. Characterising the distribution and morphology of creeks and pans on salt marshes in England and Wales using Google Earth. Estuar. Coast. Shelf Sci. 129, 112-123 DOI:10.1016/j.ecss.2013.05.015

Guilcher, A., 1957. Morfología litoral y submarina. Barcelona: Omega S.A., pp. 274.

Hayes, M., 1975. Morphology of sand accumulation in estuaries: An introduction to the symposium. In: Cronin, L.E. (Ed.), Estuarine Research. Academic Press, New York, pp. 3-22.

Isacch, J.P., Costa, C.S.B., Rodriguez-Gallego, L., Conde, D. Escapa, M., Gagliardini, D.A., Iribarne, O.O., 2006. Distribution of salt marsh plant communities associated with environmental factors along a latitudinal gradient on the south-west Atlantic coast. J. Biogeography 33, 888-900 https://doi.org/10.1111/j.1365-2699.2006.01461.x

Jaramillo, E., Dugan, J., Hubbard, D.M, Melnick, D., Manzano, M, Duarte, C., Campos, C., Sánchez, R., 2012. Ecological implications of extreme events: Footprints of the 2010 earthquake along the Chilean coast. PLoS ONE 7, 1-8 https://doi.org/10.1371/journal.pone.0035348

Jorat, M.E., Mörz, T., Moon, V., Kreiter, S., de Lange, W., 2015. Utilizing piezovibrocone in marine soils at Tauranga Harbor, New Zealand. Geomech. Eng. 9, 1-14. DOI: https://doi.org/10.12989/gae.2015.9.1.001

Kaizuka, S., Matsuda, T., Nogami, M., Yonekura, N., 1973. Quaternary tectonic and recent seismic crustal movements in the Arauco Peninsula and its environs, Central Chile. Geographical Reports Tokyo Metropolitan University 8, 1-49.

Kelleher, J.A., 1972. Rupture zones of large South American earthquakes and some predictions. J. Geophys. Res. 77, 2089–2103 https://doi.org/10.1029/JB077i011p02087

Lomnitz, C., 1970. Major earthquakes and tsunamis in Chile during the period 1535 to 1955. Soderdruck aus der Geologischen Rundschau Band 59, 690-938.

Maricle, B.R., Cobos, D.R., Campbell, C.S., 2007. Biophysical and morphological leaf adaptations to drought and salinity in salt marsh grasses. Environ. Exp. Bot. 60, 458–467 DOI: 10.1016/j.envexpbot.2007.01.001

Marín, A., Gelcich, S., Castilla, J., 2014. Ecosystem services and abrupt transformations in a coastal wetland social-ecological system: Tubul-Raqui after the 2010 earthquake in Chile. Ecol. Soc. 19, 22-34 http://dx.doi.org/10.5751/ES-05633-190122

Martínez, R., 1968. Foraminíferos y evolución de la línea de costa holocénica en la zona de Concepción. In: Cecioni, G. (Ed.), El Terciario de Chile Zona Central, Sociedad Geológica de Chile. Editorial Andrés Bello, Santiago, pp. 211-257.

Martínez, C., Rojas, O., Aránguiz, R., Belmonte, A., Altamirano, A., Flores, P., 2012. Riesgo de tsunami en caleta Tubul, Región del Biobío: escenarios extremos y transformaciones territoriales posterremoto. Revista Geografía Norte Grande 53, 85-106 http://dx.doi.org/10.4067/S0718-34022012000300006

Martínez, C., Rojas, O., Jaque, E., Quezada J., Vásquez, D., Belmonte, A., 2011. Efectos territoriales del tsunami del 27 de febrero de 2010 en la costa de la región del Bío-Bío, Chile. Revista Geográfica de América Central 2011, 1-16.

Martínez, C., Rojas, D., Quezada, M., Quezada, J., Oliva, R., 2015. Post-earthquake coastal evolution and recovery of an embayed beach in central-southern Chile. Geomorphology 250, 321-333 https://doi.org/10.1016/j.geomorph.2015.09.015

Melnick, D., Bookhagen, B., Strecker M.R., Echtler, H.P., 2009. Segmentation of megathrust rupture zones from fore-arc deformation patterns over hundreds to millions of years, Arauco peninsula, Chile. J. Geophys. Res. 114, 1-23 https://doi.org/10.1029/2008JB005788

Mitsch, W., Gosselink, J., 1993. The value of wetlands: importance of scale and landscape setting. Ecol. Econ. 35, 25-33 https://doi.org/10.1016/S0921-8009(00)00165-8

Mitsch, W., Gosselink, J., 2000. Wetlands, 3rd edition. John Wiley and Sons, New York, pp. 539.

Moscoso, E., Grevemeyer, I., Contreras-Reyes, E., Flueh, E.R. Dzierma, Y., Rabbel, W., Thorwart, M., 2011. Revealing the deep structure and rupture plane of the 2010 Maule, Chile earthquake (Mw = 8.8) using wide angle seismic data. Earth Planet. Sc. Lett. 307, 147-155 DOI: 10.1016/j.epsl.2011.04.025

Nicholls, R., Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. Science 328, 1517-1520 DOI: 10.1126/science.1185782

Nielsen, S.N., Valdovinos, C., 2008. Early Pleistocene Mollusks of the Tubul Formation, South-Central Chile. Nautilus 122, 201-216.

Nordby, C.S., Zedler, J.B., 1991. Responses of fish and macrobenthic assemblages to hydrologic disturbances in Tijuana Estuary and Los Pefiasquitos Lagoon, California. Estuaries 14, 80-93.

Packham, J.R., Willis, A.J., 1997. Ecology of dunes, salt marsh and shingle. Chapman and Hall, London, pp. 333.

Paskoff, R., 1985. Les littoraux: impact des aménagements sur leur evolution. Masson, Paris, pp. 188.

Perillo, G., 2009. Tidal courses: classification, origin and functionality. In: Perillo, G., Wolanski, E., Cahoon, D.R., Brinson, M.M. (Eds.), Coastal Wetlands: An Integrated Ecosystem Approach. Elsevier, Amsterdam. pp. 185-210.

Perillo, G., Ripley, M., Piccolo, M.C., Dyer, K.R., 1996. The formation of tidal creeks in a salt marsh: new evidence from the Loyola Bay salt marsh, Rio Gallegos Estuary, Argentina. Mangroves and Salt Marshes 1, 37–46.

Pestrong, R., 1965. The development of drainage patterns on tidal marshes. Stanford University Publications 10(2), pp. 870.

Pethick, J.,1974. The distribution of salt pans on tidal marshes. J. Biogeography 1, 57-62.

Pineda, V., 1986. Evolución paleográfica de la cuenca sedimentaria Cretácico-Terciaria de Arauco. In: Frutos J., Oyarzún, R., Pincheira, M. (Eds.), Geología y Recursos Minerales de Chile, Editorial de la Universidad de Concepción, Chile, pp. 375–390.

Quezada, J., Jaque, E., Belmonte, A., Fernández, A., Vásquez, D., Martínez C., 2010. Movimientos cosísmicos verticales y cambios geomorfológicos generados durante el terremoto Mw=8,8 del 27 de febrero de 2010 en el centro-sur de Chile. Revista Geográfica del Sur 1, 11-45.

Quezada, J., Jaque, E., Fernández, A., Belmonte, A., Martínez, C., Vásquez, D., 2012. Cambios en el relieve generados como consecuencia del terremoto Mw = 8,8 del 27 de febrero de 2010 en el centro sur de Chile. Revista Geografía Norte Grande 53, 35-55 http://dx.doi.org/10.4067/S0718-34022012000300003

Ramírez, C., Contreras, D., Figueroa, H., San Martín, C., 1988. Estudio vegetacional en una marisma del centro-sur de Chile. Medio Ambiente 9, 21-30.

Ramírez, C., San Martín, C. Fariña, J. M., Camaño, A., Álvarez, M. Pérez, Y., Solís, J. L., Valdivia, O., 2014. Humedales costeros de la región del Biobío (Chile): Un gradiente de vegetación y una nueva asociación vegetal de marisma. Chil. J. Agric. Anim. Sci. 30, 233-246.

Ramírez, C., San Martín, C., Rubilar, H., 2002. Una propuesta para la clasificación de los humedales chilenos. Revista Geográfica de Valparaíso 33, 265-273.

Reinhardt, E.G, Nairn, R.B., Lopez, G., 2010. Recovery estimates for the Rio Cruces after the May 1960 Chilean earthquake. Mar. Geol. 269, 18–33 DOI: 10.1016/j.margeo.2009.12.003

San Martín, C., Contreras, D. San Martín, J., Ramírez, C., 1992. Vegetación de las marismas del centro-sur de Chile. Revista Chilena de Historia Natural 65, 327-342.

Sandoval, N., Valdovinos, C., Oyanedel, J.P., Vásquez, D., 2019. Impacts of coseismic uplift caused by the 2010 8.8 Mw earthquake on the macrobenthic community of the Tubul-Raqui Saltmarsh (Chile). Estuar. Coast. Shelf Sci. 226 DOI: 10.1016/j.ecss.2019.106278

Short, F., Kosten, S., Morgan, P., Malone, S., Moore, G., 2016. Impacts of climate change on submerged and emergent wetland plants Aquat. Bot. 135, 3–17 DOI: 10.1016/j.aquabot.2016.06.006

Silgado, E., 1985. Destructive earthquakes of South America 1530-1894. Center of Regional Seismology for South America, Earthquake Mitigation Program in the Andean Region, Lima, pp. 315.

Stuardo, J., Valdovinos, C., Figueroa, R., Ochipinti, A., 1993. Los ambientes costeros del Golfo de Arauco y área adyacente. Monografías Científicas EULA 9, Universidad de Concepción, Chile, pp. 157.

Thilenius, J.F., 1990. Woody plant succession on earthquake-uplifted coastal wetlands of the Copper River Delta, Alaska. Forest Ecol. Manag. 33, 439-462. DOI: 10.1016/0378-1127(90)90209-T

Thilenius, J.F., 1995. Phytosociology and succession on earthquake-uplifted coastal wetlands, Copper River Delta, Alaska. Department of Agriculture, Forest Service, Pacific Northwest Research Station, General Technical Report PNW-GTR-346, Portland, pp. 58p.

Tooth, S., 2006. Virtual globes: a catalyst for the re-enchantment of geomorphology? Earth Surf. Process. Land. 31, 1192-1194 DOI: 10.1002/esp.1383

Udías, A., Madariaga, R., Buforn, E., Muñoz, D., Ros, M., 2012. The large Chilean historical earthquakes of 1647, 1657, 1730 and 1751 from contemporary documents. Seismol. Soc. 102, 1639–1653.

Urrutia, R., Lanza, C., 1993. Catástrofes en Chile 1541 –1992. Editorial La Noria, Santiago, pp. 257.

Valdovinos, C. 2004. Ecosistemas estuarions. In: Werlinger, C. (Ed.), Biología marina y oceanografía: Conceptos y procesos. Trama Impresores S.A., Concepción, vol. 2, pp. 395-414.

Valdovinos, C. 2007. Los ambientes costeros hologénicos de Concepción y Arauco. In: Massone, M., Sánchez, M., Quiroz, D., Contreras, L. (Eds.), Cazadores recolectores costeros en la Región del Biobío. Escaparate ediciones, Concepción, pp. 47-61.

Valdovinos, C., Muñoz, M.D., Sandoval, N., Vásquez, D., Olmos, V., 2010. Natural disasters and biodiversity: the case of Tubul-Raqui coastal wetland. Sociedad Hoy 19, 33-51.

Valdovinos, C., Sandoval, N., Vásquez, D., Olmos, V. 2017. The Tubul-Raqui coastal wetland: A Chilean ecosystem of high conservation value severely disturbed by the 2010 Earthquake. In: Fariña, J.M., Camaño, A. (Eds.), The ecology and natural history of Chilean saltmarshes. Springer Nature, Switzerland, :293-327. DOI: https://doi.org/10.1007/978-3-319-63877-5_10

Van Duzor, R. G., 2011. Community structure and secondary production of aquatic macroinvertebrates in coastal wetland ponds of the West Copper River Delta, Alaska, following tectonic uplift. Loyola University Chicago, *Master's Thesis*, pp. 64.

Vásquez, D., 2013. Metodología para la delimitación y zonificación de humedales costeros de tipo mediterráneo. Rev. Geogr. Sur 4, 13-32.

Vergara, O., Carrasco, P., Saavedra, M., Ortiz, J.C., 2008. Fauna del humedal Tubul-Raqui Provincia de Arauco. El Sur, Conama Región del Biobío, Chile, pp. 72.

Wallace, K.J., Callaway, J.C., Zedler, J.B., 2005. Evolution of tidal creek networks in a high sedimentation environment: a 5-year experiment at Tijuana Estuary, California. Estuaries 28, 795-811 DOI: 10.1007/BF02696010

Wesson, R.L., Melnick, D., Cisternas, M., Moreno, M., Ely, L., 2015. Vertical deformation through a complete seismic cycle at Isla Santa Maria, Chile. Nat. Geosci. 8, 547-551 https://doi.org/10.1038/ngeo2468

Yapp, R., John, D., Jones, O., 1917. The Dovey Salt marshes. J. Ecol. 5, 65-103.

Yu, L., Gong, P. 2012. Google Earth as a virtual globe tool for Earth science applications at the global scale: progress and perspectives. Int. J. Remote Sens. 33, 3966-3986 https://doi.org/10.1080/01431161.2011.636081

Zeff, M.L.,1999. Salt marsh tidal channel morphometry: applications for wetland creation and restoration. Restor. Ecol. 7, 205-211 https://doi.org/10.1046/j.1526-100X.1999.72013.x

CAPITULO 5:

EVALUACIÓN DE PERTURBACIÓN NATURAL MEDIANTE INDICADOR EMERGÉTICO

Basado en:

Evaluación de cambios en el uso del suelo en una marisma perturbada por el terremoto 8.8 Mw de 2010-Chile, un nuevo uso del Indicador de Intensidad de Desarrollo del Paisaje (LDI).

Enviada a: Ecological Modelling

Sandoval N., P. L. Lomas, D. Vásquez, P. Fierro, C.Valdovinos.

(2020)

5.5 Capítulo 5: Evaluation of changes in soil use in a marsh perturbed by the 8.8 Mw earthquake of 2010 in Chile: A new use of the of the Landscape Development Intensity.

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Abstrac Earthquakes with coseismic uplift are natural perturbations (NPs) that may significantly modify the littoral geomorphology, altering the connectivity between freshwater and marine ecosystems in coastal wetlands, frequently causing a loss of ecosystem services too. Since current indicators to evaluate ecological impacts are restricted to their use only to the regions or ecosystems for which they were created, there is a need for tools to jointly evaluate ecological impacts and ecosystem services. In this article, the emergy-based LDI index has been assessed before and after the changes caused by the 8.8 Richter earthquake of 2010 in the coastal zone of Chile for both ecological impacts and ecosystem services. Changes in three land uses have been assessed, namely "pelillo" (*Gracilaria spp.*) harvesting, pastures (with livestock) and natural area. The pre-earthquake LDI coefficient for Pelillo harvesting was 2.53, completely disappearing after the perturbation; instead, grazing activities showed a pre-earthquake LDI of 1.73, reducing the level to around 1 after the perturbation. Changes in the total LDI reflected a sudden change in land use, decreasing around 40.6 % as a consequence of a provisioning services loss in the area and the local economy shift to other activities after Pelillo disappearance. The LDI index proved to be a tool providing decision-makers with relevant information when applied to natural perturbations together with other indicators and perspectives.

Resumen Los terremotos con levantamiento cosísmico son perturbaciones naturales (PNs) que pueden modificar significativamente la geomorfología del litoral, alterando la conectividad entre los ecosistemas de agua dulce y marinos en los humedales costeros, causando frecuentemente también una pérdida de servicios de los ecosistemas. Dado que los indicadores actuales presentan limitaciones para evaluar los impactos socio-ecológicos. En este artículo, proponemos el uso del índice de LDI, basado en la emergía para evaluar los cambios del humedal tubul Raqui antes y después del terremoto de 8,8 grados de Richter de 2010. Se evaluaron los cambios en tres usos de la tierra: la recolección del "pelillo" (*Gracilaria* spp.), la ganaderia y el área natural. El coeficiente de LDI anterior al terremoto para la recolección del pelillo fue de 2,53, desapareciendo completamente después de la perturbación; en cambio, las actividades de pastoreo mostraron un LDI anterior al terremoto de 1,73, reduciendo el nivel a alrededor de 1 después de la perturbación. Los cambios en el LDI total reflejaron un cambio repentino en el uso de la tierra, que disminuyó alrededor del 40,6% como consecuencia de la pérdida de servicios de aprovisionamiento en la zona y el cambio de la economía local a otras actividades tras la desaparición de Pelillo. El índice LDI demostró ser un instrumento útil para evaluación y toma de decisions ambientales en ecosistemas impactados por perturbaciones naturales, junto con otros indicadores y perspectivas.

Keywords: Emergy, LDI, Natural Perturbations, Earthquake, Ecosystem Services, Tubul-Raqui wetland

5.5.1 Introduction

A natural perturbation (NP) is an event of change in the biotic and abiotic environment of an ecosystem that causes different responses depending on its origin and magnitude (Goldman Martone and Wasson 2008; Paine et al. 1998; Pickett and White 1985; White, 1979). In accordance with the complexity of the ecological system impacted by a NP, two processes may be initiated. One is succession or restructuring, which allows the ecosystem to continue to function similarly to how it did before the event (Sausa, 1984; Turner et al.1997); the second response leads to a system with a different post-disturbance configuration, a different stability domain (Holling anf Gunderson, 2002; Plafker and Savage, 1970). Changes in domain are more frequently observed in ecotone ecosystems such as coastal wetlands, which due to their transitional condition are permanently exposed to perturbations of different origin (Amstein, 2016; González et al. 2017; Lugo, 2006).

Coastal wetlands have been described as one of the most productive ecosystems of the world; they have high levels of biodiversity and provide multiple ecosystem services (ES) (Daily, 1997; Janse et al. 2019; MA, 2005; McLeod and Leslie, 2009). In Chile, earthquakes that cause lifts in the continental platform in coastal areas are among the NPs that cause most impact in this type of ecosystem (Quezada et al. 2020; Lagos, 2000; Lorca and Recabarren, 1994; Palacios, 2012). These movements of the Earth's crust can modify the littoral geomorphology, altering the connectivity among limnic systems and the ocean, which sometimes causes loss of species such as fish, algae and bivalves which provide provision for nearby communities (Lagos et al. 2019; Marín, 2014).

There are currently few tools to quantify jointly the impact of NPs and their consequences on ES (Troell et al. 2005). Evaluations have traditionally been based on the aquatic biota; they have been classified into three main groups—biotic indices, multimeric indices and multivariate methods (e.g. Nelson 1990; Borja et al. 2000; Wright, 2000; Orfanidis et al. 2001). However, most of these indices were created more to evaluate anthropic perturbations than NPs. Thus they have several requirements that limit their use only to the regions or ecosystems for which they were created. These include the differences in criteria to establish the number and types of variables to include in the evaluation, errors in the application due to different sampling methods and errors in the interpretation of the indices due to seasonality, among others (Burgos and Laurent, 2011; Ligeiro et al. 2020; Martins et al. 2020). This makes it impossible to include freely the ecological factors that fit the dimension of the perturbation.

Indicators based on quantifying emergy flows provide a complementary alternative for evaluation, since they provide a unique theoretical and numerical basis to define, measure and interpret integrally the changes produced in a perturbed ecosystem. Expanding the framework originally opened by ecosystem metabolism (Odum, 1968), emergy was defined as the available energy (i.e., exergy) of one kind that is used-up in transformations directly and indirectly to make a product or service (Odum, 1988; 1996). The unit of emergy is the solar emjoule (sej), and the procedure to estimate the emergy of a certain product or service is called emergy synthesis (Odum, 1996; Brown and Ulgiati, 2004).

Based upon this concept, Brown and Vivas (2004) have developed an assessment method (Landscape Development Intensity Index or LDI), that can be used as a quantitative indicator of human disturbance gradient. The LDI has shown to be efficient in the evaluation of the state of a number of wetlands and the perturbations produced by changes in land use or human (Florida (Reiss, 2006; Lane and Brown, 2007; Nestlerode et al. 2009; Reiss et al. 2010), Minnesota (Bourdaghs et al. 2006), Ohio (Mack, 2006), Arkansas (Vivas and Brown, 2006), South Dakota (Bouchard, 2009), Taiwan (Chen and Lin, 2011), Hawaii (Margriter, 2011), St. Croix (Oliver et al. 2011)), for that the EPA standards in the USA indicate the relevance of its use in different contexts (Fennessy, 2007).

The objective of this study is to explore the use of LDI to evaluate the large-scale NP generated by a mega-earthquake (Mw = 8.8) on a coastal wetland, using the Tubul-Raqui wetland of Chile as a study case. We do this by comparing the conditions before and after the perturbation, to estimate the structural and functional changes suffered by the ecosystem and their consequences in terms of human disturbance.

5.5.2 Material and methods

5.5.2.1 The Tubul-Raqui wetland as a study case

As a study case, the Tubul-Raqui coastal wetland, located in the extreme south of the Arauco Gulf in south-central Chile (37°13´S; 73°26´W) has been evaluated (Figura 5.5-1). This wetland was developed due to the presence of an estuarine system. Until 2010, it was considered one of the most productive of the area due to its high biodiversity and active economic development linked to the red algae called "pelillo" (*Gracilaria* spp.) and harvesting of the bivalve mollusks "navajuela" and "macha" (*Tagelus dombeii, Ensis macha,* respectively) (Marín et al. 2012, 2014; Stuardo et al. 1993; Valdovinos et al. 2010, 2011).

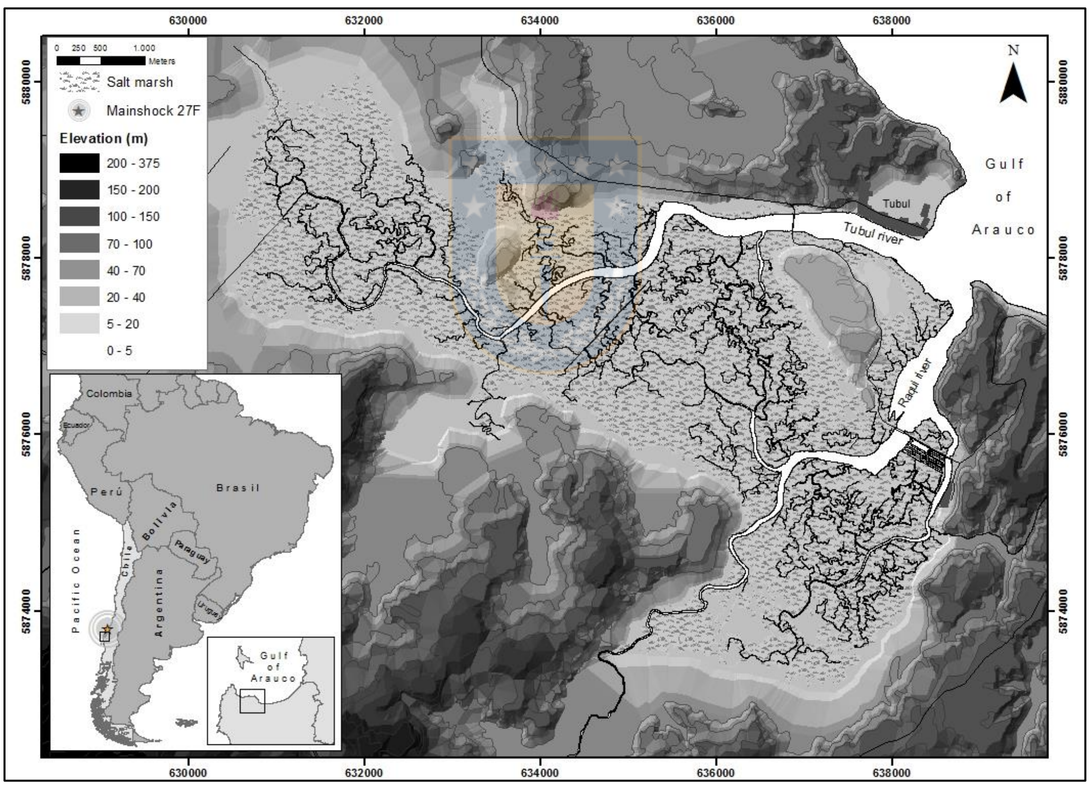

Figura 5.5-1 Study area: Tubul-Raqui wetland impacted by the 8.8 Richter earthquake which occurred on February 27, 2010.

The 8.8 magnitude earthquake of February 27, 2010 (27F) generated a coseismic uplift of ~1.6 m (Farías et al. 2010; Vargas et al. 2011; Quezada et al. 2012, Melnick et al. 2012), which interrupted the interchange between the marine and fluvial environments that originated the estuary. This blockage dried 90% of the intertidal channels and saline pools of the marsh (Vásquez et al. 2017, 2020) (Figura 5.5-2), affecting the abundance of the benthic species commercialized by nearly 200 families of the locality of Tubul (FAO, 2013), which is located in the northeast of the marsh, beside the outlet of the Tubul River (Figura 5.5-1).

Figura 5.5-2 Scenario before and after the co-seismic uplift caused by the 8.8 Mw earthquake, showing with (A) and without (B) marine intrusion.

A combination of field work and computation techniques was used to identify the area devoted to economic purposes within the Tubul-Raqui wetland, including remote sensing analysis and consultation with the government organisms in charge of controlling, regulating and supervising these activities (Servicio Nacional de Pesca and Ministerio del Medio Ambiente de Chile).

The economic activities identified were harvesting of the algae *Gracilaria chilensis*, extraction of *Tagelus dombeii* and cattle farming in the saline *Spartina densiflora* grasslands. The digitization and quantification of the hectares of the uses was performed with ArcGis© based on the Datum WGS-84 Huso 18. For this, we used the base map generated in the studies of Vázquez et al. (2017, 2020), from which we obtained the area of wetland pre- and post-earthquake based on the presence of *S. densiflora*, using a buffer of 100 m on both sides of the channel. Two satellite images were chosen to determine the changes produced by the perturbation, October, 2009 for pre-earthquake and August, 2011 for post-earthquake. Both images were concordant with those used in Vázquez et al. (2020), provided by Digital Globe (now Maxar Technologies) with a pixel resolution of ~0.50 m using the free Google Earth software.

5.5.2.2 Landscape Development Intensity Index

Two temporal scenarios were defined to analyze the modifications produced by 27F on the Tubul Raqui coastal wetland—pre-earthquake (2009) and post-earthquake (immediately after the 2010 NP). These scenarios have been evaluated by using the LDI. As mentioned before, Brown and Vivas (2004) proposed an LDI which estimated the degree of human perturbation in a given area. Following their proposal, an LDI was calculated using the following equation:

$$\mathbf{LDI_{Total} = \sum \%LUi \times LDIi}$$

Where LDI_{Total} = LDI or classification per landscape unit

%LUi = percent of the total area of influence in land use i

LDIi = landscape development intensity coefficient for land use i.

The LDI_i coefficients were calculated as the normalized natural logarithms of the non-renewable empower densities (i.e., non-renewable flows and purchased inputs, such as labor).

The metric used to quantify human activity in the LDI was the emergy per unit area per unit of time, or areal empower density (Vivas and Brown, 2006). To calculate empower density for each land use unit, an emergy synthesis has to be developed. Emergy synthesis is a well-known evaluation process of social-ecological systems performance based on the emergy concept (Odum, 1996; Brown and Ulgiati, 2004). The outcome of an emergy synthesis is the assessment of total emergy used (i.e., the areal empower density) and the unit emergy value (UEV) of the system assessed, i.e., in this case, the different land uses. The UEV is the amount of emergy used per unit of product of system. It depends on the product or system evaluated. In this case, the product is accounted in terms of the exergy (i.e., the available energy), so that the UEV is called transformity (Odum, 1988; 1996), and expressed in solar emjoules (sej) per exergy unit (J) or sej/J units. Since the geobiosphere baseline for emergy calculations is controversial (Brown et al. 2016, Brown and Ulgiati, 2016a, Brown and Ulgiati, 2016b, Campbell, 2016)), in this work we have used the baseline proposed by Brown et al. (2016) based on the global emergy flow value= 9,58E+25 sej/yr. Changing the baseline for updated calculations can be easily made, as elsewhere explained (Campbell, 2016). In these evaluations, only fuels for the different machinery and purchased labor are included as non-renewable flows within the areal empower density.

5.5.3 Results

5.5.3.1 Changes in land use before and after the earthquake

To analyze the change in territorial use pre- and post-earthquake, we quantified the total area of decrease in the inundation of the coastal wetland, then delimited the active culture zones for 2009 and 2010. The quantification shown in Figura 5.5-3 considered post-earthquake loss of wetland to desiccated areas that bordered non-humid zones; this is shown in yellow and comprises 132.85 h. (2,44 % of the wetland).

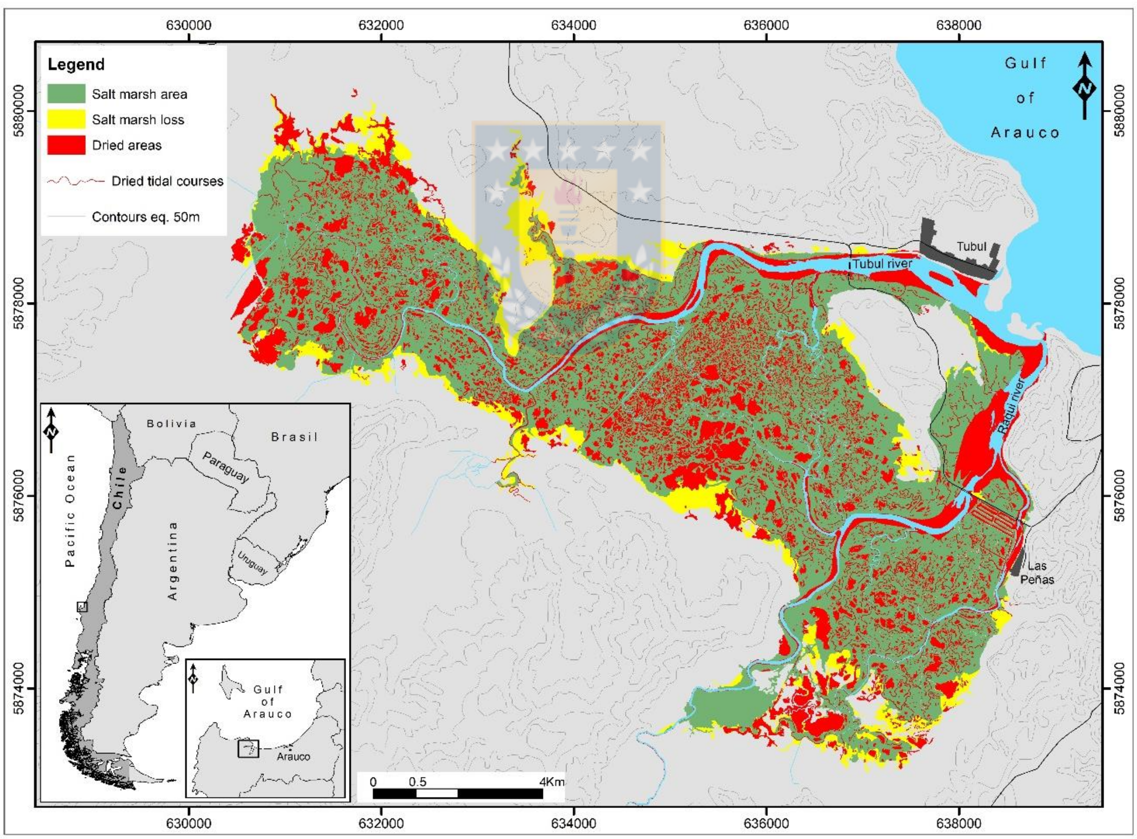

Figura 5.5-3 Effect of the decrease of marine intrusion on the Tubul-Raqui coastal wetland.

Tabla 5.5-1 Land uses in the Tubul-Raqui wetland in hectares (ha) and percentages before and after the earthquake.

Land use	Area (ha)		Percentage of the area (%)	
	2009	2010	2009	2010
Navajuela harvesting	23.00	0	0.4	0
Pelillo harvesting	166.1	0	3.1	0
Grazing	583.3	829.3	10.7	15.7
Natural area	4,654.1	4,464.4	85.8	84.3

Figura 5.5-4 y Tabla 5.5-1 show the changes in territorial use in 2009 (pre-) and 2010 (post-earthquake). Collection of Navajuela (*Tagelus dombeii*) occurred in 23 ha of the wetland, occupying 0.42% of the area. Harvesting of "pelillo" (*Garcilaria* spp.), which was about 2,000 t/year (SERNAPESCA, 2008), occurred in about 166.1 ha, around 3.1% of the wetland. Until 2009, the area where cattle grazing was possible was limited by the inundation zones which were part of the dynamics of the coastal wetland (MBN, 2008; this occurred in 583.3 ha or 10.7% of the total area. After the earthquake, the desiccation of the wetland increased the cattle grazing area to reach 4.92% (245.9 ha).

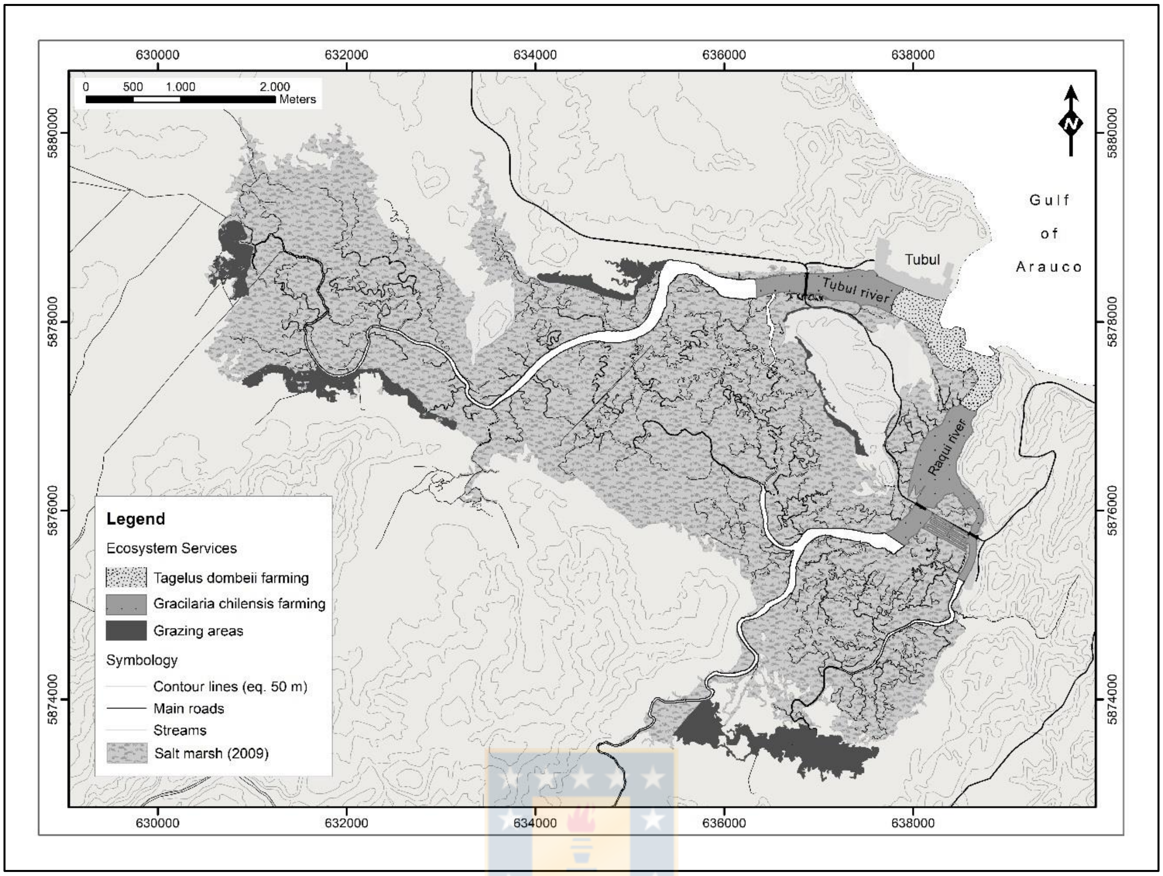

Figura 5.5-4 Provisioning ecosystem services in the study area for a pre-earthquake scenario (2009).

5.5.3.2 Estimation of changes due to the earthquake by emergy synthesis

5.5.3.2.1 Flow diagrams

To evaluate the system pre- and post-earthquake, the interactions between the biotic and abiotic environment through energy flow diagrams have been represented.. Figura 5.5-5 indicates the main sources of energy input (left of the diagram) that existed in the wetland before the NP. These included tides, which provided salty-freshwater conditions to the aquatic medium, allowing the development of halophytes (*S. densiflora*) and important commercial estuarine species (pelillo and macha) which defined the local market.

regulated the presence of small mammals (rodents) and limited movement of cattle in the wetland (CEA, 2006). Until 2009 cattle grazing occurred in only a few natural places of the wetland, open areas or those away from the outlet, where soil humidity was low enough to allow this activity. There was a high diversity of birds, which were top predators and vectors between the aquatic and terrestrial environment (right side of the diagram).

The ecosystem function shown in the 2009 flow diagram shows a complex system, which was simplified in 2010 after the earthquake (Figura 5.5-5). The influx of the ocean totally disappeared as a consequence of the co-seismic lift, limiting the estuarine condition of the wetland, which produced the loss of provisioning ecosystem services associated with the sale of benthonic estuarine products (Gracilaria spp. and Tagelus sp.). This phenomenon did not occur with the halophyte S. densiflora, whose cover was not reduced. However, it had to share the niche with opportunistic species (e.g. Cotula coronopifolia, Lythrum hissopifolia, Chenopodium album), which rapidly colonized the areas dried up (Figura 5.5-6).

The low-intensity grazing in the study area before the earthquake increased its interaction with the ecosystem after it, due to use of the dried soil (Figura 5.5-7a), where cattle could move freely and feed on the emerging opportunistic plants. The desiccation also favored the presence of macro- and micromammals (dogs and rodents) while the abundance of estuarine fish was reduced after the earthquake. Birds did not show an important reduction, nor did the benthonic infauna.

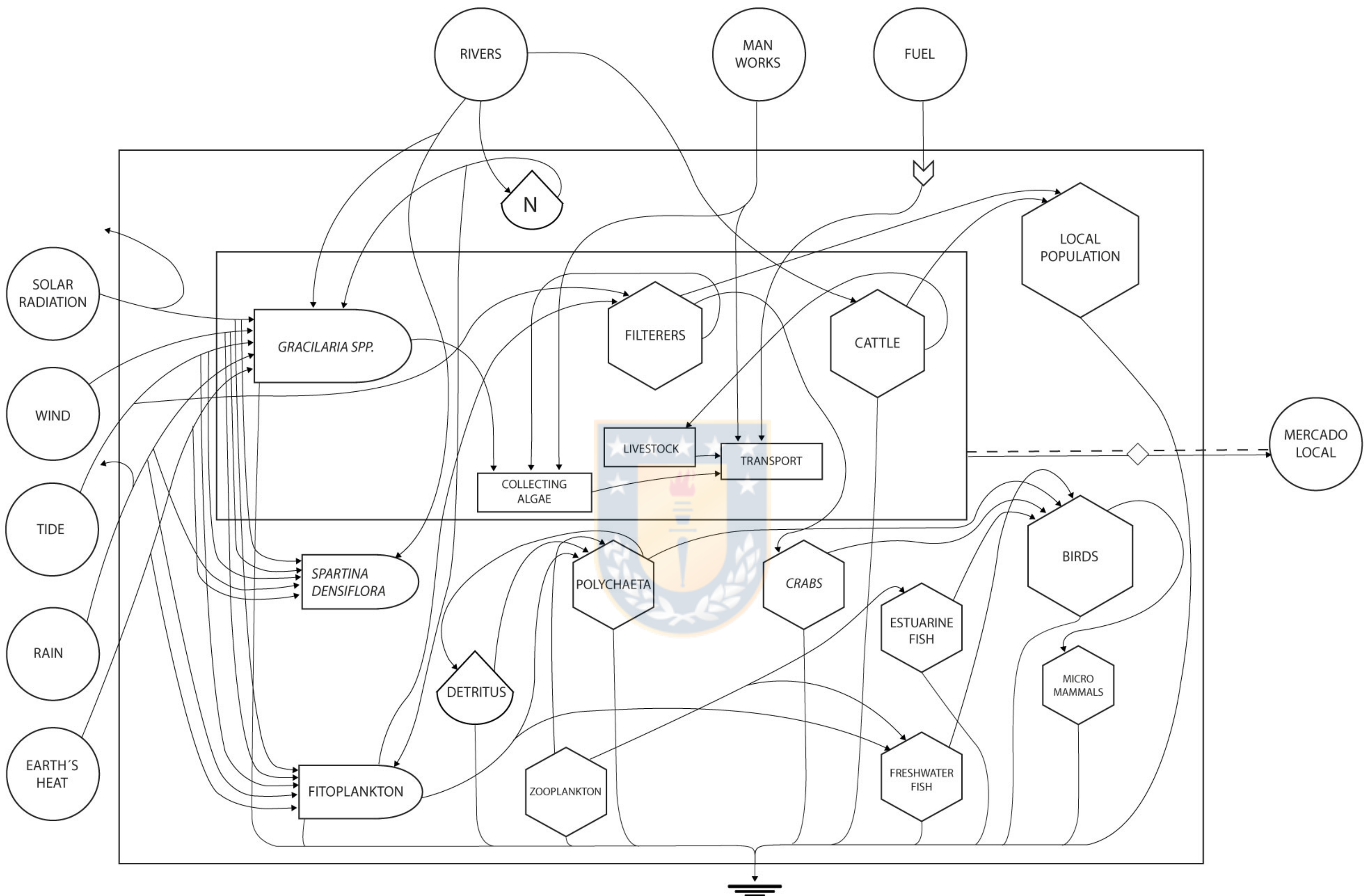

Figura 5.5-5 Pre-earthquake (2009) energy flow diagram of the Tubul-Raqui coastal wetland

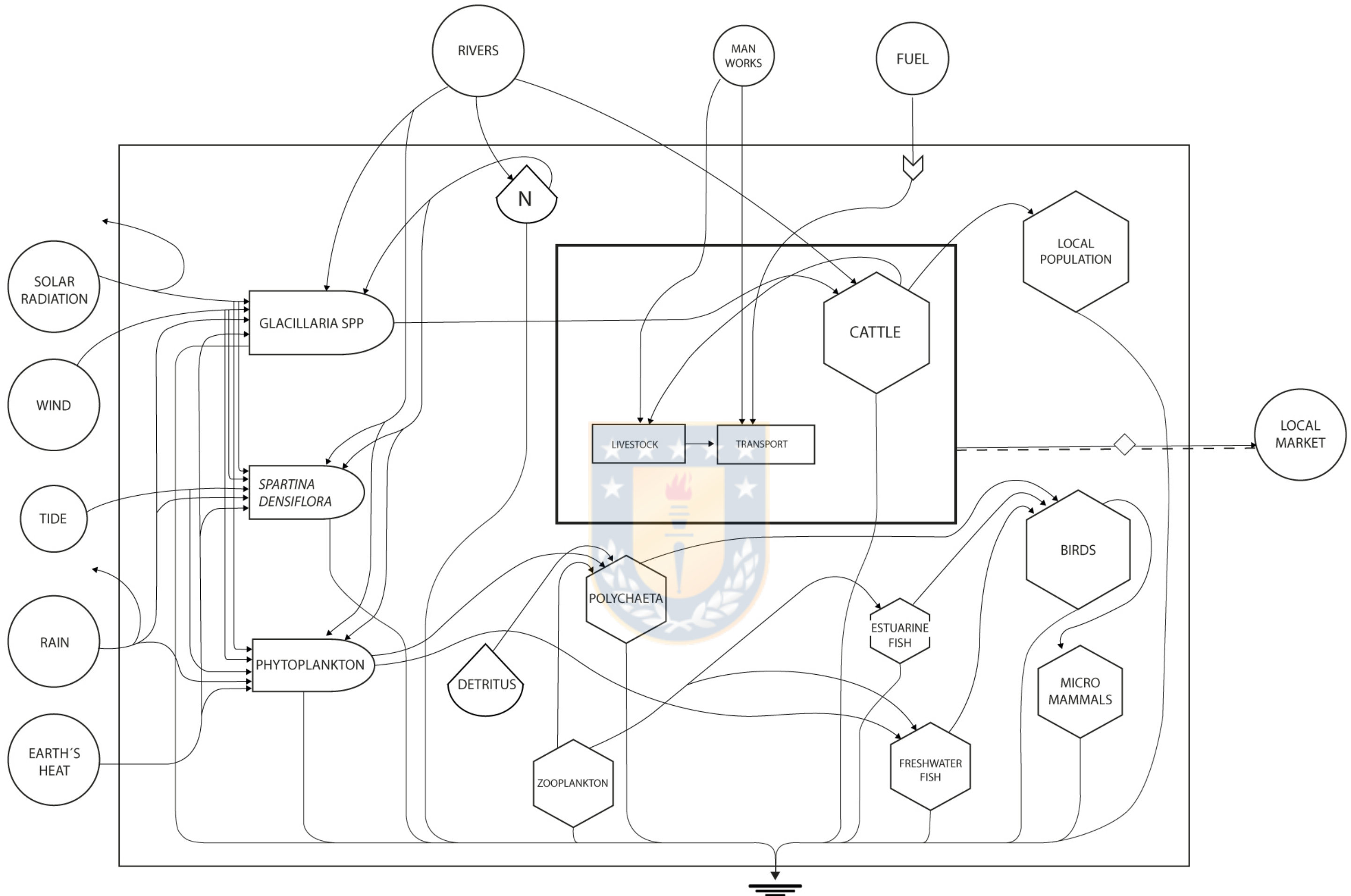

Figura 5.5-6 Post-earthquake (2010) energy flow diagram of the Tubul-Raqui coastal wetland .

Figura 5.5-7 Provisioning ecosystem services in the Tubul-Raqui coastal wetland: a) low-intensity cattle grazing in highland areas of the wetland; b) and c) different transport modes for the pelillo harvesting activity.

5.5.3.2.2 Emergy synthesis

Once the energy flows were conceptually delimited (Figura 5.5-5 y Figura 5.5-6), emergy flows for the contrasting periods were calculated. The equations given in Appendix A also included the main modifications suffered by the abiotic components of the wetland after the NP (2010).

Equations 1, 2, 4, 5 and 6 of Appendix A quantify the temporal variability of the renewable flows of the system between 2009 and 2010 for the different areas defined by land uses, while equations 3, 7 and 10 estimate the changes caused by the environmental perturbation. Equation 4 includes the area reached by the tide, which in 2009 included 2,411.12 m^2; after the earthquake its value was reduced to zero. Equation 7 differentiates the height of the inflow and outflow of the rivers; the inflow height was maintained at 5 m between 2009 and 2010, but the outflow level changed from 0 m to 1.6 m elevation in 2010 8 (AE), so that the coastal lifting was included. Equation 10 considers the waves absorbed by the shore; this estimation considered the upper limit of the coastline to be the height reached by the sea at high tide (SHOA, 2013). The non-renewable source were fossil fuels, which are used to feed vehicles and machines, and purchased labor.

Tabla 5.5-2 Emergy values of renewable source for the different land uses in the Tubul-Raqui wetland, before (2009) and after (2010) the earthquake

Land use	Energy flow	Exergy (J) 2009	Exergy (J) 2010	Transformity (sej/J)	Ref. trans.	Empower density (sej/ha/yr) 2009	Empower density (sej/ha/yr) 2010
Pelillo harvesting	Direct sunlight	9.85E+15	----	1	A	5.93E+13	----
	Kinetic energy of wind used at surface	2.42E+13	----	832	B	1.21E+14	----
	Tide absorbed in estuaries	4.34E+12	----	30,900	C	8.07E+14	----
	Chemical potential energy in rain	1.82E+13	----	7,276	B	7.96E+14	----
	Chemical potential energy in river	7.81E+02	----	82,684	A	3.89E+05	----
	Geopotential in inflowing rivers	3.97E+01	----	47,560	A	1.14E+04	----
	Earth cycle	3.20E+12	----	12,000	D	2.31E+14	----
	Ocean waves absorbed at the shore	1.54E+13	----	52,126	A	4.82E+15	----
	Σ					**6.83E+15**	**0**
Navajuela harvesting	Direct sunlight	1.36E+15	----	1	A	5.93E+13	----
	Kinetic energy of wind used at surface	3.35E+12	----	832	B	1.21E+14	----
	Tide absorbed in estuaries	4.34E+12	----	30,900	C	5.83E+15	----
	Chemical potential energy in rain	2.52E+12	----	7,276	B	7.96E+14	----
	Chemical potential energy in river	7.81E+02	----	82,684	A	2.81E+06	----
	Geopotential in inflowing rivers	3.97E+01	----	47,560	A	8.20E+04	----
	Earth cycle	4.43E+11	----	12,000	D	2.31E+14	----
	Ocean waves absorbed at the shore	1.54E+13	----	52,126	A	3.48E+16	----
	Human work (collecting)	8.49E+07	----	682,505	A	2.52E+12	----
	Σ					**4.18E+16**	**0**
Cattle Grazing	Direct sunlight	3.46E+16	4.78E+16	1	A	5.93E+13	5.76E+13
	Kinetic energy of wind used at surface	8.50E+13	1.13E+14	832	B	1.21E+14	1.13E+14
	Chemical potential energy in rain	6.38E+13	4.68E+13	30,900	B	3.38E+15	1.74E+15
	Chemical potential energy in river	7.85E+03	4.45E+02	7,276	A	9.80E+04	3.90E+03
	Geopotential in inflowing rivers	3.97E+01	1.54E+01	82,684	A	5.62E+03	1.53E+03
	Earth cycle	1.12E+13	1.60E+13	47,560	D	9.16E+14	9.15E+14
	Σ					**4.48E+15**	**2.83E+15**

Note: A. Odum, 1996; B. Brow and Ulgiati, 2016; C. Brown et al. 2016; D. Odum et al. 2000; All transformities have been reported to 1.58E+25 baseline (Brown et al. 2016).

5.5.3.2.3 Coefficients of intensity of landscape development (LDI) for each unit of soil use

The Figura 5.5-8 shows the different units of land use and their emergy values for the renewable flows of the system. Land dedicated to pelillo and navajuela collection, which before the earthquake presented a renewable emergy of 6.83E+15 y 4.18E+16 sej/ha/yr, respectively, showed an important change after the NP, given that the sources of renewable energy that entered the system were not used by these species in 2010. The renewable empower density for cattle grazing decreased from 4.48E+15 (sej/ha/yr) in 2009 to 2.83E+15 (sej/ha/yr) in 2010, due to the 2009-2010 change in the river chemical potential (9.80E+04 sej/ha/yr to 3.90E+03 sej/ha/yr).

The total renewable emergy in 2009 was 5.32E+16 sej/ha/yr, and after the earthquake in 2010 it was 2.83E+15 sej/ha/yr. The total non-renewable flows before the earthquake were 1,96E+15 sej/ha/yr, and after the earthquake (2010) 2,80E+14 sej/ha/yr, showing a decrease of 85.7%.

The total emergy of the renewable sources in 2009 was 2,00 E+18 sej/ha/yr, and after the earthquake in 2010 it was 5,50E+17 sej/ha/yr, indicating that 72.4% of the emergy was not used for the uses described in 2010. The total non-renewable sources before the earthquake was 1,57E+15 sej/ha/yr, and after the earthquake (2010) 9,96E+14 sej/ha/yr, a decrease of 33.5%.

The emergy evaluation of non-renewable sources (Tabla 5.5-3), applies for the collection of the alga pelillo and cattle grazing. The non-renewable sources for pelillo collection are the use of petroleum for the functioning of the tractors (Figura 5.5-7b) and labor. This machinery enters the estuary and moves the bales of algae to the beach shore, to be deposited in trucks that take the product to different destinations (Figura 5.5-7c). The nonrenewable empower density until 2009 was 1.36E+15 sej/ha/yr, and due to the loss of the service it could not be quantified in 2010. The non-renewable sources for cattle grazing were also the fuel used and labor. Before the earthquake in 2009, its value was 5.96E+14 sej/ha/yr, and after the earthquake in 2010 it was 2.80E+14 sej/ha/yr. The difference in the total non-renewable emergy of the system between 2009 and 2010 was 1.68E+15 sej/ha/yr. There was a non-renewable flow (labor) of 2.52E+12 sej/ha/yr associated with navajuela collection, but it has been considered as negligible.

Tabla 5.5-3 Emergy values of non-renewable sources and LDI coefficients for the different land uses in the Tubul-Raqui wetland, before (2009) and after (2010) the earthquake.

Land use	Non- renewable sources	Exergy (J)		Transformity (sej/J)	Ref. trans.	Non-renewable Empower density (E+14 sej/ha/yr)		Ln Non-renewable empower density		LDI coefficients (1 to 10)	
		2009	2010			2009	2010	2009	2010	2009	2010
Pelillo harvesting	DIESEL TRACTOR	7.95E+08	----	49,289	E	13.6	----	2.61	----	2.53	----
	LABOR	3.31E+11	----	682,505	A						
Cattle grazing (low-intensity)	DIESEL VEHÍCULO	1.65E+10	1.10E+10	49,289	E	5.96	2.8	1.79	1,03	1.73	1.00
	LABOR	5.09E+11	3.39E+11	682,505	A						

5.5.3.3 *Landscape Development Intensity (LDI) index for each unit of land use*

Changes in the area and LDI coefficients for the different land use units are illustrated in Figura 5.5-8. We calculated the LDI coefficient using non-renewable empower density. For the pelillo harvesting land use unit, the coefficient was 2.53 in the year 2009. After the earthquake in 2010 the area used for pelillo harvesting changed to a natural use, thus its LDI = 1, according to the definition of Brown & Vivas (2005). Cattle grazing presented a pre-earthquake LDI index of 1.73, decreasing to around 1 after the event.

The total LDI decreased from 26.33 for 2009 to 15.63 for 2010. This LDI index reflects a sudden change in the intensity of land uses, which decreased by 40.6%.

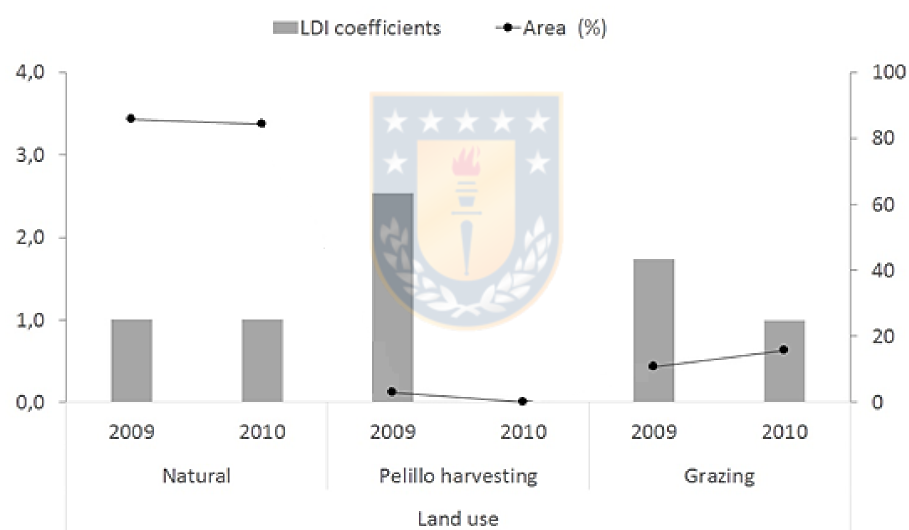

Figura 5.5-8 LDI coefficients and percentages of area for each land use defined in the Tubul-Raqui wetland before and after the earthquake.

5.5.4 Discussion

Given the evident impacts of the 8.8 Richter earthquake on the Tubul-Raqui wetland, there is a need to find criteria and evaluation methods to include the results produced in this ecosystem by using different scientific disciplines, including geomorphology (Vásquez et al., 2017, 2020), ecological economics (Marín et al. 2012, 2014), limnology (Valdovinos et al., 2010, 2011) and plate tectonics (Quezada et al., 2012), among others. For this reason, the LDI was used for the first time in Chile to analyze large-scale natural perturbations.

The LDI was selected because it allowed to have a complex vision of the perturbed system using emergy, which reflected the changes in the ecosystem structure and function and made them comparable for different periods (Ulgiati & Brown, 2009). As showed by the energy flow diagrams for pre- and post-earthquake conditions, the removal of the sea entrance to the wetland changed the estuarine condition of the system, making it freshwater; this impeded the colonization of *Gracilaria* spp. algae after the earthquake (Rojas et al. 2017). Along with this, lack of connectivity with the ocean limited the influx of larvae of *Tagelus dombeii* into the estuary, which reduced significantly the collection of this bivalve (Belnal et al. 2010, Castilla et al. 2010). These two species had complex interactions in the aquatic ecosystem before 27F which were significantly reduced after the earthquake. Regarding the energy outflows, the local market was reduced to small-scale cattle farming for the elaboration of milk and other products (Cid-Aguayo, 2019).

The LDI equation included the quantification of land uses, which are direct drivers of change in ecosystem services provision (MEA, 2005; Uddin et al., 2015). Our results show a complete wetland transformation mainly in the external borders as a result of the desiccation. However, the wetland still covered a wide area, delimited by the *Spartina densiflora*, whose land cover was maintained after the earthquake despite the huge desiccation of channels and borders of rivers (Valdovinos et al. 2010). The disappearance of the algae and bivalves harvesting after the earthquake re-naturalized the outlet zone, so that the ecosystem retrieved a more natural functioning. This may favor a greater entrance of coastal migratory birds which use the wetland as a refuge (Senner et al., 2017; CECPAN, 2012).

The estimation of renewable and non-renewable flows needed to emergy synthesis in the LDI calculation (Brown & Vivas 2005) stress the traditional characterization of the activities performed in the Tubul-Raqui wetland until 2009, since the non-renewable emergy flows were limited only to the use of fossil fuels for a reduced number of vehicles and machines (collection of pelillo and cattle grazing) and labor. The highest value of the empower density was for pelillo, which was the most important extraction from the wetland (Bravo, 2011). This result reflects that emergy is capable of covering the cost of nature to generate a product or service (Odum, 1996). The total emergy shows the loss of the estuarine species used as a resource after the earthquake. In the cattle grazing unit, this effect has not been found, and pre- and after-earthquake differences were the result of environmental changes.

Changes in the estuarine algae LDI are explained by the direct effects of the earthquake. Instead, changes in the cattle grazing LDI can be explained by the increase in land use area (4.9 %), but maintenance in the livestock numbers, leading to a decrease in the land use intensity. Also, the partial destruction of pathways and bridges as a consequence of the earthquake limited the activity during 2010, so that the LDI coefficients have been affected.

The total LDI of the emergy showed an important decrease in the intensity of activities over the area after the earthquake. The decrease quantifies the initial impact on an ecosystem that change of LDI total= 26.33 (before PN) to 15.63 after for that (decreased 40,6%). That is, the wetland configuration changed due to the coastal uplifting from a highly productive estuarine system with a rich variety of provisioning ecosystem services (Marín et al 2014, Rojas et al., 2017) to a freshwater wetland with important desiccated zones, and a loss of ecosystem services (Sandoval et al, 2019). This could be interpreted as a positive effect from a pure ecological point of view, but at the same time it can increase the vulnerability of the wetland to anthropic and natural perturbations given that the wetland does not have a protection category that guarantees its conservation.

5.5.5 Conclusions

The 27F earthquake in Chile was a natural perturbation of great magnitude that modified the structure and functioning of the Tubul-Raqui wetland. The main consequence of this NP was the transformation of the ecosystem from an estuarine to a freshwater stability domain, which caused the loss of ecosystem services such as artisanal collection of estuarine products and an increase in cattle grazing activities.

In this article, the emergy-based LDI index has been used to unify some of the most relevant assessments elaborated by different disciplines and compare the new status reached after the earthquake with that existing before the natural perturbation in the Tubul-Raqui wetland.

This first use of the LDI in Chile validated its use to quantify the effects of a seismic natural perturbation on a coastal wetland, and proved to be a relevant tool which may be applied in environmental evaluations to support decision-making processes regarding natural areas.

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5.5.6 References

Amstein, S., 2016. Los humedales y su protección jurídica en Chile. Memoria para optar al grado de Licenciada en Ciencias Jurídicas y Sociales. Universidad de Chile, Santiago.

Bastianoni, S., Campbell, D.E., Ridolfi, R., Pulselli, F.M., 2009. The solar transformity of petroleum fuels. Ecol. Modell. 220, 40-50.

Bernal, C., Ariz, L., Olguín, A., Aguilera, A., Villarroel, N., Mora, S., López, H., 2010. Efectos del terremoto y maremoto del 27 de febrero en las caletas de la V a la IX Regiones. Informe Especial IFOP-SERNAPESCA, Valparaíso.

Beyá, J., Álvarez, M., Gallardo, A., Hidalgo, H., Aguirre, C., Valdivia, J., Parra, C., Méndez, L., Contreras, F., Winckler, P., Molina, M., 2016. Atlas de Oleaje de Chile. Primera edición. Universidad de Valparaíso, Valparaíso, Chile.

Borja, A., Franco, J., Pérez, V., 2000. A marine biotic index to establish the ecological quality of soft bottom benthos within European estuarine and coastal environments Mar. Pollut. Bull. 40, 1100-1114.

Bouchard, M., 2009. Wetland resources of Eastern South Dakota; drainage patterns, assessment techniques, and predicting future risks. South Dakota State University, South Dakota.

Bourdaghs, M., Campbell, D., Genet, J., Gernes, M., Brandt-Williams, S., 2006. Development of the Landscape Development Index as a Wetland Condition Assessment Tool. Final status report under EPA assistance AW-96569201-0. US Environmental Protection Agency, Washington, DC.

Brandt-Williams, S.L., 2002. Folio 4: emergy of florida agriculture (2nd printing).In: Handbook of Emergy Evaluation. Center for Environmental Policy.University of Florida, Gainesville, FL, USA.

Bravo, G., 2011. 3:34 A.M. la apuesta del Amanecer: crisis y resurgimiento de las comunidades de pescadores artesanales de Tubul y Lico tras el 27/F. Memoria de título conducente al grado de Periodista. Universidad de Chile.183 pp.

Brown, M.T. and Ulgiat S., 2016. Updated evaluation of exergy and emergy driving the geobiosphere: A review and refinement of the emergy baseline,Ecological Modelling.Vol. 221, 20: 2501-2508.

Brown, M.T. and Ulgiati, S., 2016. Emergy assessment of global renewable sources. Ecol. Modell. 339, 148-156.

Brown, M.T. and Ulgiati, S., 2016a. Assessing the global environmental sources driving the geobiosphere: A revised emergy baseline. Ecol. Modell. 339, 126-132.

Brown, M.T., Campbell D. E., De Vilbissa C., Ulgiati S., 2016. The geobiosphere emergy baseline: A synthesis. Ecological Modelling. 339 92–95.

Brown, M.T., Vivas, M.B., 2005. Landscape development intensity index. Environ. Monit. Assess. 101, 289–309.

Burgos, E., Laurent, J.M., 2011. Términos de referencia línea base de las áreas protegidas de la bahía de tela. Secretaría de Turismo de Honduras, Banco Interamericano de Desarrollo

Campbell, D. E., 2016. Emergy baseline for the Earth: A historical review of the science and a new calculation. Ecological Modelling. 339, 96-125.

Castilla, J.C., Manríquez, P.H., Camaño, A., 2010. Effects of rocky coseismic uplift and the 2010 Chilean mega-earthquake on intertidal biomarker species. Mar. Ecol. Prog. Ser. 418, 17-23.

CECPAN (Centro de Estudio y Conservación del Patrimonio Natural), 2012. Censos Nacionales de Aves Acuáticas (Resumen de Información de Censos y Monitoreo 2011 – 2012). Servicio Agrícola y Ganadero, Santiago.

Centro de Ecologia Aplicada (CEA) - Conama., 2006. Estúdios de línea de base Humedal Tubul-Raqui. Informe final. 102 pp

Chen, T., Lin, H., 2011. Application of a landscape development intensity index forassessing wetlands in Taiwan. Wetlands 31, 745–756.

Cid-Aguayo, B., Vanhulst, J., Rojas, C., 2019. Retroinnovación y sustentabilidad socioecológica: el caso de quesos campesinos de leche cruda en el Golfo de Arauco, Chile. Mundo Agrario. 20, e119.

Daily, G.C. (Ed.), 1997. Nature's Services: Societal Dependence on Natural Ecosystems. Island Press, Washington, DC.

DGA (Dirección General de Aguas), 2020. Información Oficial Hidrometeorológica y de Calidad de Aguas en Línea. Estación Curanilahue en Curanilahue, Biobío-Chile. https://snia.mop.gob.cl/BNAConsultas/reportes (accessed 15 June 2020).

DGAC (Dirección General de Aeronáutica Civil), 2010. Anuario climatológico 2009. 2010. Ed. Dirección Meteorológica de Chile. Subdepartamento Climatología y Meteorología Aplicada, Santiago.

Dooley, J.M., Brown, M.T., 2020. The quantitative relation between ambient soundscapes and landscape development intensity in North Central Florida. Landsc. Ecol. 35, 113–127.

Faranda, F., Parra, O., Stuardo, J., 1993. . Los ambientes costeros del Golfo de Arauco y área adyacente. Serie Monografías Científicas, Centro EULA (Chile), Concepción.

Farías, M., Vargas, G., Tassara, A., Carretier, S., Baize, S., Melnick, D., Bataille, K., 2010. Land level changes produced by the 2010 Mw 8.8 Chile earthquake. Science 329, 916-920.

Fennessy, M.S., Mack, J.J., Deimeke, E., Sullivan, M.T., Bishop, J., Cohen, M., Micacchion, M., Knapp, M., 2007. Assessment of wetlands in the Cuyahoga River watershed of northeast Ohio. Ohio Environmental Protection Agency, Division of Surface Water, Wetland Ecology Group, Columbus.

Garcés-Vargas, J., Ruiz, M., Pardo, L.M., Nuñez, S., Pérez-Santos, I., 2013. Caracterización hidrográfica del estuario del río Valdivia, centro-sur de Chile. Lat. Am. J. Aquat. Res. 41, 113-125.

Goldman Martone, R., Wasson, K., 2008. Impacts and interactions of multiple human perturbations in a California salt marsh. Oecologia 158, 151–163.

González, P., Ortiz, S., Jerez, R., Pávez, M., Arcos, D., 2017. Effects of the 2010 Tsunami on the Mataquito River Wetland, in: Fariña, J.M., Camaño, A. (Eds.), The Ecology and Natural History of Chilean Saltmarshes. Springer, Charm, pp. 265-292.

Grob, C., Quiñones, R.A., Figueroa, D., 2003. Cuantificación del transporte de agua costa-océano a través de filamentos y remolinos ricos en clorofila a, en la zona centro-sur de Chile (35.5-37.5ºS) Gayana 67, 55-67.

Holling, B., Gunderson, L., Peterson, G., 2002. Sustainability and Panarchies, in: Gunderson, L.H., Holling, C.S. (Eds.), Panarchy: Understanding Transformations in Human and Natural Systems. Island Press, Washington, D.C, pp. 63-102.

Janse, J.H., van Dam, A.A., Hes, E.M.A., de Klein, J.J.M., Finlayson, C.M., Janssen, A.B.G., van Wijk, D., Mooij, W.M., Verhoeven, J.T.A., 2019. Towards a global model for wetlands ecosystem services, Curr. Opin Env. Sust. 36, 11-19.

Khalil, A., Asheini, A., 2015. The chances and challenges for renewable energy in Libya The 4th International Conference on Renewable Energy Research and Applications, Palermo, pp. 1-6.

Lagos, N., Labra, F.A., Jaramillo, E., Marín, A., Fariña, J.M., Camaño, A., 2019. Ecosystem processes, management and human dimension of tectonically-influenced wetlands along the coast of central and southern Chile. Gayana. 83, 57-62.

Lane, C.R., Brown M.T., 2007. Diatoms as indicators of isolated herbaceous wetland condition in Florida, USA. Ecol Ind 7:521–54.

Ligeiro, R., Hughes, R.M., Kaufmann, P.R., Heino, J., Melo, A.S., Callisto, M., 2020. Choice of field and laboratory methods affects the detection of anthropogenic disturbances using stream macroinvertebrate assemblages. Ecol. Indic. 115, 106382.

Lorca, E., Recabarren, M., 1994. Terremotos y Tsunamis o Maremotos. Servicio Hidrográfico y Oceanográfico de la Armada de Chile, Comisión Oceanográfica Intergubernamental, Centro Internacional de Informaciones de Tsunami, Santiago.

Lugo, A.E, 2006. Ecological lessons from an island that has experienced it all. Ecotropicos. 19, 57-71.

MA (Millennium Ecosystem Assessment). 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washingon, DC.

Mack, J.J., 2006. Landscape as a predictor of wetland condition: an evaluation of the landscape development index (LDI) with a large reference wetland dataset from Ohio. Environmental Monitoring and Assessment 120, 221–241.

Margriter, S.C., 2011. Assessing the condition of Hawaiian coastal wetlands using amulti-scaled approach. University of Hawaii, Manoa, Hawaii (Masters thesis).

Marín, A., Gelcich, S., Castilla, J.C, 2014. Servicios ecosistémicos y transformaciones abruptas en un sistema socio-ecológico de humedales costeros: Tubul-Raqui después del terremoto de 2010 en Chile. Ecol. Soc., 19, 2.

Marín, A., Gelcich, S., Castilla, J.C., 2014. Ecosystem services and abrupt transformations in a coastal wetland social-ecological system: Tubul-Raqui after the 2010 earthquake in Chile. Ecol. Soc. 19. 22-34.

Marín, A., Gelcich, S., Castilla, J.C., Berkes, F., 2012. Exploring Social Capital in Chile's Coastal Benthic Comanagement System Using a Network Approach. Ecol. Soc. 17, 13.

Martins, I., Rodrigues Macedo, D., Hughes, R.M., Callisto, M., 2020. Are multiple multimetric indices effective for assessing ecological condition in tropical basins? Ecol. Indic. 110, 105953.

McLeod K.L., Leslie, H.M., 2009. Why ecosystems-based management?, in: McLeod K.L., Leslie, H.M (Eds.), Ecosystem-based management for the oceans. Island Press, Washington, pp. 3-12.

Melnick D., Cisternas, M, Moreno, M., Norambuena, R., 2012. Estimating coseismic coastal uplift with an intertidal mussel: calibration for the 2010 Maule Chile earthquake (Mw = 8.8). Quat. Sci. Rev. 42, 29-42.

Millenium Ecosystems Assessment (MEA), 2005. Millennium Ecosystem Assessment (MA) synthesis report. World Resources Institute, Washington.

Ministerio de Energía (MMA), 2014. Evaluación del recurso eólico. Universidad de Chile, Santiago.

Ministerio de Energía (MMA), 2014. Evaluación del recurso solar. Universidad de Chile, Santiago.

Ministerio de Trasporte y Telecomunicaciones (MTT). 2014. Informe de compatibilidad para Base Rendimiento Oficial.160914. https://www.mtt.gob.cl/

Mohor, S., 2013. Informe Arauco, las caletas y su gente. Proyecto de apoyo al desarrollo socio-económico y organizacional de la pesquería. Food and Agriculture Organization.

National Aeronautics and Space Administration (NASA), 2014. Surface meteorology and Solar Energy. https://eosweb.larc.nasa.gov/. (accessed 1 October 2014).

Nelson, W. G., 1990. Prospects for Development of an Index of Biotic Integrity for Evaluating Habitat Degradation in Coastal Systems, Chemistry and Ecology, 4:4,197-210.

Nestlerode, J., Engle, V.D., Bourgeois, P., Heitmuller, P.T., Macauley, J.M., Allen, Y.C., 2009. An integrated approach to assess broad-scale condition of coastalwetlands—the Gulf of Mexico Coastal Wetlands pilot survey. Environmental Monitoring and Assessment 150 (1–4), 21–29.

Odum, E.P., 1968. Energy flow in ecosystems: A historical review. American Zoologist 8: 11–18.

Odum HT, Brown MT, Brandt–Williams S. 2000. Handbook of emergy evaluation: A compendium of data for emergy computation. Folio #1: Introduction and global budget. Center for Environmental Policy–Environmental Engineering Sciences. University of Florida. Gainesville. 17 pp.

Odum, E.P., 1996. Environmental Accounting. Emergy and Environmental Decision Making. John Wiley & Sons, Inc., New York.

Odum, H.T. 1996. Environmental accounting: Emergy and decision making. John Wiley & Sons, New York, USA, 384 pp.

Odum, H.T., 1988. Self-organization, Transformity, and Information. Science 242, 1132–1139.

Odum, H.T., Brown, M.T., Brandt-Williams, S.B. (Eds.), 2000. Handbook of Emergy Evaluation. A Compendium of Data for Emergy Computation [Consulted: 1/6/2005]. Center for Environmental Policy, University of Florida, FL, USA. http://www.emergysystems.org/folios.php.

Odum, H.T., Odum, E.P., 2000. The Energetic Basis for Valuation of Ecosystem Services. Ecosystems. 3, 21–23.

Oliver, L., Lehrter, J., Fisher, W., 2011. Relating landscape development intensityto coral reef condition in the watersheds of St. Croix, US Virgin Islands. MarineEcology Progress Series 427, 293–302.

Orfanidis, S., Panayotidis P., Stamatis N., 2003.An insight to the ecological evaluation index (EEI), Ecological Indicators, Volume 3(1): 27-33.

Organismo de Certificación de Implementos y Maquinaria Agrícola (OCIMA), 2017. Consumo de Combustible John Deere. http://www.magussa.com.mx/node/1306 (accessed 19 July 2020).

Paine, R.T., Tegner, M.J., Johnson, E.A., 1998. Compounded Perturbations Yield Ecological Surprises. Ecosystems. 1, 535–545.

Palacios, A., 2012. Sismicidad histórica de la ciudad de Concepción desde su fundación en 1550 hasta su traslado en 1751. Servicio Nacional de Geología y Minería, Santiago.

Parada, C.E., Sobarzo, M.A., Figueroa, D., Castro, L., 2001. Circulación del Golfo de Arauco en un período de transición estacional: Un nuevo enfoque. Investig. Mar. 21, 11-23.

Parga, J., Teuber, N., 2006. Manejo del pastoreo con vacas lecheras en praderas permanentes. Instituto de Investigaciones Agropecuarias – Centro Regional de Investigación Remehue. Boletín INIA. 148.

Pickett, S.T.A and White P.S. 1985. Natural disturbance and patch dynamics: an introduction. In: Pickett STA, White PS (eds) The ecology of natural disturbance and patch dynamics. Academic Press, Orlando, 3–13 pp.

Plafker, G., Savage, J., 1970. Mechanism of the Chilean Earthquakes of May 21 and 22, 1960. Geol. Soc. Amer. Bull. 81, 1001-1030.

Quezada, J., Jaque, E., Belmonte, A., Fernández, A., Vásquez, D., Martinez, C., 2012. Movimientos cosismicos verticales y cambios geomorfológicos generados durante el terremoto Mw=8,8 del 27 de febrero de 2010 en el centro-sur de Chile. Rev. Geo. Sur 2, 11-45.

Quezada, J., Jaque, E., Catalán, N., Belmonte, A., Fernández, A., Isla, F., 2020. Levantamiento inesperado de la superficie coseismica en el área de la isla Tirúa-Mocha del sur de Chile antes y durante el terremoto de Mw 8.8 Maule 2010: una posible falla de la placa superior. Andean Geol. 47, 295-315.

Reiss, K.C., 2006. Florida wetland condition index for depressional forested wet-lands. Ecological Indicators 6, 337–352.

Reiss, K.C., Brown, M.T., Lane, C.R., 2010. Characteristic community structure of Florida's subtropical wetlands: The Florida wetland condition index for depressional marshes, depressional forested, and flowing water forested wetlands. Wetlands Ecology and Management 18, 543–556.

Rojas, O., Zamorano, M., Saez, K., Rojas, C., Vega, C., Arriagada, L., Basnou, C., 2017. Social Perception of Ecosystem Services in a Coastal Wetland Post-Earthquake: A Case Study in Chile. Sustainability. 9, 1983.

Sandoval, N., Valdovinos Zarges, C., Oyanedel, J.P., Vásquez, D., 2019. Impacts of coseismic uplift caused by the 2010 8.8 Mw earthquake on the macrobenthic community of the Tubul-Raqui Saltmarsh (Chile). Estuar. Coast. Mar. Sci. 226, 106278.

Senner, S.E., Andres, B.A., Gates, H.R., 2017. Estrategia de Conservación de las Aves Playeras de la Ruta del Pacífico de las Americas. National Audubon Society, New York.

Servicio Hidrográfico y Oceanográfico De La Armada De Chile (SHOA), 2009. Tablas de marea de la costa de Chile. Publ. SHOA, Valparaíso.

Servicio Hidrográfico y Oceanográfico De La Armada De Chile (SHOA), 2010. Tablas de marea de la costa de Chile. Publ. SHOA, Valparaíso.

Servicio Hidrográfico y Oceanográfico De La Armada De Chile (SHOA), 2013. Tablas de marea de la costa de Chile. Publ. SHOA, Valparaíso.

Sousa, W.P., 1984. The role of disturbance in natural communities. Ann. Rev. Ecol. Syst. 15, 353-391.

Srinivas H. & Y. Nakagawa. 2008. Environmental implications for disaster preparedness: Lessons Learnt from the Indian Ocean Tsunami. Journal of Environmental Management. 89: 4 – 13.

Troell, M., Pihl, L., Rönnbäck, P., Wennhage, H., Söderqvist, T., Kautsky, N., 2005. Regime shifts and ecosystem service generation in Swedish coastal soft bottom habitats: when resilience is undesirable. Ecol. Soc. 10, 30.

Turner, M.G., Dale, V.H., Everham, E.H., 1997. Fires, Hurricanes, and Volcanoes: Comparing Large Disturbances. BioScience 47, 758-768.

Uddin, M.R., Miah, M.G.U., Afrad, M.S.I, Mehraj, H., Mandal, M.S.H., 2015. Land Use Change and Its Impact on Ecosystem Services, Livelihood in Tanguar Haor Wetland of Bangladesh. Sci. Agri. 12, 78-88.

Ulgiati, S., Brown, M.T., 2009. Emergy and ecosystem complexity. Commun. Nonlinear Sci. 14, 310–321.

Valdovinos, C., Muñoz, M.D., Sandoval, N., Vásquez, D., Olmos, V., 2011. Desastres naturales y biodiversidad: El caso del humedal costero Tubul-Raqui. Sociedad Hoy 19, 33-51.

Valdovinos, C., Muñoz, M.D., Sandoval, N., Vásquez, D., y Olmos, V. 2010. Desastres naturales y biodiversidad: El caso del humedal costero Tubul-Raqui. Sociedad Hoy.10:33-51.

Vargas, G., Farías, M., Carretier, S., Tassara, A., Baize, S., Melnick, D., 2011. Coastal uplift and tsunami effects associated to the 2010 Mw 8.8 Maule earthquake in Central Chile. Andean Geol. 38, 219-238.

Vásquez, D, 2017. Efectos geomorfológicos y ambientales del terremoto Mw=8,8 del 27 de febrero del 2010 sobre los humedales costeros de la región del Biobío: el caso de la marisma Tubul-Raqui. Tesis para optar al Grado de Doctor en Ciencias Ambientales. Centro EULA-Chile. Universidad de Concepción.

Vásquez, D., Sandoval, N., Fierro, P., Valdovinos, C. 2020. Morphological Responses of Coastal Wetlands to Major Earthquake Uplifts in South-central Chile. Estuar. Coast. Shelf Sci. In press, 106922.

Vivas, M.B., Brown, M.T., 2006. Areal empower density and landscape development intensity (LDI) indices for wetlands of the Bayou Meto Watershed, Arkansas. Report submitted to the Arkansas Soil and Water Conservation Commissionunder sub-grant agreement SGA 104. University of Florida, Florida.

Wang, G. Li, Y., Liu, H., Wright, A.L., 2019. Development of the Wetland Condition Index (WCI) by Combining the Landscape Development Intensity Index (LDI) and the Water Environment Index (WEI) for Humid Regions of China. Water. 11, 620.

White, P.S., 1979. Pattern, process, and natural disturbance in vegetation. Bot. Rev. 45, 230-299.

White, P.S., Pickett, S.T.A., 1985. Natural Disturbance and Patch Dynamics: An Introduction, in: Pickett, S.T.A., White, P.S. (Eds.), The Ecology of Natural Disturbance and Patch Dynamics. Academic Press, Orlando, pp. 3–13.

Wright, J.F., 2000. An introduction to RIVPACS, in: Wright, J.F., Sutcliffe, D.W., Furse, M.T. (Eds.), Assessing the biological quality of freswaters: RIVPACS and other techniques. Freshwater Biological Association, Ambleside, pp. 1-24.

Wu, J., 1982. Wind-stress coefficients over sea surface from breeze to hurricane. J. Geophys. Res. 82, 9704-9706.

Appendix A. Calculations for the emergy flows of the Tubul Raqui wetland before the earthquake (BE) and after the earthquake (AE).

1. SOLAR ENERGY = (TOTAL AREA) *(INSOLATION)*(1-ALBEDO) * (DAYS/YEAR) *(J/kWh)

	AREA m² (a)	INSOLATION (kWh/m²day)	(1-ALBEDO)	(DAYS/YEAR)	J/kWh
PELILLO HARVESTING BE	1,660,940				
NAVAJUELA HARVESTING BE	230,030	4.88 (b)	0.925	365	3.60E+06
CATTLE GRAZING BE	5,833,140				
CATTLE GRAZING AE	8,292,590	4.74 (c)			
ALBEDO	0.075 (d)				

2. KINETIC ENERGY OF WIND USED AT SURFACE = (AREA)*(DENS. AIR) * (COEF. DRAG) * (MEAN WIND SPEED)^3 * (SECONDS/YEAR)

	AREA m²	DENS. AIR kg/m³ (e)	COEF. DRAG	MEAN WIND SPEED (m/s)³	(s/yr)
PELILLO BE	16,60,940				
NAVAJUELA BE	230,030			3.297 (f)	
CATTLE GRAZING BE	5,833,140	1.24	1.04E-02		3.15E+07
CATTLE GRAZING AE	8,292,590			3.22 (g)	

DRAG COEFFICIENT: (0.8+0.065 U10) 10^{-3} , U (m/s): 3,7

3. TIDE ABSORBED IN ESTUARIES = (AREA) * (0.5) * (TIDES) (DENSITY) * (TIDE RANGE m)^2 * (GRAVITY)

	AREA (m²) (i)	TIDES (n°/year) (j)	DENSITY (kg/m³) (k)	TIDE RANGE (m) (l)	GRAVITATIONAL ACCELERATION (m/s²)
PELILLO, BE NAVAJUELA BE	2,411,120	730	1027	0,7	9,8

4. CHEMICAL POTENTIAL ENERGY IN RAIN=(AREA) * (PRECIPITATION) * (FREE GIBBS ENERGY) (DENSITY)

	AREA (m²)	PRECIPITATION (m/year)	FREE GIBBS ENERGY (J/kg) (o)	DENSITY (kg/m³)
PELILLO BE	1,660,940			
NAVAJUELA BE	230,030			
CATTLE GRAZING BE	5,833,140	2.21 (m)		1,000
CATTLE GRAZING AE	8,292,590	1.14 (n)	4.94E+03(p)	

5. CHEMICAL POTENTIAL ENERGY IN RIVER= (FLOW) * (DENSITY) * (FREE GIBBS ENERGY) (1000 g) (SEC./YEAR)

	FLOW (m^3/año) (q)	DENSITY (kg/m^3) (r)	FREE GIBBS ENERGY (J)
PELILLO BE			
NAVAJUELA BE	0.79	1.025	9697.431
CATTLE GRAZING BE			
CATTLE GRAZING AE	0.45		9697.506

G= (8.33 J/moles/deg) (300°K) / (18 g/moles) Ln (1.000000 - S) ppm/965,000 ppm) J/g

SST(PPM) BE	8.3E+01
SST(PPM) AE	1.9E+02

6. EARTH CYCLE= (AREA) * (EARTH HEAT)

	AREA (m^2)	EARTH HEAT (J/m^2/año) (u)
PELILLO HARVESTING BE	1660940	
NAVAJUELA HARVESTING BE	230030	
GRAZING BE	5833140	
GRAZING AE	8292590	$6.10E^{-02}$

7. GEOPOTENTIAL IN INFLOWING RIVERS= (CAUDAL) * (DENSIDAD) * (ALTURA DE ENTRADA DEL RÍO - ALTURA DE SALIDA) * (GRAVEDAD)

	FLOW (m^3/año)	DENSITY (kg/m^3)	ALT. ENTRADA (m elevation) (v)	ALT. EXIT (m elevation) (w)	GRAVITY (m/s^2)
PELILLO HARVESTING BE					
NAVAJUELA HARVEST BE	0.79	1.025	5	0	9.8
GRAZING BE					
GRAZING AE	0.45			1.6	

8. PERSONS COLLECTING ALGAE= (WEIGHT) * (GRAVITY) * (DISPLACEMENT) * (TIMES IN ONE YEAR) * (N° WORKERS)

	WEIGHT (kg)	GRAVITY (m/s^2)	DISPLACEMENT (m)	TIMES/YEAR	N° WORKERS (dd)
PELILLO HARVEST BE	30(x)	9,8	20 (z)	15 (bb)	600
NAVAJUELA HARVEST BE	4.5(y)		300 (aa)	10.7 (cc)	

9. WORK OF MEN MANAGING MACHINERY= (kcal/DAY) * (DAYS/YEAR) * (4186 J/cal) (WORKERS/AÑO)

	kcal/DAY (ee)	DAYS/YEAR	JOULE (kcal) (hh)	WORKERS
PELILLO HARVEST (TRACTOR AND BOATMAN) BE		15(bb)		65(ii)
GRAZING (VEHICLE) BE	81.000	150(ff)	4.186	10(jj)
GRAZING (VEHICLE) AE		100(g)		

10. OCEAN WAVES ABSORBED AT THE SHORE= (COASTLINE) * (1/8) * (DENSITY) (GRAVITY m/s^2) * (WAVE HEIGHT m)^2* (VELOCITY) * (SECONDS/YEAR)

	COASTLINE (m) (kk)	DENSITY (kg/m^3)	GRAVITY (m/s^2)	WAVE HEIGHT $(m)^2$ (ll)	WAVE VELOC. (m/s) (mm)	sec/year
PELILLO AND NAVAJUELA HARVESTING BE	1.462	1.027	9.8	0.8836	0.3	31500000

11. HARVESTING VEHICLE FUEL= (DISTANCE COVERED) * (TIMES/YEAR) / (MEAN MILEAGE OF VEHICLE) * (36872.95 J)

	DISTANCE (km)	TIMES	MEAN MILEAGE (km/L)	N. VEHICLES	Joules
PELILLO HARVESTING BE (TRACTOR)	11.2(nn)	15 (bb)	23.4(pp)	3	36872.9 (rr)
GRAZING BE (VEHICLE)	7.4 (oo)	150 (ff)	12.4(qq)	5	
GRAZING AE (VEHICLE)		100 (gg)			

a Software Google Earth vectorized by photointerpretation in ArcGis for 2009 and 2010.
b (Ministry of Energy Government of Chile, 2014). Modeling performed in Latitude 37.23 S; Longitude 73.48W; Elevation 8 meters. Year 2009.
c (Ministry of Energy Government of Chile, 2014). Modeling performed in Latitude 37.23 S; Longitude 73.48W; Elevation 8 meters. Year 2010.
d (NASA, 2014).
e (Parada et al.2001).
f (Ministry of Energy Government of Chile, 2014). Modeling performed in Latitude 37.23 S; Longitude 73.48W; Elevation 8 meters. Year 2009.
g (Ministerio de Energía Gobierno de Chile, 2014). Modeling performed in Latitude 37.23 S; Longitude 73.48W; Elevation 8 meters. Year 2010 .
h (Wu,1982). U is wind velocity at 10m from the ocean surface.
i ArcGis 2010. We used historical data on salinity in the estuary (Valdovinos et al.2017).
j (SHOA, 2009); k (Grob,2003); l(SHOA,2010).
m (DGAC. 2010). Lebu Station 2009.
n (DGAC. 2010). Lebu Station 2010.
o (Odum, 1996).
p This is a unique value (Odum, 1996).
q Mean flows of the Tubul and Raqui Rivers in 2011, used as post-earthquake time. To estimate the pre-earthquake flows, we compared with the variance of the annual flow of the nearest river with a flow measuring station, that of the Curanilahue River (Lat. S: 37° 28' 50''; Long. W: 73° 20' 13''). Given that both rivers are fluvial, we summed the value of the anual variance of 2009, which had more precipitation (DGA, 2020).
r (Garcés-Vargas et al. 2013).
s (Valdovinos et al.2017). For calculating G of STS 2009.
t (Valdovinos et al.2017). For calculating G of STS 2010.
u www.heatflow.und.edu/data.html (Lat.33°46′67″; Long. 70°16′67″).
v ArcGis 2010.
w ArcGis 2010.
x Estimated weight of a bale of algae (Interview director of collectors Malita Vidal P.).
y Estimated weight of a collection pail (Interview director of collectors).
z Mean of routes to collection zones (Arcgis. 2010).
aa Mean of routes to collection zones (Arcgis. 2010).

bb (Vega and Pool, 2014). Three harvest per year of 5 days each.

cc Days of the year 2009 less holidays and 7 days with bad weather. 600 persons formed 30 groups of 20 persons/ 321 days.

dd (Vega and Pool, 2014). The total was the number of persons who belong to the collectors union.

ee (Odum, 1996).

ff (Parga and Teuber, 2006). Grazing occurs in spring and summer (6 months per year). (30 days x 6 months) **-** (holidays + 10 days with bad weather).

gg (Parga and Teuber, 2006). Same criterion as de ff (2009), subtracting days of work suspension after the earthquake.

hh (Odum, 1996).

ii N° boatmen + N° tractors (Interview director of collectors Malita Vidal P).

jj (Cid-Aguayo et al. 2019). Mean of estimations of the authors. One family has 10 ha with 14 animals. There are about 5 people per family, but only the men go to look for the animals. Thus, given that there was a mean of 50 animals in the wetland, we assume there are three families, 10 men out of 15 persons.

kk Measured by interpretation of Google Earth 2009-2010 satellite images using the definition of the coastline by SHOA (2013).

ll Elevation heights measured with GIS (Arcgis, 2010).

mm (Beyá et al. 2016). Estimations made by (Bellá et al. 2016) and averages from database of San Vicente port measuring station, 1986, in Dec.-Jan.-Feb., Biobío region.

nn Estimation of trajectories of tractors in the extraction area (Interview director of collectors).

oo Dimension of the highway that crosses the wetland, obtained by photointerpretation (Google Earth).

pp (OCIMA .2017). Mileage of tractor MODEL 6125D.

qq (MTT,2014). Mean mileage of sedans present in Chile in 2010.

rr (Khalil and Asheini, 2015). Equivalent in Joules of a barrel of petroleum of 159 L.

6 DISCUSIÓN

La región del Biobío tiene la menor área de protección de humedales a nivel nacional, por lo tanto, es la zona que presenta el mayor desafío de alcanzar un mínimo de 17% de protección de sistemas acuáticos continentales, propuesto en las metas del Convenio sobre la Diversidad Biológica (CDB) que firmó Chile en los años 90´ (MMA, 2018). No obstante, de manera local se ha estado avanzando en temas protección. Actualmente el humedal Tubul-Raqui forma parte del grupo de humedales definidos como prioritarios de su conservación en el Plan Nacional Protección de Humedales 2018-2022. En este proceso se pretende proteger 650,0 ha de este ecosistema (MMA, 2019).

La inclusión de Tubul-Raqui en el presente plan nacional responde a amplios esfuerzos de la comunidad, científicos y gobierno local, quienes posterior al terremoto de 2010 han debido demostrar que este ecosistema sigue siento una importante zona de conservación, pese a las grandes modificaciones sufridas por el alzamiento cosísmico y tsunami (Ladera sur, 2020). En este sentido, recientes estudios de línea base desarrollados por exigencias de la autoridad ambiental, frente a propuestas de proyectos de generación eléctrica (parques eólicos) en la zona (Ibarra, 2012), reflejan que el humedal costero sigue siendo un importante refugio para especies de aves migratorias y costeras, muchas de las cuales se encuentran bajo alguna categoría de conservación (RCE, 2018). Junto con ello, si bien los servicios ecosistémicos de aprovisionamiento fueron reducidos en 2010 (Marín et al. 2014), varios otros permanecen. Rojas et al. (2017) por medio de encuestas, describe los servicios culturales y regulatorios como los de mayor importancia para la comunidad local post-terremoto.

Como se comentó en el Capítulo I, el mecanismo de protección más efectivo para los humedales es declararlos santuarios de la naturaleza, no obstante, una de las mayores dificultades que presenta este proceso, es el derecho de propiedad de estos ecosistemas. La mayoría de los humedales en Chile han sido “loteados” por lo que poseen propietarios de diferentes origen (privados, municipales, bienes nacionales, entre otros), lo que se transforma en una importante limitación en el avance de este proceso, el cual pretende que los dueños de estas tierras expresen la voluntad de proteger su propiedad y por lo tanto sean parte del proyecto de conservación. Tubul-Raqui no es la excepción a esta complejidad, por otra parte, su protección tiene tiempos acotados, ya que hoy proyectos eólicos pretenden cruzar el humedal con líneas de alta tensión (SEIA, 2020), por lo que urge avanzar en su protección e impedir que el humedal tenga usos que afecten su condición natural.

Posterior al 27F Tubul-Raqui se transformó en una interesante zona de exploración para dimensionar la magnitud del terremoto, hacer registros de alzamiento cosísmico, determinar mortandad de especies, valorar la pérdida de servicios ecosistémicos, entre otros. Sin duda esto fue posible gracias a los antecedentes históricos que se tiene del humedal en sus distintas variantes. En caso de la limnología, Stuardo y Valdovinos desde 1990 registraron antecedentes de la calidad del agua, biota acuática y valoraron ecológicamente el humedal revelando la importancia de los servicios que este prestaba por la explotación de recursos naturales. Del mismo modo, las autoridades gubernamentales marítimas como Sernapesca, ha generado valiosos registros históricos (FIP, 2013), que dan cuenta de cómo una actividad, como la extracción de pelillo, puede realizarse de manera sustentable y favorecer por décadas el bienestar económico de familias vulnerables (Martínez et al. 2012).

La experiencia del Capítulo II revela la importancia no solo del registro sino del seguimiento de las variables ambientales. Los humedales son sistemas altamente complejos y dinámicos que a esta latitud están profundamente modelados por la estacionalidad (Novoa et al. 2020), el conocimiento de esta variabilidad entre otras cosas permite valorar el ecosistema y dimensionar cambios frente a perturbaciones de gran magnitud.

El 27F trajo consigo también grandes interrogantes, dado que en Chile nos enfrentábamos por primera vez a un cambio tan abrupto, con herramientas tecnológicas que no existía para el terremoto de 1960, por ejemplo. En este sentido, este primer gran evento pudo ser aprovechado en mayor medida si ya hubiesen existido mesas de trabajo interdisciplinarios, que establecieran un ordenamiento en el desarrollo de la investigación y favorecieran la mirada holística. Este capítulo (II), por ejemplo, forma parte de un compilado de estudios de mucho humedales costeros perturbados por el terremoto y tsunami de 2010, en donde se trabajó paralelamente en estudios locales, que, si bien es un importante registro y aporte a las ciencias, revela también el trabajo fragmentado que seguimos desarrollando en torno a eventos de amplio espectro y que requieren del análisis y discusión de variadas disciplina de manera conjunta.

En relación con lo anterior y en la búsqueda de seguir dimensionando los cambios más significativos del ecosistema acuático, en el Capítulo III se utilizaron macroinvertebrados bentónicos como bioindicadores de perturbaciones naturales (Miura et al. 2011; Watanabe et al. 2014). Los resultados muestran que por medio de esta metodología podemos evaluar la perturbación mediante la estructura comunitaria del macrobentos, el que se manifiesta con cambios en las especies dominantes dentro del ecosistema, donde organismos que habitaban normalmente en zonas transicionales, fueron capaces de tolerar mejor los cambios producidos por esta perturbación, es decir, su abundancia sobrepasó a las especies con menor rango de distribución.

Por otro lado, las especies que previo al evento eran abundantes vuelven a alcanzar abundancias similares o incluso mayores a las registradas previo a la perturbación. Este resultado, sería confuso si las variables físicas no hubiesen sido consideradas, ya que nos haría pensar que se vuelve a un estado inicial. No obstante, la modificación del hábitat causada por el alzamiento costero y que generó una importante desecación, define un antes y un después en el humedal. Alrededor de 1,25 km^2 del bentos quedó permanentemente expuesto en superficie, es decir, en esta zona especies como las aves migratorias no encontraran infauna para alimentarse, sino más bien especies vegetales colonizadoras, que pueden ser aprovechadas por otros grupos de organismos.

Por lo tanto, a través de indicadores biológicos podemos dimensionar los primero cambios funcionales y estructurales del ecosistema, al describir un sistema estuarino pre-terremoto y comenzar a caracterizar un humedal dulceacuícola, post-terremoto. No obstante, esta herramienta de evaluación carece de alcance para otras modificaciones observadas, como la relación entre la mortandad de especies acuáticas y sus efectos sobre los servicios ecosistémicos.

Lo anterior nos obliga a pensar en la escala de evaluación, dado que a gran modificación correspondería ampliar el objetivo (Cueto, 2006). En este sentido, las herramientas remotas mediante el uso de imágenes satelitales son capaces de definir un paisaje y determinar cambios en el tiempo (Ferral et al. 2019). De este modo es posible cuantificar estructuras tan significativas para una marisma como la vegetación. En el capítulo IV se analiza la geomorfología del humedal y sus cambios post perturbación natural, aquí se observa que la estructura vegetacional del humedal fue la que sufrió menor modificación, es decir, presenta una gran resistencia al impacto del terremoto y tsunami. La *Spartina densiflora* hace que el humedal permanezca en dimensiones claras para todos, ya que, pese a la enorme reducción de zonas de inundación, el espartal sigue siendo una unidad vegetacional costera de amplia cobertura, cumpliendo un rol estabilizador post-perturbación, ya que protege el suelo y medio acuático de invasiones directas, y a la vez, limita en gran medida el transito dentro del humedal protegiéndolo de diversas amenazas.

Frente a perturbaciones naturales o antrópicas, el análisis geomorfológico puede ser aplicado para comprender la extensión y magnitud de los cambios, debido a que las formas del relieve son extremadamente sensibles a los movimientos tectónicos (Fagherazzi et al. 2004). Este estudio nos permitió cuantificar y relacionar los cambios morfológicos con la hidrodinámica en los canales del humedal, antecedentes que pueden ser explorados con gran precisión mediante las herramientas utilizadas. De este modo, los cambios en el paisaje aportan nuevos antecedentes a los descritos previamente.

Finalmente, y a modo de implementar una forma de evaluación que nos permita complementar lo ya desarrollado en este estudio e incluir antecedentes de diferentes disciplinas, es que utilizamos la emergía por medio del Indicador de Intensidad de Desarrollo del Paisaje (LDI). Este indicador es aplicado por primera vez en Chile y a la vez puesto a prueba frente a la evaluación de ecosistemas perturbados naturalmente, ya que su uso en humedales está enfocado a impacto por perturbaciones antrópicas (Oliver et al. 2011; Reiss y Brown, 2007; Reiss, 2006).

Los resultados muestran que LDI permite tener una visión holística del sistema perturbado al incluir las variables que no habían sido incluidas previamente y relacionarlas bajo un solo valor numérico. LDI a través de la emergía, refleja los cambios en la estructura y funcionamiento del ecosistema y lo hacen comparable para períodos contrastantes (Ulgiati y Brown, 2009), incorporando la cuantificación en superficie del uso del suelo, que es un conductor directo del cambio de los servicios de los ecosistemas.

El LDI total, resultante de la emergía y los porcentajes de usos de suelo muestran un importante disminución en la intensidad de uso del paisaje entre la condición pre-terremoto y post-terremoto (40,6%), es decir, cuantifica el impacto inicial sobre un ecosistema que producto del alzamiento costero cambia su configuración pasando de un sistema estuarino altamente productivo (Marín et al. 2014, Rojas et al. 2017) a un humedal dulceacuícolas con importantes zonas desecadas (Sandoval et al. 2019), que favorecen el uso del suelo del ganado y posiblemente de otros usos proyectados para esta zona (e.g. instalación de torres de energía eólica). Dado que actualmente no presenta una categoría de protección que garantice su conservación, este evento aumentaría la vulnerabilidad del humedal frente a impactos de origen antrópico o natural. En este sentido, LDI es un buen indicador del estado ambiental de humedales costeros perturbados naturalmente para ser utilizado como herramientas de gestión y protección de estos ecosistemas.

7 CONCLUSIONES

Este estudio ha presentado una síntesis de las principales características del ecosistema del humedal de Tubul-Raqui, así como los importantes cambios causados por el terremoto 27F en comparación con los antecedentes históricos que se tiene del ecosistema.

a) Los distintos métodos usados para evaluar esta perturbación natural de gran magnitud indican que se produjo una modificación relevante de la estructura, función y dimensión del Humedal Tubul-Raqui.

b) Los principales cambios en el humedal costero derivan del alzamiento cosísmico de aproximadamente 1,6 m.s.n.m. La medición de estos cambios mediante herramientas remotas revela que la sismotectónica desempeña un importante rol en el control de la dinámica de los rasgos morfológicos y ecológicos de la marisma salina de Tubul-Raqui

c) Las especies bentónicas se presentan como buenos indicadores de la condición ambiental de un humedal naturalmente perturbado. En relación con los macroinvertebrados (> 500 μm) los cambios fisicoquímicos que más influyeron en la disminución de su diversidad fueron: la disminución de la salinidad, la pérdida de hábitat y la descomposición de la materia orgánica.

d) Los resultados de este estudio muestran la capacidad de resiliencia de importantes componentes biológicos presentes en la marisma. Entre ellos, los poliquetos (e.g *Prionospio* (*Minuspio*) *patagónica*), anfípodos (*Paracorophium hartmannorum*) y la planta halófita *Spartina densiflora*. No obstante, especies de importancia comercial desaparecen post perturbación como el alga roja "Pelillo" (*Gracilaria* spp.) y el bivalvo "navajuela" (*Tagelus dombeii*).

e) El indicador energético LDI nos permite unificar los antecedentes más relevantes generados post-terremoto por diferentes disciplinas y compararlos con un estado pre-terremoto. El uso del indicador emergético LDI demostró ser un instrumento útil para evaluación ambiental de humedales costeros impactados por una perturbación natural de origen sísmico, por lo que puede ser utilizado en medidas de gestión junto con otros indicadores como los utilizados en este estudio.

8 REFERENCIAS

Adam P. 2002. Saltmarshes in a time of change. Environmental Conservation. 1:39-61.

Adger N., T. Hughes, C. Folke, S. Carpenter, J. Rockstro. 2005. Social-Ecological Resilience to Coastal Disasters. Science. 309: 1036-1039.

Almeida C. M.V.B., A.J.M. Rodriguez, S.H. Bonilla, B.F. Giannetti. 2010. Emergy as a tool for Ecodesign: evaluating materials selection for beverage packages in Brazil. Journal of Cleaner Production. 18 (1): 32–43.

Angermeier P.L. J. R. Karr.1994. Biological Integrity Versus Biological Diversity as Policy Directives: Protecting Biotic Resources. Ecosystem Management pp 264-275.

Atwater B.F., M. Cisternas, J. Bourgeois, W.C. Dudley, J.W. Hendley and P.H Stauffer. 1999. Surviving a Tsunami - Lessons from Chile, Hawaii and Japan. Circular 1187 USGS. 18 pp.

Barbier E. B. 2007. Valuing ecosystem services as productive inputs. Economic Policy. 22(49):177–229.

Bird E. 2014. Coastal geomophology, an introduction. 2da edición. Ed. Wiley. How much wetland has the world lost? Long-term and recent trends in global wetland área. Nick C. Davidson. Marine and Freshwater Research. 65(10) 934-941.

Borja A., Ranasinghe, A., Weisberg, S.B. 2009. Assessing ecological integrity in marine waters, using multiple indices and ecosystem components: challenges for the future. Mar. Pollut. Bull. 59:1-4.

Brandt-Williams S., C. Wigand and D.E. Campbell. 2013. Relationships between watershed emergy flow and coastal New England salt marsh structure, function, and condition. Environ Monit Assess. 185:1391–1412.

Brown M.T. and S. Ulgiati. 2004. Energy Quality, Emergy, and Transformity: H.T. Odum's contribution to quantifying and understanding systems. Ecodinamica.5:58-67.

Brown M.T. and T. McClanahan. 1996. Emergy Analysis Perspectives for Thailand and Mekong River Dam Proposals. Ecological Modeling. 91:105-130.

Brown M.T. and V. Buranakarn. 2003. Emergy indices and ratios for sustainable material cycles and recycle options. Resources, Conservation and Recycling. 38:1-22.

Brown M.T., Campbell, D.E., De Vilbiss, C., Ulgiati, S. 2016. The geobiosphere emergy baseline: A synthesis. Ecological Modelling. 339, 92-95.

Brown M.T., Ulgiati, S. 2010. Updated evaluation of exergy and emergy driving thegeobiosphere: a review and refinement of the emergy baseline. Ecol. Model. 221(20), 2501–2508.

Brown M.T., Ulgiati, S., 2016a. Assessing the global environmental sources drivingthe geobiosphere: a revised emergy baseline. Ecol. Model. 339. 126–132.

Brown M.T., Ulgiati, S., 2016b. Emergy accounting of global renewable sources. Ecol.Model. 339, 148–156.

Burgos E. y J.M. Laurent. 2011. aproximación al análisis de integridad ecológica - valoración del estado de conservación de las áreas protegidas de la Bahía de Tela. Secretaría de turismo de honduras, Banco Interamericano de Desarrollo. 34 pp.

Campbell D.E. 2000. Using energy systems theory to define, measure, and interpret ecological integrity and ecosystem health. Ecosystem health. 6(3):181–204.

Campbell D. E., and Cai, T. T. 2006. Emergy and economic value. In M. T. Brown, E. Bardi, D. Campbell, V. Comar, S.-L. Huang, T. Rydberg, D. Tilley, S. Ulgiati, (Eds.), Emergy synthesis 4, proceedings of the 4th biennial emergy conference. Center for Environment Policy, Department of Environment Engineering Science. Gainesville, FL: University of Florida. 24.1–24.16 pp.

Campbell D.E., 2016. Emergy baseline for the Earth: review of the science and a new calculation. Ecol. Model. 339, 96–125.

Campos J., D. Hatzfeld, R. Madariaga, G. Lopez, E. Kausel, A. Zollo, G. Iannacone, R. Fromma, S. Barrientos and H. Lyon-Caen. 2002. A seismological study of the 1835 seismic gap in south-central Chile. Physics of the Earth and Planetary Interiors. 132: 177–195.

Cardona O. 2001. La necesidad de repensar de manera holística los conceptos de vulnerabilidad y riesgo, "una crítica y una revisión necesaria para la gestión". En: International Work-Conference on vulnerability in disaster theory and practice: 29 y 30 de junio de 2001.Wageningen, Holanda. Disaster studies of wageningen University and Research Centre.

Castilla J.C.1998. Earthquake-caused coastal uplift and its effects on rock intertidal kelp communities. Science. 242:440-443.

Chang S.E., B.J. Adams, J. Alder, P.R. Berke, R. Chuenpagdee, S. Ghosh and C. Wabnitz. 2006. Coastal ecosystems and tsunami protection after the December 2004 Indian Ocean tsunami. Earthquake Spectra. 22: 863-887.

Chen B., Z.M. Chen, Y. Zhou, J.B. Zhou and G.Q. Chen. 2009. Emergy as embodied energy based assessment for local sustainability of a constructed wetland in Beijing. 14: (2) 622–635.

Christensen V. 1995. Ecosystem maturity—toward quantification. Ecological Modelling. 77:3–32.

Cisternas M., A. Araneda y I. Contreras. 2000. Reconocimiento y caracterización de la facies sedimentaria depositada por el tsunami de 1960 en el estuario Maullín, Chile. Revista Geológica de Chile. 27(1): 3-11.

Constanza R., R. d'Arge, R. de Groot, S. Farber, M. Grasso, B. Hannon, K. Limburg, S. Naeem, R. V. O'Neill, J. Paruelo, R. G. Raskin, P. Sutton and M. van den Belt. 1997. The value of the world's ecosystem services and natural capital. Nature. 387: 253-260.

Cueto V. 2006. Escalas en ecología: su importancia parael estudio de la selección de hábitat en aves, Hornero. 21(1):1–13.

De Groot R.S.1987. Environmental functions as a unifying concept for ecology and economics. The Environmentalist. 7 (2), pp. 105-109.

Dolan S. L. 2007. Life cycle assessment and emergy synthesis of a theoretical offshore wind farm for jacksonville, Florida. Thesis presented to the graduate school of the University of Florida in partial fulfillment of the requirements for the degree of Master of Science. University of Florida. 125 pp.

Ehrlich P.R. and Ehrlich A.H. 1981. Extinction: the causes and consequences of the disappearance of species. Random House, New York.

Espinoza Guzmán, D. y Zumelzu Scheel, A. 2016. Valdivia y su evolución post-terremoto 1960: Enfoques, factores escalares y condicionantes. Urbano, 19(33):14-29.

Esty C.D., A.M. Levy, T. Srebotnjak and A. de Sherbinin. 2005. Environmental sustainability Idex: Benchmarking National Environmental Stewardship. Yale Center for Environmental Law and Policy, New Haven, USA.

Fabiano M., P. Vassallo, L. Vezzulli, V.S. Salvo and J.C. Marques. 2004. Temporal and spatial change of exergy and ascendency in different benthic marine ecosystems. Energy. 29:1697–1712.

Fagherazzi S., M. Marani, L.K. Blum, 2014. The Ecogeomorphology of Tidal Marshes Coastal and Estuarine. Studies 59 American Geophysical Union, Washington DC. 266 pp.

Ferral A., E. Luccini, A. Aleksinkó, C. M. Scavuzzo. 2019. Flooded-area satellite monitoring within a Ramsar wetland Nature Reserve in Argentina, Remote Sensing Applications, Society and Environment.15: 2352-9385.

Ferreyra M.C. 2001. Emergy perspectives on the argentine economy and food production systems of the rolling pampas during the twentieth century. A thesis presented to the graduate school of the University of Florida in partial fulfillment of the requirements for the degree of Master of Science, University of Florida.

FIP, 2013. Informe Final "estudio de emplazamiento de áreas de acuicultura de pequeña escala en la zona sur (VI a XIV regiones)". Subsecretaría de Pesca y Acuicultura. 435 pp.

Guevara Sangines, A. y J. Lara-Pulido. 2009. Desastres naturales, cambio climático y efectos macroeconómicos: una revisión de la evidencia.

Gunderson L. H. 2000. Ecological Resilience—In Theory and Application. Annual Review of Ecology and Systematics 2000 31(1): 425-439.

Hasan Reza M. I. Arif Abdullah S. 2011.Regional Index of Ecological Integrity: A need for sustainable management of natural resources. Ecological Indicators.11(2): 220-229.

Hilsenhoff W. L.1987. An improved biotic index of organic stream. the great lakes entomologist. Pollution. 20 (1) 31-36.

Hilsenhoff W. 1988. Rapid field assessment of organic pollution with a family-level biotic index. Journal of the North American Benthological Society. 71: 65–68. DOI:10.2307/1467832.

Hong S., Koh, C., Harris, R.R. et al. 2010. Land Use in Korean Tidal Wetlands: Impacts and Management Strategies. Environmental Management. 45, 1014–1026.

Ibarra Vidal H., 2012. Informe de Avance: Plan de monitoreo del Cormorán gris (*Phalacrocorax gaimardi*) en el área de influencia del parque eólico arauco, comuna de arauco, VIII region. Parque Eólico Arauco S.A. 205 pp.

Ibarrarán M.E, M. Ruth, S. Ahmad, M. London. 2009. Climate change and natural disasters: Macroeconomic performance and distributional impacts. Environ. Dev. Sustain. 11:549–569.

International Conference on Sustainable Urbanization (ICSU). 2010. The Faculty of Construction and Land Use (FCLU) of The Hong Kong Polytechnic University in Hong Kong. 15-17 pp.

Jacobs M. D., M.E. Kentula, A. T. Herlihy. 2010. Developing an index of wetland condition from ecological data: An example using HGM functional variables from the Nanticoke watershed, USA. Ecological Indicators. 10: 703-712.

Jaramillo E, J.E. Dugan, D.M. Hubbard, D. Melnick, M. Manzano. 2012. Ecological Implications of Extreme Events: Footprints of the 2010 Earthquake along the Chilean Coast. Plos One. 7(5): e35348.

Jiang M.M., B. Chen, J.B. Zhou, F.R. Tao, Z. Li, Z.F. Yang, G.Q. Chen. 2007. Emergy account for biomass resource exploitation by agriculture in China. Energy Policy. 35:4704–4719.

Jorgensen S.E. 1994. Review and comparison of goal functions in systems ecology. Vie le Milieu.44(1):11–20.

Jorgensen S.E. 2000. Application of exergy and specific exergy as ecological indicators of coastal areas. Aquatic Ecosystem Healthand Management. 3:419–30.

Jorgensen S.E. 2006 Eco-energy as sustainability (chapter of encyclopedia or book).

Junk WJ, An S, Finlayson CM, Gopal B, Květ J, Mitchell SA, Mitsch WJ, Robarts RD. 2013. Estado actual de conocimiento sobre los humedales del mundo y su futuro bajo el cambio climático global: una síntesis. Aquat Sci. 75: 151-167.

Kaplan M., F.G. Renaud and G. Lüchters. 2009. Vulnerability assessment and protective effects of coastal vegetation during the 2004 Tsunami in Sri Lanka. Nat. Hazards Earth Syst. Sci. 9:1479–1494.

Karr J.R. and W.W. Chu. 1999. Restoring life in running Waters. Better Biological Monitoring. Island Press. Washington, D.C.209 pp.

Karr J.R.1991. Biological integrity: a long-neglected aspect of water resources management Ecological Applications. 1(1):66-84.

Karr J. and Chu, Ellen. 1997. Biological Monitoring and Assessment: Using Multimetric. Indexes Effectively. Nature.

Kerans BL, Karr J. 1994. A benthic index of biotic integrity (B-IBI) for rivers of the Tennesse Valley. Ecological Applications. 4: 768–785. DOI: 10.2307/1942007.

Ladera Sur.2020. La nueva oportunidad para proteger Tubul-Raqui, el resiliente humedal que se recupera del terremoto y que está bajo amenaza. https://laderasur.com/articulo/la-nueva-oportunidad-para-proteger-tubul-raqui-el-resiliente-humedal-que-se-recupera-del-terremoto-y-que-esta-bajo-amenaza/(visitado 14 agosto 2020).

Lagos M. y M. Cisternas. 2004. Depósitos de tsunami como indicadores de riesgo: evidencias sedimentarias. Revista Geográfica de Chile Terra Australis. 49: 329-351.

Lagos M. 2000. Tsunamis de origen cercano a las costas de Chile. Revista de Geografía Norte Grande. 27:93-102.

Marín, A., Gelcich, S., Castilla, J.C., 2014. Ecosystem services and abrupt transformations in a coastal wetland social-ecological system: Tubul-Raqui after the 2010 earthquake in Chile. Ecology and Society. 19(1): 22.

Martínez, C., Rojas O., Aránguiz R., Belmonte A., Altamirano A. y Flores P., 2012. Riesgo de tsunami en caleta Tubul, Región del Biobío: escenarios extremos y transformaciones territoriales posterremoto. Revista de geografía Norte Grande. (53), 85-106.

MEA (Millennium Ecosystem Assessment). 2005. Ecosystems and Human Well-being: Synthesis. Island Press, Washingon, DC.

MMA, 2018. Plan Nacional de Protección de Humedales 2018-2022. Ministerio del Medio Ambiente.

Morse S. and E. Fraser. 2005. Making dirty'nations look clean? The nation state and the problem of selecting and weighting indices as tools for measuring progress towards sustainability. Geoforum. 36(5): 625-640.

Mouslopoulou, V., O. Oncken, S. Hainzl, and A. Nicol. 2016. Uplift rate transients at subduction margins due to earthquake clustering, Tectonics. 35: 2370–2384.

Müller F., R. Hoffmann-Kroll, H. Wiggering. 2010. Indicating ecosystem integrity theoretical concepts and environmental requirements. Ecological Modelling.130: 1–3, 13-23.

Nichols M. M. and R. B. Biggs. 1985. Estuaries. In: Coastal sedimentary environments, R. A. Davis Jr, editor, Springer-Verlag, New York. 77-186 pp.

Nichols, M. Y Biggs, R. 2007. Estuaries. En: DAVIS, R.A (Ed.) Coastal Sedimentary Environments, 1985, p. 77-125.

Novoa, V., O. Rojas, R. Ahumada-Rudolph, K. Sáez, P. Fierro and C. Rojas, 2020. Coastal Wetlands: Ecosystems Affected by Urbanization? Water. 12(3), 698.

Odum, E.P., 1968. Energy flow in ecosystems: A historical review. American Zoologist 8: 11–18.

Odum E.P. 1969. The Strategy of Ecosystem Development Science. Vol. 164, No. 3877, pp. 262-270.

Odum E.P. 1985. Trends Expected in Stressed Ecosystems. Eugene P. Odum. BioScience. Vol. 35, No. 7, pp. 419-422.

Odum H.T. and E.P. Odum. 2000. The Energetic Basis for Valuation of Ecosystem Services. Ecosystems. 3:21–23.

Odum H.T. and J.E. Arding. 1991. Emergy analysis of shrimp mariculture in Ecuador. Environmental Engineering Sciences and Center for Wetlands University of Florida.

Odum HT, Brown MT, Brandt–Williams S. 2000. Handbook of emergy evaluation: A compendium of data for emergy computation. Folio #1: Introduction and global budget. Center for Environmental Policy–Environmental Engineering Sciences. University of Florida. Gainesville. 17 pp.

Odum HT. 1975. Energy quality and the carrying capacity of the Earth. Trop Ecol. 16(1):1–8.

Odum HT. 1988. Self organization, transformity, and information. Science. 242:1132–1139.

Odum, E.P., 1996. Environmental Accounting. Emergy and Environmental Decision Making. John Wiley and Sons, Inc., New York.

Odum, W.P., E.P. Odum and H.T. Odum. 1995. Nature's pulsing paradigm. Estuaries 18(4):547-555.

Ortega, M., Velasco, J., Millan, A., Guerrero, C., 2004. An ecological index for litoral wetlands in agricultural catchments of semiarid Mediterranean regions. Environ. Manage. 33(3): 412–430.

Parra, O. A Acuña., C. Valdovinos, R. Urrutia and B. Ruiz. Ecologically sustainable water management role of the academy to face the development? Pressures and challenges-experiences in Chile. Chapter 4. In: Ecological dimensions for sustainable socio economic development. Ed: Yáñez-Arancibia A., R. Dávalos-Sotelo, J. W. Day and E. Reyes. Boston, 600 pp.

Parrish, J. D., D.P. Braun and R.S. Unnasch. 2003. Are We Conserving What We Say We Are? Measuring Ecological Integrity within Protected Areas. BioScience. 53 (9):851-860.

Plafker, G. and J.C. Savage. 1970. Mechanism of the Chilean Earthquakes of May 21 and 22, 1960. Geological Society of America Bulletin. 81(4):1001-1030.

Potschin, M. and R. Haines-Young. 2016: Defining and measuring ecosystem services. In: Potschin, M., Haines-Young, R., Fish, R. and Turner, R.K. (eds) Routledge Handbook of Ecosystem Services. Routledge, London and New York, pp. 25-44.

Prescott, Allen R. 2001. The wellbeing of nations: A contry by Country Index of Quality of life and the environmental IDRC/Island Press, Canada.

Quezada, J., E. Jaque, A. Belmonte, A. Fernández, D. Vásquez and C. Martinez. 2012. Movimientos cosismicos verticales y cambios geomorfológicos generados durante el terremoto Mw=8,8 del 27 de febrero de 2010 en el centro-sur de Chile. Rev.Geo. Sur. 2:11-45.

Raffaelli, D. and S. J. Hawkins. 1996. Intertidal ecology. Chapman and Hall, London, UK.

RCE, 2018. Resolución Exenta Nº 1247 Reglamento de Clasificación de Especies 15to proceso. Ministerio de Medio Ambiente.

Renzi, J., H. Qiang, S. Brian R. 2019. Harnessing Positive Species Interactions to Enhance Coastal Wetland Restoration. Frontiers in Ecology and Evolution. 7:131.

Rojas, O., M. Zamorano, K. Saez, C. Rojas, C. Vega, L. Arriagada and C. Basnou, 2017. Social Perception of Ecosystem Services in a Coastal Wetland Post-Earthquake: A Case Study in Chile, Sustainability. 9(11), 1983. https://doi.org/10.3390/su9111983

Salas, F., J. Patrício, C. Marcos, M.A. Pardal, A. Pérez-Ruzafa, J.C. Marques. 2006. Are Taxonomic Distinctness measures compliant to other ecological indicators in assessing ecological status? Marine Pollution Bulletin. 52(7):817–829.

Scienceman, D.M.1987. Energy and Emergy. 257-276 pp. in Environmental Economics.Ed by G Pillet and T. Murota. Roland Leimgruber, Geneva.308 pp.

Solimini, A.G., Bazzanti, M., Ruggiero, A., Carchini, G., 2008. Developing amultimetric index of ecological integrity based on macroinvertebrates of mountain ponds in central Italy. Hydrobiologia. 597:109–123.

Srinivas, H. and Y. Nakagawa. 2008. Environmental implications for disaster preparedness: Lessons Learnt from the Indian Ocean Tsunami. Journal of Environmental

Management. 89: 4 – 13

Su M., B.D. Fath, Z. Yang, B. Chen, G. Liu. 2013. Ecosystem health pattern analysis of urban clusters based on emergy synthesis: Results and implication for management. Energy Policy. 59:600–613.

Sutton P. 2003. “An Empirical Environmental Sustainability Idex Derived Solely from Nighttime Satellite Imageru and Ecosystem Service Valuation”. Population and Environment. 24:293-311.

Tan X. Mac P., Bunn S. E., Zhang Q. 2015. Development of a benthic diatom index of biotic integrity (BD-IBI) for ecosystem health assessment of human dominant subtropical rivers, China Journal of Environmental Management Volume 151(15): 286-294.

Tilley, D. R. and W. T. Swank. 2003. EMERGY-based environmental systems assessment of a multi-purpose temperate mixed-forest watershed of the southern Appalachian Mountains, USA. Journal of Environmental Management. 69: 213–227.

Tilley, D.R. and M.T. Brown. 2006. Dynamic emergy accounting for assessing the environmental benefits of subtropical wetland stormwater management systems. Ecological Modelling. 192:327–361.

Ulgiati, S., M.T. Brown. 2009. Emergy and ecosystem complexity. Communications in Nonlinear Science and Numerical Simulation. 14:310–321.

Valdovinos, C., M.D. Muñoz, N. Sandoval, D. Vásquez, V. Olmos. 2011. Desastres naturales y biodiversidad: El caso del humedal costero Tubul-Raqui. Sociedad Hoy. 19: 33-51.

Valdovinos, C., Muñoz, M.D., Sandoval, N., Vásquez, D., y Olmos, V. 2010. Desastres naturales y biodiversidad: El caso del humedal costero Tubul-Raqui. Sociedad Hoy.10:33-51.

Valiela, Ivan and Fox, Sophia. 2008. Ecology - Managing coastal wetlands. Science (New York, N.Y.). 319. 290-1. 10.1126/science.1153477.

Vargas, G., M. Farías, S. Carretier, S. Baize y A. Tassara. 2010. Alzamiento cosísmico asociado al terremoto Mw8.8 en Chile central y efectos del tsunami entre los 33,2ºS y 39,8°S. LIA-MB. U. de Chile, U. de Concepción, IRD, IRSN. 22 pp.

Vassallo, P., I. Beiso, S. Bastianoni, M. Fabiano. 2009. Dynamic emergy evaluation of a fish farm rearing process. Journal of Environmental Management. 90:2699–2708.

Vivas, M.B. and M.T. Brown.2006. Areal Empower Density and Landscape Development Intensity (LDI) Indices for Wetlands of the Bayou Meto Watershed, Arkansas. Howard T. Odum Center for Wetlands, University of Florida. 160 pp.

Watanabe, K., Yaegashi S., Tomozawa H., Koshimura S. and Omura, T.,2014. Effects on river macroinvertebrate communities of tsunami propagation after the 2011 Great East Japan Earthquake, Freshw Biol. 59: 1474-1483.

Whitfield, A.K. 1994. An stuary-association classification for the fishes of southern Africa. South African Journal of Science.90:411-417.

Yang, X., P. Sui, X. Zhang, H. Dai, P. Yan, C. Li, X. Wang, Y. Chen.2019. Environmental and economic consequences analysis of cropping systems from fragmented to concentrated farmland in the North China Plain based on a joint use of life cycle assessment, emergy and economic análisis. Journal of Environmental Management. 251,109588.

Zhou, J.B., M.M. Jiang, B. Chen and G.Q. Chen. 2009. Emergy evaluations for constructed wetland and conventional wastewater treatments. Communications in Nonlinear Science and Numerical Simulation. 14:1781–1789.